ALPINE TECTONICS and the STUDY of ANCIENT MOUNTAIN-CHAINS: with special reference to the metamorphic rocks of the Scottish Highlands.

By

DONALD B. McINTYRE, B.Sc., Ph.D. (Edinburgh).

Thesis presented for the Degree of Doctor of Science,
The University of Edinburgh, 1951.

EXPLANATION of PLATES

N.B. The plates are enclosed in the roll accompanying the thesis.

PLATE 1. Structure-contour map of the base of the Dent Blanche gneiss (Pennine Alps). The elongated basin-shape of the base of the gneiss, made evident by the structure contours, shows that the Dent Blanche nappe is preserved in an axial depression. Between Zermatt and Zinal the plunge of the grand-scale structure is towards the south-west (cf. fig. II, 3); between the Valpelline and Aosta it is steeply towards the N.N.E. Some of the relatively small complications can be seen even on the scale of the figure.

PLATE 2. Structure contour map of the Hauenstein region (Jura)

PLATE 3. Three Jurassic sections constructed according to the principles outlined in the text.

PLATE 4. Block diagram &c., to illustrate the relationship between regional strike and axial-trend.

PLATE 5. Structure-map of the area from the Fannich Forest to Attadale (Wester Ross). (Observations made jointly with Dr. H. Rutledge).

PLATE 6. Geological map of the area between Grantown and Tomintoul, Mid-Strathspey.

B	Bridge of Brown	CH	Cromdale Hills
BG	Ballenluig	CL	Carn Liath
BH	Broomhill	D	Dulnain Bridge
BM	Beinn Mhor	G	Grantown
C	Cnoc Lochy	N	Nethy Bridge
CF	Cnoc Feargan	T	Tomintoul
CG	Craig Garten	TB	Tom Beag

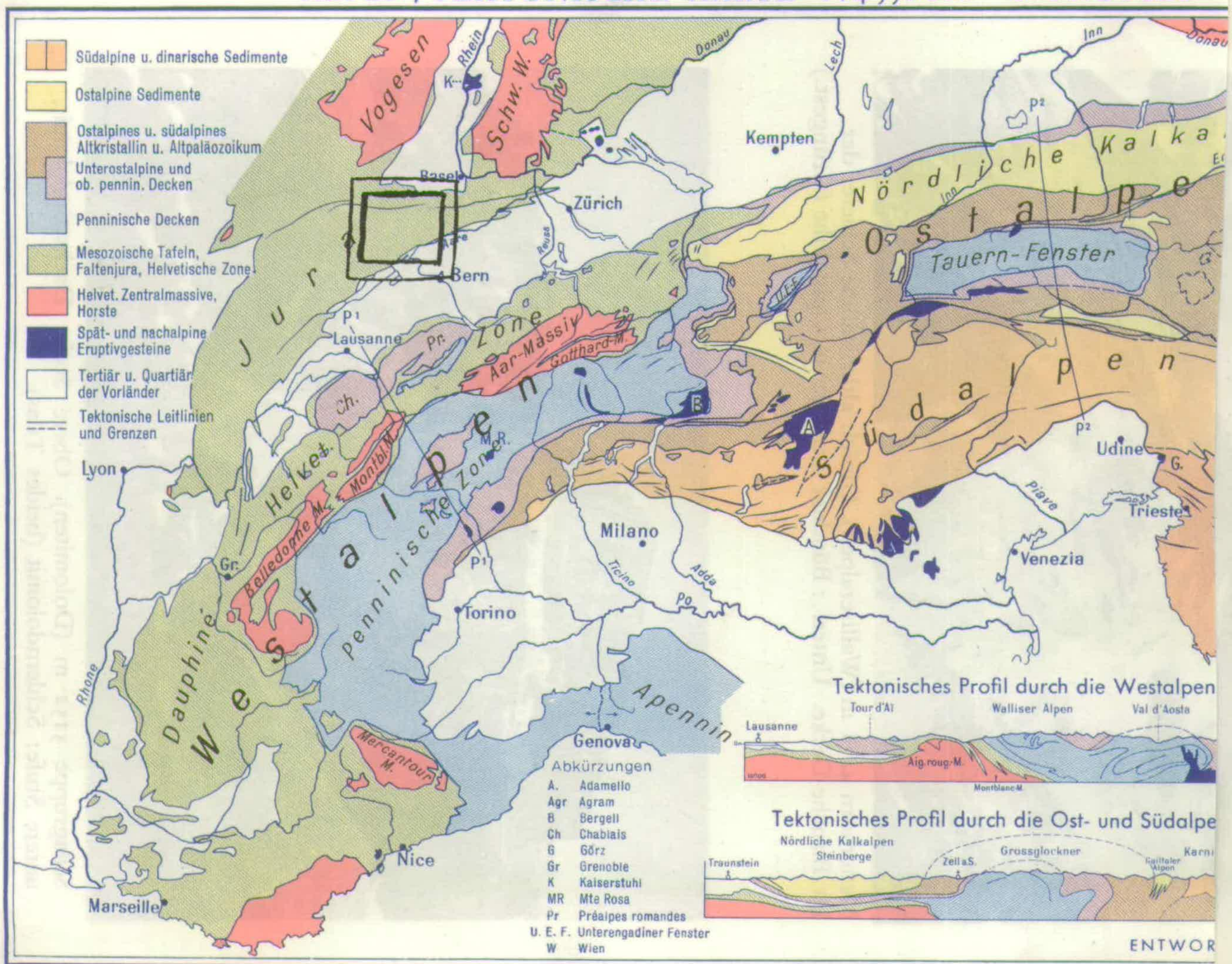
PLATE 7. Geological map of the Aviemore area, Mid-Strathspey.

PLATE 8. Structure-map of Garabal Hill.

PLATE /

Index. Plate 2.

ALPEN, TEKTONISCHE KARTE 1:4 550 000 U. PROFILE



Encyclios Verlag

PLATE 9. Structure-map of the environment of the Garabal Hill pluton.

PLATE 10. Provisional map of axial-trends in the Scottish Highlands.

I. INTRODUCTION

The work of the Alpine geologists, particularly the classic syntheses of Lugeon and Argand, constitutes the basis of modern tectonics. These workers, however, relied in considerable measure on the high topographic relief of the Alpine regions. The possibility of widespread application of their methods was not realised until Wegmann, Argand's pupil, assistant, and now successor, unravelled the complexities of the ancient orogenic belts of Fennoscandia and Greenland.

The writer was the guest of the University of Neuchâtel from July 1947 until August 1948, when he learnt at first hand something of Alpine geology. He wishes to record his gratitude to the Rector and Faculty of Sciences for their kind hospitality, and to the Carnegie Trustees and the Cross Trustees for the generous assistance which made the visit possible.

During and subsequent to his stay in Switzerland, the writer benefited from Professor Wegmann's unique knowledge of Alpine Tectonics and Ancient Mountain-Chains. Professor Wegmann gave most liberally of his time and experience; for this, and for his hospitality, patience, and continued guidance, the writer is deeply grateful.

Application of modern tectonic methods to Highland geology constitutes the major part of the present work. The preliminary /

preliminary sections of the thesis are devoted to an outline of the principles involved; after a brief historical review, the practical details of the method are summarised. This is followed by a discussion of the nomenclature; the latter, written in collaboration with Mr R.H. Clark, has been accepted for publication in the American Journal of Science.

Four illustrations are then given of the application of the method to the study of structures on a macroscopic scale. The first three of these have each been accepted for publication in the Geological Magazine. The fourth, a study of a Southern Upland section, describes structures on a somewhat larger scale than that of the other three. It is included here because the method of investigation employed in all four examples is the same the exposures are such that the folds may be observed directly.

Application of the method to larger areas is demonstrated in the principal part of the thesis. Two regions are described: the first is an area of some 200 square miles of Moine, with "Lewisian inliers", in Wester Ross; the second covers about 1,000 square miles of Moine and Dalradian in Strathspey and Strathavon. Each of these regions is discussed in two parts. The Beinn Dronaig area, Attadale, in Wester Ross, is described first and is discussed in detail. This is followed by a general account of the tectonics of the Fannich Forest, to the north, and /

and of the area between Fannich and Attadale; Dr. H. Rutledge collaborated with the writer in the study of the Fannich Forest. The description of the Strathspey and Strathavon region begins with an account of the tectonics of the area between Grantown and Tomintoul; this account has been accepted for publication by the Geological Society of London. The paper was read at a meeting of the Society in November 1950, and a summary of the discussion is included in the thesis. This is followed by a general account of the tectonic environment of the Grantown-Tomintoul area. In this, special attention is given to the area around Aviemore, to the south of Grantown.

The final chapters of the thesis are devoted to granite tectonics, and their inclusion requires explanation. Macroscopic methods of investigation of plutonic complexes were first elaborated by Professor Hans Cloos of Bonn, Germany. His pupils have carried his technique to other countries, particularly to the United States, and the importance of this field of study is at last being recognised. Since 1947 the writer has been in close touch with Professor Cloos. Relations between the Edinburgh and Bonn schools were greatly strengthened by the visit, in 1948-49, of Dr. G. Oertel, a member of Professor Cloos' staff. During his stay of a year in Edinburgh, Dr. Oertel investigated both volcanic and plutonic complexes, and the writer was privileged to /

to accompany Dr. Oertel while he was engaged in that work. As a result of the interest thus stimulated in granite tectonics, the writer has made a structure-map of the Garabal Hill pluton.

For convenience, a brief resumé is given of the technique used by the Bonn school. This is followed by an account of a modification of the Cloos method that has been developed by the writer in collaboration with Mr R.H. Clark. The account of the structure of the Garabal Hill pluton represents a combination of the methods of Wegmann (on the country rocks), and Cloos (on the granitic rocks).

Since his return from Switzerland in 1948, the writer has been preparing a structure-map of the whole of the Scottish Highlands. Although much more work remains to be done, it is felt that even in its present form, as a generalised map, it is of sufficient importance to be included here.

The final section is a summary of the whole, and contains some general conclusions. The appendix includes illustrations of Scottish examples of cylindroidal folds.

II. ALPINE TECTONICS AND THE STUDY OF ANCIENT MOUNTAIN-CHAINS: a historical review.

ABSTRACT

Geosynclinal chains are frequently characterised by regularity of plunge of the fold-axes over wide areas. Profiles, representing undistorted cross-sections, are constructed by projecting the map, in the direction of plunge, on to a surface at right angles to the fold-axis. Longitudinal sections follow the direction of the fold-axis. The integral relation of map and profile is pointed out and its three-dimensional aspect is emphasised. Only by this method can the style of the grand-scale structures be determined. Some of the errors arising from the use of the conventional methods of section-drawing are discussed.

The development of the method by the Alpine tectonicians (Schardt, Lugeon, Argand) is outlined, and Wegmann's adaption of the technique to the study of peneplained ancient mountain-chains is described. Some preliminary results of the application of Wegmann's method to the Scottish Highlands are given.

CONTENTS

D. SOME COMMENTS by PROFESSOR LUGEON

E. BIBLIOGRAPHY

A. INTRODUCTION

Many of the varied methods used in modern tectonics were conceived in the Swiss Alps; hence the history of Alpine Research is of fundamental importance in the study of mountain-chains of all ages. We do not wish to suggest that the Alps be taken as a pattern to which all other chains correspond; we wish to stress the methods rather than the results.

The history and results of Alpine structural geology are available for English readers in the excellent summaries made by Professor Collet and Sir Edward Bailey, to whose writings and the literature therein referred to, one must turn for the broader picture. A particular aspect of Alpine Research, however, calls for further study and exposition. It is the axial method of tectonic analysis which has been developed by a succession of brilliant Swiss geologists, Maurice Lugeon, Emile Argand, and Eugène Wegmann. The present paper is an attempt to expound this method and to illustrate its application to countries of low topographic relief.

It must be emphasised that the axial method is only one of many techniques used in modern tectonics. It will not solve /

solve all problems, and its application is justified only within certain limits.

(i) <u>On Cylindroidal Surfaces</u>

The most surprising feature of a section deep within a geosynclinal chain is the regularity of the plunge of the folds. In two dimensions one sees the amazing complexity of disharmonic folding and <u>décollement</u>; each layer seems to have folded independently, and no order can be seen in the disorder. For this reason some have claimed that the complications were so great that they would never be resolved. In marked contrast to the apparent chaos in two dimensions is the relative order and simplicity in the third. Unfortunately the "réglage" (Lugeon and Argand) of the folds, i.e. the parallelism of fold-hinges over more or less wide areas, is not always noticed. Faced with such structures, "two-dimensional" thinkers see nothing but the complexity; they are blind to the third dimension that often contain paradoxically, the one element of simplicity present, and the key to the tectonics.

The degree of regularity in the third dimension is not always the same. Each layer follows its own law, and analysis of this phenomenon gives valuable data for estimating the relative mobility of the rock-types present (Wegmann). Under certain conditions the complexity may be equally great in all dimensions. Wegmann /

Wegmann has shown this phenomenon to be widespread in the Fenno-scandian migmatite complexes, and the writer has found it to be equally common in the Scottish migmatites. Similar mobility without "réglage" has been found in the aureoles of so-called apotectonic or "circonscrits" granodiorites (D.L. Reynolds; H. Rutledge).

In spite of the fact that mobilisation may affect certain parts, many highly-folded regions are characterised by the "réglage" of their folds. Schardt employed the concept of cylindroidal surfaces, conceived on the grand-scale, to demonstrate the tectonic relations of the Pre-Alps and the Klippes. Lugeon defined it, used it as the key to the High Calcareous Alps, and indicated its application to the great gneiss masses of the Pennine Alps. His pupil, Argand, worked out the application to the Pennines in a manner at once so detailed, so concise, and so lucid, that his monograph (1911) ranks as one of the great classic of our science. Wegmann, Argand's pupil, assistant and now successor, served his apprenticeship in the Pennine Alps; there he had a thorough grounding in the methods of "external tectonics" so wonderfully developed by his teachers.

Argand had deciphered the grand-scale structures in the Pennine Alps, and had realised that he had there the key to the French-Italian Alps as well. The detail, which had always been emphasised by Heim, was added by Wegmann, and the science of "internal /

"internal tectonics" was developed. Continued work in the Pennine Alps is showing today how much further one can go by adding the measurement and analysis of the small and intermediate-scale structures to Argand's analysis of the grand-scale structures. This work also shows how dangerous would have been an attempt to decipher the structure of the Alps from the micro-analysis (petrofabrics) of a few random specimens collected without knowledge of their position in the big-scale structures.

On every scale, each tectonic element must not only fit into a larger environment, but it must have an internal structure. In Wegmann's metaphor, if we use a hand-lens to study a large mosaic we will fail to see the picture; on each scale there are appropriate instruments and methods. The correspondence or non-correspondence of the external form and the internal structure of a tectonic unit is vital for elucidation of its history.

Wegmann's knowledge of the relation of small- and big-scale structures stood him in good stead when he joined Sederholm's band of workers on the Pre-Cambrian of Finland. He adapted the Lugeon-Argand technique, and showed how it could be used to unravel the structure of peneplained mountain-chains. The Scandinavian maps were well-furnished with structural data, but only Wegmann realised their significance. He had learnt to use the data so often recorded and so seldom understood. Before setting /

setting out for Scandinavia, Wegmann had constructed profiles across the Norwegian and Finnish maps, had understood the style of the tectonics he was about to see in the field, and knew where the data were most in need of elaboration or of revision. He was thus able to proceed at once to the critical areas to check his interpretations and to collect further data where they were most required. In his own metaphor, the study of Pre-Cambrian tectonics had been conducted as if one were to go rabbit-shooting blindfolded with a machine-gun; he took a rifle to Finland and got a rabbit with every shot.

Not only has Wegmann provided us with many examples of tectonic analysis from Scandinavia and from Greenland, but, in a paper (1929) as important as Argand's 1911 monograph, he has given us a detailed description of the method employed. Yet twenty years after the publication of this paper there is no sign that English-speaking geologists are aware of its existence.

The Lugeon-Argand method gave the key to the external tectonics of the Alps. Wegmann adapted this method and made it the key to peneplained complexes. The present writer has found immediate success in applying the technique to the Scottish Highlands. It is obvious that there is great need for its more widespread application, and it is hoped that this paper will bring it to the notice of English-speaking geologists, demonstrate its /

its utility, and assist the field-worker in its practical application.

It must not be thought that the axial method will solve all structural problems. Its application, though wide, is not universal. The Dinarides of the Tessin are characterised by faulting, and separate fold-systems prevail in each fault-block; in a region of such tectonic style, indiscriminate application of the axial method is subject to obvious danger. Again, in the Eastern Alps an imbricate (or schuppen) style often predominates. For this reason there was at one time a certain amount of misunderstanding between East and West Alpine geologists. In short, axial methods are of greatest utility when applied to regions with a style characterised by cylindroidal folds rather than faulting.

Argand distinguished foundation folds (plissements de fond), geosynclinal folds, and cover folds (plissements de couverture). Foundation chains, he wrote, tend to be "réglées", i.e. to possess an approximate cylindroidal parallelism of the <u>external</u> structures. Foundation folding is the folding of the continental mass itself; cover folding, on the other hand, affects only the thin layer down to the "great basal discordance". It is with geosynclinal chains that we are particularly concerned in this paper.

(ii) /

(ii) Tectonic Analysis

"Tectonics is the study of a three-dimensional solid undergoing deformation in all its parts" (Argand, 1920). Tectonic analysis must therefore begin with geometric analysis, i.e. the study of the final forms of the tectonic units considered. Argand defines this "tectonique en arrêt" as the art of defining the present state of the structures. Reliable observations are the prime requirement. The question is essentiall one of geometric fact, not of theory. But for its completion, to the geometric analysis must be added the kinematic, the analysi of the movements, the "tectonique en mouvement". "The volumes, surfaces, and lines, in a word the structures that compose a tectonic edifice are not all; there is the movement that animated that still animates these things, for history continues and we live, without any kind of privilege, at a random moment in this great affair. The 'tectonique en mouvement' would be in the end tectonics achieved, an uninterrupted history of the deformation of the planet, where the evidence would be complete and without gaps. This ideal cannot be realised, but for a long time yet we will move towards it, provided that the geometry, the necessary starting point, be correctly elucidated to the fullest possible extent, and provided that this most delicate and subtle art of kinematic analysis be practised correctly. For we cannot /

cannot see the movement as we can the structures: the mind must recreate the movement; and this must be done in such a way as will explain, throughout the ages, the evidence preserved: and finally it must be suggested in the form of a picture. There is no tectonic synthesis without the vision of a continuity in three dimensions undergoing deformation" (Argand, 1924).

This philosophy has been elaborated by Wegmann. All structural analysis, he insists, must start with observation. The first task is therefore to obtain as complete as possible a spatial image of the present structure. In tectonics, embryology comes out of anatomy (Argand). Forces, pushes, and energies cannot be observed by geological methods. Elementary physics teaches that the same movement can result from an infinite number of combinations of forces. Whereas the movement traces are directly observable, the choice between the possible forces is always arbitrary. The distinction between Geometry, Kinematics, and Dynamics is part of the ABC of Tectonics.

(iii) Stratigraphy as a Tectonic Tool

Tectonicians owe a great debt to stratigraphers. Indeed in the past it was the stratigrapher who was the structural geologist. Today many still consider that structural geology is but a branch of stratigraphy; they have failed to realise that the developments during the past fifty years have made tectonics /

tectonics as much a separate study as stratigraphy is. The tectonician must use stratigraphy, just as the stratigrapher uses palaeontology. The contribution of stratigraphy is obvious in the study of cover folding; in the study of the Jura, of the High Calcareous Alps, and of other non-metamorphic terrains, it has played a vital role; in the Pennine Alps it is of less importance and its concepts cannot be applied so rigidly. As Argand pointed out (1911), in order to reconstruct the great folds it is not necessary to have sharp stratigraphic junctions: "the stratigraphic continuity, based on material, does not at all contradict the tectonic continuity, based on form. These are different things, partially oblique one to the other. ..... It is possible in certain cases to recognise the structural forms by using a certain minimum of stratigraphy, and then to unroll them to find out, so far as is possible, how the material studied in detail by the stratigrapher is distributed in the forms recognised by the tectonician".

In completely metamorphic terrains, deformation may have been so great that the rules of stratigraphy cease to apply. In many parts of the Scottish Highlands the general degree of décollement has been at least as great as in the Alps. Every layer has glided over those layers with which it is now in contact; some have become unstuck and, having moved off on their own /

own, are now found between layers with which they have no direct stratigraphic relation, and this has taken place on almost every scale. Many of the contacts, possibly the majority, are tectonic and not stratigraphic; yet the layers are thoroughly welded together and show no obvious field-evidence of thrusting in the commonly understood sense of the term. This style of deformation (signaled by Sir Edward Bailey in 1908-1909), together with the metamorphic grade and consequent absence of palaeontological evidence, makes it impossible to use stratigraphical methods and criteria to work out the structure.

In recent years much work has been done in the Scottish Highlands on the basis of the interpretation of such sedimentary structures as current- and graded-bedding, and of the correlation of distant rocks on purely lithological grounds. Such evidence must be used with caution. The writer has seen excellently preserved current-bedding in the Loch Leven district, and therefore does not deny the fact of its existence in some of the Highland metamorphics. Nevertheless one must remember that structures closely resembling current-bedding can be produced tectonically. Each example must be subjected to the most rigorous three-dimensional analysis before it can be accepted.

A more serious difficulty is raised by the style of the tectonics. The writer is familiar with many exposures in the Mid-Strathspey /

Mid-Strathspey region where siliceous quartzites can be seen in a series of "concertina folds", the limbs of which are nearly horizontal. In some exposures a thin layer of mica schist within the quartzite makes the folding conspicuous; but in other cases the quartzites are reduplicated by concertina folding in such a way that, without the most careful examination, the exposure would pass for one of massive quartzite. The effective plasticity of the rocks has been so great that it is doubtful whether any sedimentary structures that might be preserved would be of any structural value. In a tectonic environment characterised by concertina folding, such evidence would be of use only if every turn and twist of the folding could be determined; and he would indeed be bold who claimed that he could do this with certainty.

Even if it should some day prove possible to determine the top and bottom of such a quartzite, this would carry us very little further. The tectonic style is characterised by gliding of layer over layer, and moreover not all necessarily moved in precisely the same direction or at the same speed. Many layers are sandwiched between beds that have no direct stratigraphic relation one to the other, yet the structure is not imbricate for there was no fracturing. In such terrains stratigraphy can come only from tectonics. To attempt to determine the structure by the /

the supposed stratigraphy can easily lead to error. The key to such a region is the axial method of tectonic analysis.

(iv) Correlation of Orogenies by their Trends

For some years it has been current practice to date orogenies by their supposed trends. This cannot but lead to serious error unless the chains compared have been subjected to rigorous tectonic analysis or the trend is determined on the largest scale. Apart from certain features of the internal tectonics that belong to pre-Alpine movements, the structural features of the Alps are due to one single, if prolonged, orogeny. This is why the Alps form so useful a standard for comparative tectonics. In the Alps we know the shapes of all the great folds and can deduce the direction and sense of the general movement. The great majority of the folds are perpendicular to the direction of transport; but there are some notable exceptions, particularly in the root region and the frontal folds of the Pennine nappes.

The Pennine nappes consist of gneiss cores mantled and separated one from another by the schistes lustrés. The latter played the tectonic role of lubricants for the great nappes, and their detailed structure is accordingly highly complex. The writer was fortunate in accompanying Professor Wegmann for some weeks at Zinal (south of Sierre) where Professor Wegmann has made /

made a detailed study of the complications below the Dent Blanche nappe. The writer was amazed at the clear demonstration of movement in different directions at different levels. Differential movement is also easily seen above and below the famous tectonic inclusion ("worm") of Trias in the Trift gorge at Zermatt. We must accept the fact that in one orogeny differential "flowage" can occur, and that over neighbouring areas, which may be measured in miles, the tectonic directions can be totally different. Moreover this phenomenon is found even where the movement has been so constant in direction on the grand-scale that no complications arise when the first approximation, the study of the external tectonics, is made.

(v) The present Position in Scotland

Over an area of some five hundred square miles in the Scottish Highlands, the Moine and Dalradian are folded together along axes trending north-west - south-east. But in other areas of the Highlands, totally different directions are followed. In fact even in the area referred to, local complications have given rise to "anomalous" regions similar to those mentioned in the Pennine Alps. It is obvious that much more work must be done before we can determine the dominant direction of the Highland folding. We must begin with the largest scale structures that /

that we can determine and work down to those of the smallest scale. Study of samples measuring a few cubic inches taken at random, may give a totally false picture of the big-scale structures, no matter with how much care those samples are studied.

Highland work has too often been characterised by the introduction of kinematics, and even of dynamics, at a stage when the geometric analysis had not been completed; by the attempt to decipher structure using very uncertain stratigraphy; and by the extrapolation from the micro-scale to the grand-scale, when the data of the intermediate-scales had been totally ignored. In short, methods, facts, and theories have often been in confusion. Geometric analysis is essentially a question of fact; it is the study of what is actually there; therefore, in general, difference of opinion is capable of resolution, provided that fact and theory are distinguished on the maps <u>and on the sections</u>.

The Swiss téctonicians have shown the way. Fold-directions must be distinguished from fold-traces; sections must be oriented relative to the fold-directions, and must be constructed by geometric projection of the whole data available on the map. "We must conceive the picture in three-dimensions. Maps and sections are two aspects of the same body deformed at the same time by the same agents" (Argand, 1912). Too often it is believed that lines drawn "in the air" are incapable of verification /

verification and may be drawn to fit the particular hypothesis supported. Too often do full lines drawn below ground give the appearance of a reality which they do not in fact possess; this is a fact that can frequently be verified by comparison of the section and the map (cf. Bailey, Textbook of Geology, 1939, fig. 52). Sections should differentiate clearly between lines that represent projected observed fact, and lines that are purely speculative.

How was it that the Swiss geologists were able to lead the world in the development of modern tectonics? The prime reason was doubtless the wonderful exposures on the bold precipices of their beautiful mountains. As Lugeon expressed it in 1913: "By the fact that our Alps profoundly dissected by deep valleys, present these great phenomena [the nappes] so convincingly, it is in our Swiss Alps, and in particular in our Vaud chains, that the new theory has found a sure basis and become triumphant". Certain it is that we in Scotland cannot compete with such exposures as these; but our data[1] can be used just as the Swiss data have been. If we construct our sections according to the principles of three-dimensional geometry, fact and theory will be separated naturally. And let us point out, with Argand, that we are concerned here with concrete tectonics and not with orogenic theory.

[1]In all his publications, Sir Edward Bailey has stressed the importance of "pitch".

B. THE SWISS ALPS

(i) The Structural Elements of Switzerland

Thinking of Switzerland as a mountainous country, many people forget that Geneva, Lausanne, Neuchâtel, Berne, Lucerne, Zurich, and St. Gallen are cities of the plain. The extensive tract of relatively flat ground on which they stand is called the Swiss Plateau. To the south rise the imposing chains of the Alps; to the north and west is the long arc of the Jura. Each of these three topographic divisions is a structural unit of the first order.

The High Alps is the country *par excellence* of nappes. The deepest and most deformed are the nappes of the Pennine Alps; these "root" on the Italian side of the Alps, and their frontal folds reach the Rhone between Martigny and the Simplon tunnel. The crystalline cores of the Pennine nappes are mantled by the Mesozoic *schistes lustrés* in which cleavage has nearly everywhere obliterated the bedding. As the Pennine nappes are traced eastwards, the great axial culmination over the Tessin (approximately between Locarno and the St. Gotthard), carries the highest of them into the air and exposes the deepest. The tectonic depression to the east of the Tessin brings the Pennine nappes down again to the present surface. East of St. Moritz, the highest of the Pennine nappes is carried below the Austrian Alps, but /

but may be seen again in the Tauern window.

The nappes of the High Calcareous Alps (Helvetic) lie immediately north of the Pennines. They root along a line that follows the valleys of the Upper Rhone and the Upper Rhine, from Martigny to Chur (Coire). Because of axial culminations, the crystalline basement on which they rest emerges in the massives of the Mont Blanc - Aiguilles Rouges and of the Aar - St Gotthard. The Aar culmination (north of the Simplon tunnel) corresponds to that of the Tessin in the Pennine zone to the south. A small window north-west of Chur is the last appearance of the crystalline basement before it and its cover of nappes disappear, to the east of the Rhine, underneath the Rhätikon of the Austrian Alps. The demonstration of the passive role of these crystallines was one of the most important milestones in the history of Alpine Research.

Between the High Calcareous Alps and the Swiss Plateau lie the Pre-Alps. They were separated by Renevier as the "Pré-Alpes romandes" (i.e. of French-speaking or western Switzerland) because of the stratigraphic contrast between them and the High Calcareous Alps. The Pre-Alps stretch from the River Arve (which enters the Rhone at Geneva) to the River Aar at the Lake of Thun. They are thus divided in two by the Rhone; the south-west or French Pre-Alps are known as the Chablais: the Swiss Pre-Alps extend from the Rhone at Montreux to the Lake of Thun, and /

and include the prominent peak of the Stockhorn. The famous Klippes of Unterwalden and of Schwytz (on either side of the Lake of Lucerne, and including the Mythen) to the north-east, and of Annecy (south of Geneva) to the south-west, are tectonic outliers of the Pre-Alps; they are the type klippes. The whole mass of the Pre-Alps is a nappe-complex which has come from the south over the top of the High Calcareous Alps, and perhaps in part over the Pennines as well, but which is now separated from its roots by erosion. It is a gigantic klippe.

The debris of the growing chain accumulated in front of it, and is now seen in the conglomerates and sandstones of the Swiss Plateau. This great deposit thins rapidly when traced northwards, and there is no doubt that it was nourished from the south. These sediments, the Molasse, find their equivalents in many of the older chains of the world; we may cite the Old Red Sandstone of the Caledonides as an examples.

The arc of the Jura Mountains is a chain of peculiar interest. Its sediments, mainly Mesozoic, became unstuck (décollement) from the crystalline basement and folded separately. The décollement was facilitated by the basal Trias which contains gypsum and salt. The folded Jura, which rises above the Plateau, has been thrust at some localities over the tabular Jura, which extends into France.

(ii) /

(ii) The Pre-Alps

As long ago as 1825, B. Studer had noticed that the Miocene conglomerates of the Plateau contained rocks of types unknown along the northern front of the Alps. He suggested (1834) that they were derived from a marginal chain which had been denuded down to its crystalline core. The presence of exotic blocks in the Flysch of the north front of the Alps was also recognised by Studer. These facts may appear to have little relevance to the Pre-Alps, but in the early years of Alpine Research it was believed that in fact the Klippes represented an ancient marginal chain. They were supposed to be relics, rooting in situ of an ancient chain almost entirely destroyed by erosion and now half buried under younger sediments. Thus the young base and old summits of these hills was explained by the hypothesis that they were fossil cliffs (Kaufmann, 1875) protruding from the debris which had covered them.

In 1884, Marcel Bertrand put forward the very bold hypothesis that the Stockhorn Pre-Alps were part of a great nappe coming from the south and now detached from its root. This suggestion was put forward by Bertrand before he had visited the ground, and although his paper created considerable interest, it did not win much support. Meanwhile the detailed field-studies continued. Stutz (1890) recorded that the Mythen and neighbouring Klippes consist of Jurassic resting on Trias; that these Jurassic /

Jurassic-Trias masses occur in a Cretaceous-Tertiary syncline; and that the Trias had once formed a complete basin. As Schardt has pointed out Stutz came very near to realising that the Klippes were relics of a Mesozoic sheet resting on a Tertiary substratum.

In 1890 Schardt submitted a memoir which gained the Schläfli prize of the Swiss Society of Natural Sciences. His object, he tells us, was to show the way in which the problem could be solved. "The majority of our geologists have not dared to deduce that which the eye cannot see; however the definition of the invisible underground structure is one of the essential tasks of a geologist, assuming, of course, that his theory is based on numerous facts observed on the ground". A great amount of data had been recorded; the facies contrast between the Pre-Alps and the Helvetics, for example, was well known. Schardt emphasised that tectonics had to be used as well as stratigraphy. "The way that can lead to a solution is to define the relations between the exotic blocks in the Flysch and the Klippes on one hand, and between the latter and the terrains of the Stockhorn zone, which is missing to the north-east of the Lake of Thun, on the other. But this can be done only on the basis of close tectonic study, applying the new views just brought to light by the researches of tectonicians like Heim, Bertrand, and /

and Gosselet". Even in this early memoir, he considered the Klippes as gigantic exotic blocks resting on top of the Flysch; the origin of the rocks of Austro-Alpine facies in the Miocene conglomerates he connected with the disappearance of larger Klippes which had once existed along the northern front of the Alps, and which were destroyed by Miocene erosion.

Schardt gradually became convinced that the tectonics of the Pre-Alps and the Klippes, the exotic blocks, and the facies of the Flysch formed but one chain of enigmas, and that one single phenomenon must explain them all. He realised that everywhere the Trias, Permian, or Carboniferous base of the Pre-Alps rests on a younger, usually Tertiary (Flysch), substratum. This is the famous "Law of the Pre-Alps". Moreover he saw that this travelled sheet was preserved in a structural depression. It was geometry that led him to the view that the whole mass of the Pre-Alps is a gigantic Klippe, and that the Klippes of Annecy, in the south-west, and those of Unterwald, Schwytz, and Glarus, in the north-east, are but relics of a once continuous sheet. Each individual Klippe represents in miniature the whole mass of the Pre-Alps.

The Klippes and the largest of the exotic blocks are relics of the enormous, superposed, pre-alpine sheet. Miocene rivers eroded it, and its debris nourished the conglomerates of the Plateau. At the beginning of the Miocene, the nappe was /

was still continuous. Originating in the Central and Southern Alps, it slid towards the north, lubricated by the Triassic gypsum and dolomite at its base. It is not a recumbent fold. It passed over the top of the High Calcareous Alps and over the crystalline massives (St Gotthard, Aar, Mont Blanc, Aiguilles Rouges, Belledonne, &c.), pushing and dragging huge slices of the crystallines with it. Its debris nourished the breccias and sandstones of the Flysch over which the mass advanced.

Between the Aar and the Rhine, and again south-west of the Arve, the sheet has been almost wholly destroyed by erosion; but the Klippes remain as evidence of its former extension. Following the syncline, which contains the Klippes, towards the east, one is led by a trail of Klippes, exotic blocks, and breccias in the Flysch, to the Vorarlberg. Immediately to the south, the Flysch, with its breccias, disappears below the Trias-Lias cover of the Rhätikon. It is thus probable that the pre-alpine nappe was once continuous with the Rhätikon of the Austrian Alps. The facies of the Pre-Alps and Klippes passes gradually into that of the Austrian Alps. The Klippes of Annecy, the Pre-Alps, the Klippes of Unterwalden and of Schwytz, and the Rhätikon originally formed one single nappe, resting with a tectonic discontinuity on the terrains of Helvetic facies. This, in brief outline, is the theory put forward in its classic form in 1893. It explains:

1. /

1. The contrast of stratigraphic facies and tectonic style between the Pre-Alps and the Helvetics.

2. The superposition of older beds on younger.

3. The facies of the Flysch (breccias of exotic material &c.)

4. The origin of the exotic blocks in the conglomerates of the Plateau.

5. The origin of the Klippes.

For Hans Schardt all this was but one single "jet d'idées". Based on a vast amount of detail, it is one of the great syntheses of our science. Schardt, a meticulous and infinitely painstaking worker, had the rare gift of being able to conceive surfaces in three-dimensions. His was the genius that realised that the Pre-Alps were but a fragment of an immense sheet. By following the structural depression in which this great and complex fragment is preserved, he discovered that the Klippes were merely smaller fragments of the same great nappe. This, surely, is "solid" thinking on the grand-scale.

(iii) The High Calcareous Alps

When the science of mountain-structures was very young, great importance was attached to the concept of fan-folding. As a result of the work of Escher and of Heim, it was generally believed that the famous "Double-Fold" of Glarus was an example of this type of folding. In the Glarus Alps some of the summits are composed of ~~younger~~ older rocks than those found on the valley floors /

floors. Heim explained this by the hypothesis that the nose of a great recumbent fold coming from the north had almost met the nose of a similar fold advancing from the south. Some felt that inversions on such a scale weré inconceivable, but Marcel Bertrand in his classic paper of 1884, without ever having visited the area, pointed out that mechanically it was simpler to picture one gigantic overfold coming from the south; this effectively doubled the extent of the inversion. The southern of Heim's folds was the root, and the northern was the half-buried nose of Bertrand's great nappe. The nappe itself was arched into a huge antiform; erosion having attacked the crest of this arch, the nose of the nappe is now separated from its roots. Heim, and the majority of Swiss geologists, was won to the new view only as a result of the work embodied in Maurice Lugeon's publications of 1901. Heim's recognition of the northward travelling nappe is recorded in an appendix (1902) to Lugeon's 1901 memoir; the gracious terms of Heim's note is a magnificent indication of the magnanimity of this great pioneer.

The Glarus fold lies to the east of the Aar culmination. Lugeon's detailed work, however, was on the chain of the High Calcareous Alps between the Mont Blanc and the Aar. It was to this latter region that Jean and Phillippe de la Harpe referred (1859) when they wrote: "We have before our eyes in the chain of the Meuvran /

Meuvran, the remains of an immense fold that embraces the whole chain and in which the present topographic surface has been carved". The basis for further advance was established by Renevier's careful mapping of this region, and the publication of his classic memoir in 1890 in which he demonstrated that the massif of Morcles was a great recumbent fold.

In his masterly study of the origin of the valleys of the Western Alps (1901), Lugeon demonstrated that the surface of the Aiguilles Rouges crystallines descends from south-west to north-east when followed across the Rhone Valley north of Martigny. The great recumbent fold of the Dent du Midi (west bank) - Dent de Morcles (east bank) rests on this basement and descends with it towards the north-east. See figs. II,1 and II.2. This fact had already been shown in the sections of Renevier and of Schardt, but it is to Lugeon that we owe the demonstration of its significance.

Pointing out the errors that can arise by employing incorrect methods of determining the fold-axis, Lugeon stressed that "this evaluation can be made on any line whatever, provided that it be parallel to the hinge of the fold".

"At Saint Maurice, in the narrow defile of the Rhone, we can assure ourselves that, to the north-east of the river, the descent of the lower normal limb of the fold continues in a straight /

straight line. On a line perpendicular to the valley [and parallel to the fold-axis] we determine the following altitudes of the Flysch-Cretaceous contact: west bank 840 m.: east bank 540 m. It is therefore beyond question that the fold continues to descend after having crossed the valley. If we try to determine the form of the median limb of the great recumbent fold, we find that it is nearly horizontal in the Dent du Midi [west bank] , and that it appears in the Dent de Morcles [east bank] at an altitude almost equal to that in the Dent du Midi. But beyond the Dent de Morcles [i.e. to the north-east] , once the Rhone has been passed, the plunge of the fold-axis is seen with the clarity of a diagram. ... This descent of the folds to the north-east is explained by the plunge of the crystalline massif that acts as their basement". See fig. II.1.

To the north-east of the Dent de Morcles lies the great massif of the Diablerets. See fig. II.2. Realising the immense significance of the continued axial-plunge to the north-east, Lugeon continued: "I believe today that the massif of the Diablerets must be considered as a vast recumbent fold that lies on top of that of Morcles at the point where the latter disappears The north-south direction of the outcrops in the Val de Treis Coeurs is due only to erosion and to the fact that the recumbent /fold-nappe ~~of the Diablerets plunges to the north-east like that of~~ /

fold-nappe of the Diablerets plunges to the north-east like that of Morcles. Under these circumstances, the Diablerets nappe at one time must have covered a good part of the Morcles nappe, well beyond its present westerly limits. ... Now, without entering into a detailed description, one can see that on the nappe of the Diablerets there existed yet another, the Jurassic core of which builds the Mont Gond". Shortly afterwards Lugeon's great memoir on the nappes of the Chablais and of Switzerland was published. In it he showed that the nappes continue to plunge towards the north-east from the Dent de Morcles to the Wildstrubel; thereafter they rise again. There is thus a vast axial depression between the Aiguilles Rouges and the Aar massives. See fig. II.2. Lugeon refers here to the "virtual continuation" of the Diablerets nappe over the top of that of the Dent de Morcles, because the effect of the Diablerets nappe on the Pre-Alps can be traced as far west as the Rhone valley. Thus the proof is complete that "on top of the great recumbent fold of the Dent de Morcles there must have existed a second fold quite as considerable, but this has been entirely destroyed by erosion. ... As the crystalline core of the prolongation of the Aiguilles Rouges, on which the Morcles nappe rests, sinks towards the north-east, the mass of the upper fold then occupies the ground surface, covering completely and decisively the lower fold /

fold. ... The great zone of axial depression between the Aiguilles Rouges and the Aar massives brought it down and protected it from erosion".

Applying the same method, Lugeon went on to show that the Wildhorn nappe (Mont Gond) was even bigger and tectonically higher than the Diablerets nappe, and that the Internal (i.e. southern) Zone of the Pre-Alps is the relic of a still higher nappe that can be traced to its roots in the Rhone between Sion and Sierre. See fig. II.2. Conceiving the whole chain of the High Calcareous Alps with the breadth and depth of vision that belongs to genius, Lugeon showed that there was no possibility of finding another pre-alpine fold attached to its root, whereas the Morcles nappe could be expected to occur again west of the Aar massif. See fig. II.2.

(iv) The Pennine Alps

The complexity of the geology in the neighbourhood of the Simplon has long been known. B. Studer recognised the superposition of gneiss on limestone there as long ago as 1846. But it was the early proposal (1853) to drive the Simplon tunnel that gave the area a special importance. In order to choose the best line for the tunnel, much attention was focussed on the region, and numerous geological sections were published. Already in 1859, H. Gerlach submitted a report and sections, but unfortunately /

unfortunately, the oldest of Gerlach's sections still preserved is one of 1869. In it the Antigorio gneiss is shown in the form of a gigantic recumbent fold closing towards the north. Gerlach's death in 1871, as a result of an accident, robbed Alpine geology of one of its greatest pioneers.

From 1877 onwards a whole army of brilliant geologists concentrated on the Simplon; among the famous names are those of Renevier, Heim, Lory, Taramelli, Golliez, Schmidt, and Traverso. In 1890 Hans Schardt began work for the tunnel engineers, and he submitted his first manuscript report during the same year. Schardt tells us that by 1899 he had become convinced that the region consisted of an anticline of nappes; their roots are in the south, and their heads are buried in the schistes lustrés in the north, so that the structure simulates a gigantic anticlinorium. The lowest nappe is the Antigorio; the wedges of gneiss of the Monte Leone and the Lebendun, above it, were interpreted by Schardt as the cores of higher folds which, like the Antigorio nappe, were due to a movement from the south towards the north.

These great folds are not confined to the Simplon massif. In 1898 Schardt expressed his belief that the massives of the Monte Rosa, to the south-west, and of the Adula, to the east, were the backs of recumbent folds comparable with the nappe of the /

the Antigorio gneiss.

Unfortunately many of these views and interpretations remained in manuscript. This is why Lugeon's interpretations, published in 1901 and 1902, are essentially the same as the views of Schardt outlined above. For us Lugeon's publications are of particular importance, for he alone described his methods. As in the High Calcareous Alps his method was based on the study of the plunge of the fold-axes. If others had realised the significance of this before Lugeon, he it was who recorded it. It is said that the purest originality has a parentage.

In the Simplon region the gneiss-folds plunge gently to the south-west, so that higher tectonic elements appear in that direction. See fig. II.3. Lugeon concluded that the gneiss massif of the Tessin consists of a pile of huge nappes. East of the Simplon there is an axial culmination; the axial depression that lies to the west brings down the nappes in succession to the present surface. Further west the then existing maps were insufficient to enable Lugeon to reach definite conclusions. He pointed out, however, that the westward plunge continues under the Weissmies massif. Phenomena on such a scale, he insisted, cannot terminate suddenly: they must continue in depth. And so he was led to the hypothesis that the next massif to the south-west, the famous Monte Rosa, is another nappe, and not /

not a dome rooting in situ as was the current opinion. As we have mentioned above, Schardt had already suggested that the Monte Rosa was the back of a recumbent fold.

Knowing that his method was sound, Lugeon did not hesitate to point out that his interpretations would soon be put to the test, first by the drilling of the Simplon tunnel, and second by detailed mapping in the Monte Rosa region. In 1902 he addressed the Swiss Society of Natural Sciences in the following words: "I do not address you with the prudence and fear of one making a hypothetical announcement, but with the strength and faith that one can have in a theory when one sees the predictions that follow from it so naturally, all confirmed one after the other, and all fitting together so marvellously in the tracing out of the grand lines".

Lugeon did not have long to wait before the accuracy of his predictions were confirmed. Addressing the International Geological Congress in Vienna in 1903, he announced: " I have the joy to tell you that today my hypothesis is verified in the drilling of the Simplon tunnel". In 1905 Lugeon, with his pupil, Argand, announced that there was, in the Pennine Alps, a great axial depression between the Monte Rosa and the Grand Paradiso, thus confirming Baretti's hypothesis (1877) that there was a great structural depression between these two massives. This /

This axial depression corresponds to that shown by Lugeon to exist between the massives of the Aiguilles Rouges and the Aar. The Pennine Alps, between the Simplon and the Dent Blanche, is a region in which the fold-axes plunge towards the south-west. See fig. II.3. Because of this phenomenon, as we travel from south-west to north-east, we see the arrival at the surface of deeper and deeper nappes. Lugeon's prediction that the Monte Rosa would prove to be a great nappe, of which both top and bottom are exposed, was verified; seven gigantic nappes were recognised from the Antigorio at the base to the Dent Blanche at the top. (In the following year, Argand reduced this number to six, but this is a matter of detail that does not concern us in our study of the method.)

In the years that followed, Argand took over the detailed study of the Pennine zone of axial emergence. In 1906 he published the results of the first analysis of the internal tectonics of a crystalline Pennine nappe, that of the Dent Blanche. But these internal folds were still on such a large scale that no change in the method was necessary. In the same year he published his first account of the "unrolling" of the Pennine nappes. In 1908 his classic map of the Dent Blanche on the scale of 1: 50,000 was published, and this was followed in 1909 by a descriptive memoir. A study of this map and of the /

the illuminating sections in the memoir is sufficient to convince anyone that those who had the genius to realise the significance of axial-plunge were not armchair dreamers.

Lugeon had long before outlined the principle of axial tectonics and had employed the method with great success. But tectonicians must ever be grateful to Argand for his concise, and brilliantly lucid monograph of 1911. Here is an account of the method illustrated and described so clearly that the veriest novice can follow every step.

Argand presents us with a block diagram (stereogram) of the Pennine Alps, which we reproduce in fig. II.3. The upper surface represents the tectonic map of the region, i.e. the data observed at the surface. The front face shows the structure in depth as deduced from these surface phenomena by the principle of continuity in the axial-direction. The presence of all these elements in one block diagram brings out their multiple interdependence and their space co-ordination. Because of the gradual ascent of their axes towards the north-east, the great recumbent folds come to the surface one after the other, the deepest being found furthest to the north-east. Therefore to reconstruct the mean transverse profile from the observed surface data, the tectonic elements must be placed one below the other in the order that they appear on the ground from south-west to north-east. The front face of the block diagram achieves this /

this. If, inversely, one were to start with the system of recumbent folds drawn on the front face of the block, then if the mean axial-plunge were given, one could predict the general shape of the outcrops, <u>and also the dips at the surface</u>. Except for local complications, observation of the facts in nature always verifies these predictions, and thus verifies the hypothesis. (Summarised from Argand, 1911).

The construction is intended to show the essential relations of the folds, and has no pretension to do more. Argand did not imagine that continuity in the axial-direction was complete; it is obvious that folds do not go on for ever. Nevertheless it is very surprising to see how little the cross-section of such folds changes when followed, in the direction of the fold-axis, a distance measuring many times the amplitude of the fold. The axis is the geometrical generatrix of the cylindroidal surface; it is the direction of least change, not of no change. Any extrapolation that is made, should therefore be in this direction.

The upper surface of the block diagram summarises the tectonic facts visible at the surface; the front face explains these facts and co-ordinates them into a single visual picture. Everything happens at the surface as if the great recumbent folds had the relations indicated on the front face; Argand believed that /

that this entitled him to conclude that these relations actually do exist in depth. In its grand lines, he wrote, the map of the Pennine Alps is only the picture of the profile, deformed and elongated by oblique intersection with the present topographic surface. The longitudinal dimensions at the surface are the vertical dimensions in depth, except that, at the surface, they are elongated in the south-west - north-east direction by the oblique axial emergence; the transverse dimensions, on the other hand, are equal at the surface and in depth.

The outcrop of the syncline between nappes III and IV runs north-west - south-east and was interpreted by Schmidt (1907) as representing the roots of a system of transverse recumbent folds. The block diagram shows the true relations: it is not the fold-direction that is transverse, but the fold-trace on the topographic surface. The block diagram brings out clearly the reason why the trace of the folds at the surface is more or less transversal; it is the result of the intersection of rather flat, gently plunging, folds with the surface of the ground.

Schmidt's difficulty arose, Argand wrote, because he did not differentiate between the strike of the beds, which gives the direction of the fold-traces, and the direction of the folds themselves. These two tectonic elements coincide only if the beds /

beds be vertical or the fold-axis be horizontal. It is vital to distinguish between the dip relative to the horizontal, and the inclination of the beds relative to the fold-axis. This is the first and basic principle in the study of internal tectonics.

Argand's censure of Schmidt was rather severe. But Renevier had long before warned geologists that fold-traces must not be confused with fold-directions. Lugeon had repeated that warning over and over again. We may refer in particular to his lecture before the International Geological Congress at Vienna in 1903: "Those who have put fowards ideas of longitudinal, oblique, or even circular movements, like Rothpletz and Lorenz, have been deceived by simple problems in descriptive geometry that they did not know how to solve. The study of the nappes of the Berne and Valais Alps, as well as the fundamental discoveries of Bertrand and Ritter in Savoie, has shown that the base on which the nappes rest is inclined perpendicular to the sense of movement. I mean that, just like folds, the axis of a nappe is not necessarily horizontal. As the lower surface of a nappe is often slightly incurved, it is obvious that its intersection with the horizontal must be an arc. It is in committing this error that Lorenz has put forward the hypothesis of the 'Glarnerbogenfalte'".

Argand claimed that Schmidt's errors were ten or twenty years /

years behind the times. If that were true in 1907, what are we to think when the same errors are made today? Yet several instances could be cited from the recent literature on the Scottish-Irish metamorphic rocks alone.

The key forged by Lugeon and Argand had now been presented to the geological world. In Argand's words: "From the tectonician's point of view, the topographic surface [in the Pennine Alps] is a random section through a series of recumbent folds that are endowed with a certain continuity; the key region is simply the result of a favourable relation between the height of the topography and the height of the structures" (1911). "The geometrical key to the interpretation is the <u>principle of oblique axial emergence</u> of the folds. It is our guide for the reconstruction of the eroded parts and for the diagnosis of the structures that still lie buried. Thanks to it we can establish twenty kilometers of matter removed from the axial culmination of the Tessin, and penetrate an equal amount under the regions of axial depression. For the first time, geometry furnishes the means of gauging tectonic space of about forty kilometers height" (1912). But it is to Wegmann that we owe the demonstration that this key will unlock the secrets of regions of low relief just as efficiently as it will those of the High Alps. Given the axial-plunge, the geological map has only to be projected on to a surface at right angles to the axis to give us the undistorted profile.

C. ANCIENT MOUNTAIN-CHAINS

(i) Wegmann's Method and the Fennoscandian Chains

Without knowledge of the axial-plunge, interpretation of a map of a geosynclinal chain is impossible, and it is very seldom that its direction or value is recorded on published maps. Is it possible, then, to determine the axial-plunge from the data normally given on a geological map? Provided that the topographic relief is sufficiently great, and the mapping is good, the answer is "yes".

On his classic map of the Dent Blanche at 1: 50,000, Argand does not record any measurements of axial-plunge. Moreover few measurements of dip and strike are given. Argand did not record such data on his map because it was not necessary for his purpose. His stereograms showed the general axial-plunge and further details can be determined by anyone who wishes to study Argand's map. As an exercise in analysis, at Professor Wegmann's suggestion, the writer determined the structural contours of the base of the Dent Blanche gneiss by study of Argand's maps and those of the Italian Geological Survey. The Italian maps are on a small scale, but the writer was aided by reference to Argand's manuscript maps of the same region, that are housed in the Geology Department of the University of Neuchâtel. The resulting structure-contour map (Plate 1) brings out at a glance the /

the change that takes place in axial-direction, and more important still, in the sense of axial-plunge over the outcrop of the Dent Blanche nappe. Argand's conception of the Dent Blanche nappe as the highest Pennine element, that has been spared erosion because of a great axial depression, is given visual expression. The axial emergence in the eastern Pennine Alps is fact not theory.

The topographic relief in the Pennine Alps is exceptional and such an analysis as that described is not of universal application. It is Wegmann who has taught us how to deal with regions of low relief. A preliminary account was given by him in a lecture to the Geological Society of Helsinki in 1927 under the title, "On Alpine Tectonics and its Application to the Finnish Basement Complex". This was followed by a detailed description of the method published in 1929, and it has been illustrated by a great number of actual examples.

The basis of Wegmann's method is still the concept of the fold-axis. In the examples discussed by him this had to be determined indirectly; it was thus necessary for him to give a precise definition. He pointed out that a typical fold is an elongated structure; along a certain part of its length it is possible to place a straight-line against the fold-surface, so that the line is parallel or approximately parallel to the surface

This /

This line is referred to as the mantle-line or generatrix of the fold. Any direction parallel to the mantle-line, or to the best approximation to this line, is called the fold-axis. Thus a fold-axis, like a crystallographic axis or a north-south meridian, has an orientation but no fixed position. Geometrically, a fold may be described or generated, by the movement of a line parallel to itself in space and following a curve traced on a plane perpendicular to it; the generating-line or generatrix, is the fold-axis, and the curve it follows is the profile or true cross-section.

Wegmann stressed that the fold-axis is an important kinematic as well as geometric direction. The concept applies not only to folds but to other deformation structures, such as shear-planes, cleavages &c. The principal shear-planes define bodies with wedge, fish, or spindle-shapes (schuppen &c.), and these have axes just as folds have. The axis is normally more or less perpendicular to the movement direction.

How can this axial-direction, now defined precisely, be determined by the study of an ordinary geological map? Many assume that it is given, at least approximately, by the general strike. This hypothesis, for it is nothing more, has again and again been shown to be false by Alpine geologists. The divergence between the two directions is brought out very clearly in Wegmann's /

Wegmann's block diagram reproduced in fig. II.4. To appreciate the full significance of such a diagram, one must make the construction oneself, following Argand's 1911 receipe. It is a geometrical fallacy to assume that the axial-direction need coincide with the general strike. There are examples in the Alps, in Scandinavia, and in Scotland, where these two are mutually perpendicular.

How then are we to proceed? In 1911 Argand pointed out that the axial-direction coincides with the strike of the vertical beds; the axial-plunge coincides with the least dip. Hence the horizontal and vertical beds assume a peculiar significance. It is thus unfortunate that Bailey's presentation of Argand's structural map of the Pennine Alps to English-speaking geologists (1935, plate 5) fails in this respect. On Argand's original map (1911) special signs are used for horizontal and vertical beds; on Bailey's copy the continental dip-symbols are changed to those used by the British Geological Survey, and the horizontal and vertical beds are ignored. This omits from the map an important part of the data by which alone it can be read.

In a fold-system with constant axial-plunge (i.e. with good réglage), strike and dip are not independent variables. For example, if the axis is horizontal, no variation is possible in /

in the strike direction, but the dip may vary from 0° to 90°. Again, if the fold-axis should be vertical (as sometimes it is), the strike may be in any direction, but the dip is always 90°. Similarly, in every intermediate case, if we know the axial-plunge then given the dip we can predict the strike. It is to Wegmann that we owe the demonstration of the interdependence of axial-plunge and the dip-and-strike of folded beds. His observations and measurements in the Swiss Alps led him early to see the significance of this relation, and to work out a method for handling the space co-ordinates. This technique is fully described in his 1929 paper; if the axial-plunge is constant, the normals to the bedding will lie on a great circle of a stereographic projection, and the pole of this great circle defines the space co-ordinates of the fold-axis.

This is the key to the tectonics of ancient mountain-chains. Even in the complete absence of topographic relief, it is possible to construct the axis from the dip and strike of the beds. Even on Scottish Highland maps where the value of the dip is seldom recorded, it is often possible to determine the axis with surprising exactitude, and so to interpret the tectonics of the region immediately. Usually a few direct measurements in the field are sufficient to test the interpretation. The folding is so intense that, at first sight, the dips seem to be at /

at random. Indeed one could excuse a student, unfamiliar with the traditions of the Scottish Geological Survey, if he were to imagine that the dips had been added in the smoke-room of the hotel. But if the dips are plotted on a stereographic projection (and this can be done directly in the field), one will quickly discover that the dips are not so haphazard as they appear on the map. Indeed by employing a statistical method, the determination of the axis is very accurate because errors are smoothed out. Moreover, any anomalous dips are at once apparent.

If the topographic relief is sufficient to use straightforward structure-contour methods, the dip and strike of the main contacts can be determined and plotted; in this way the axial-plunge of the major structures can be determined. Moreover it is possible to do this even if no dips are given on the map. Theoretically the normals to the bedding should define a great circle; in practice there is always a certain dispersion from this theoretical curve. The degree of dispersion depends on the mobility (lack of réglage) of the fold-system, and on the exactitude of the mapping; it gives us a control. Many geologists judge mobility from the complexity of the folding as seen in a two-dimensional section, which is often an oblique one. This method of judging is not suited for a problem in three-dimensions.

At Professor Wegmann's suggestion the writer determined the degree of dispersion in the Jura, in the High Calcareous Alps (both /

(both in the frontal folds and in the roots), and in the Pennine Alps. These represent different styles and different depths, and the results form an excellent basis for comparative tectonics The first application of the structure-contour method attempted by the writer was to Lugeon's beautiful map of the Dent de Morcles (1937). The axis determined by analysis of this map was confirmed by numerous measurements in the field, both of dip-and-strike and of the plunge of small folds.

In his 1929 paper, Wegmann illustrates the technique of projection in a most lucid manner by reference to actual examples from Finland. Wegmann claims that his profiles show the style of the tectonics with the greatest possible approximation. Anyone who takes the trouble of comparing Wegmann's profiles with the sections previously published, will realise that the earlier methods gave results that do not even approximate to the actual style.

The essential feature of Wegmann's method is the use of a base-line placed on the map perpendicular to the axial-direction; all distances measured parallel to this line remain unaltered on transference to the profile; all distances measured perpendicular to it are reduced according to the relation $m. \sin \alpha = p$, where m is the dimension on measured on the map, p is the equivalent dimension on the profile, and α is the axial-plunge.

In /

In the analysis of already published maps one can use only the data presented. This seldom amounts to more than the dips and strikes. In one's own field-work, however, one can use measurements of any linear structure that is parallel to the fold-axis, e.g. the plunge of small folds, the intersection of bedding and cleavage, &c., &c. The frequent parallelism between small folds and great nappes has long been familiar to Alpine geologists. In 1902 Lugeon wrote: "Comparative study shows that there is no difference other than magnitude between a fold observed in a hand-specimen and a recumbent fold developed over more than a hundred kilometers". It must be remembered, however, that structures on different scales are not always parallel. As it is our immediate concern to show how a first approximation is achieved, we cannot enter into a discussion of the intricacies of internal téctonics. Nevertheless it may be pointed out in passing that Lugeon's 1930 paper on the Dent de Morcles contains a well-illustrated example of the basic principle; to obtain an undistorted profile, projection must be parallel to the axis on to planes perpendicular to the axis, and for every element with different orientation, a different projection is required, no matter how small that element may be.

Wegmann (1929) described and illustrated (see fig. II.5) the method of projection on to a plane perpendicular to the axis. In /

In addition he discussed the method of profile construction <u>en coulisse</u>. Presentation of structural data in the form of serial (parallel) sections has been practised for many years. Usually each section portrays the same tectonic elements at different positions along the direction of the axis. In such examples the axis is generally sub-parallel to the present topography and we see little, if any, deeper into the structure than the topographic relief permits. Wegmann's coulisse method, on the other hand, is applicable to those very important areas where the axis plunges. A series of profiles, each perpendicular to the axial-direction is constructed from the data on the map. But because of the axial-plunge, each successive profile represents a different tectonic level. If the value of the axial-plunge be known, then each successive profile can be raised, like a portcullis, to its appropriate tectonic level. See fig. II.6. The resulting coulisse-series represents, like all correctly constructed profiles, the same data as are recorded on the map, but it succeeds in doing so in a way that even a beginner in tectonics can visualise the structure in three-dimensions. For the tectonician who is primarily interested in the <u>form</u> of the structural elements rather than in their position with respect to the present ground-surface, the direct projection suffices.

The /

The coulisse method was perfected and employed by Wegmann. Its basic principle is inherent in Argand's 1911 publication, and Lugeon used it as long ago as 1901, as fig. II.7 shows. It is obvious that we have much ground to make up. The present generation of tectonicians whose responsibility this is, has the prospect before it of a pleasant and fruitful task. From one side we have inherited a wealth of beautifully executed maps; from the other we have been presented with the key to their secrets.

(ii) The Scottish Highlands

The preparation of a longitudinal section across the Scottish Highlands is made difficult by the existence of several very important transverse complications. The latter are, in fact, so pronounced that it is by no means easy to determine the "normal" trend. The data already published, supplemented by many new observations which will be published in due course, make it probable that, on the grand-scale, the Dalradian is everywhere tectonically higher than the Moine of the Central Highlands.

As an illustration of the application of the method to the Scottish Highlands, fig. II.8 shows the relations of the Moine and the Dalradian north of the Grampians. The figure is part of a profile constructed from the maps of L.W. Hinxman (1895) and E.M. /

E.M. Anderson (1917), on the basis of numerous field-measurements made by the writer.

The known complexity of the longitudinal section makes it necessary for the writer to warn that fig. II.8 is presented merely as the best approximation to the correct illustration of the Moine-Dalradian relations so far available. It is not possible to extrapolate beyond the limits of the area analysed by the writer.

- - - - - - - - - -

High topographic relief is not at all necessary for tectonic analysis. The Alps are very small compared with the magnitude of the structures out of which they have been carved. Provided that we have key-areas of moderate axial-plunge, we have immense tectonic thicknesses waiting to be recognised in all ancient mountain-chains.

"C'est fantastique, peut-être, mais c'est vrai".
(Lugeon to Bertrand in 1893.)

D. SOME COMMENTS BY PROFESSOR LUGEON

It is not easy for us to discover just how much the early /

early pioneers realised. The writer is therefore grateful to Professor Lugeon for very kindly supplying the answers to the following questions.

Q. Did Renevier use the concept of axial-plunge for his discovery of the Morcles nappe?

A. Renevier, who was not a geometer, did not see or understand axial-plunge, for like many geologists (and alas like many at present) he worked by sections only, and saw only two dimensions in space. Yet curiously enough, he constructed longitudinal sections. I ought to tell you that towards the end of his life, I may say thanks to me, my teacher had the joy of understanding the fold of the Argentine. (The Argentine is a summit in the Vaud Alps.)

Renevier saw the fold of the Morcles only in the natural section in the transverse valley of the Rhone. He never imagined that the nappe made up almost the whole of the High Vaud Alps, because he did not know how to use the axial-plunge.

Q. Had Gerlach already used this concept for his discovery of the great fold of the Antigorio?

A. Gerlach was an extraordinary man. He was an engineer, and I have every reason to believe that he understood the phenomenon of axial-plunge when he saw the great recumbent fold of the Antigorio /

Antigorio gneiss; but he did not know how to utilise the method.

Q. If not, were you the first to use it?

A. I do not know whether I was the first to realise how axial-plunge could be used, but I do know that it is only since I used it that so much progress has been accomplished.

Q. Do you know the origin of the happy idea that small folds are in general "régles" with the large ones?

A. As I have always seen that small folds were in general "régles" with the large ones, I never bothered myself as to who first conceived the idea, for it seems to me that it should come naturally to the mind. Besides, when one becomes old, one accepts a gentle philosophy, and bothers less and less about "author's rights". The essential thing is that all progress, including progress in observation, be for the welfare of everyone.

Q. You have used the term "tectonic style" for a very long time. Do you know its origin?

A. I think that you are probably correct in stating that it is I who introduced the term "tectonic style". I would have to search through all my publications to find out when I used it for the first time. That this expression should have come to my mind is understandable, for I am the son and brother of artists and sculptors.

E. /

E. BIBLIOGRAPHY

General

ARGAND, Emile. 1924. La tectonique de l'Asie. C.R. 13th Internat. Geol. Congress, Brussels, 1922. p. 171.

LUGEON, Maurice. 1930. Trois tempêtes orogéniques: la Dent de Morcles. Livre Jubilaire: Soc. géol. de France. p. 499.

WEGMANN, Eugene. 1947. Note sur quelques problèmes de la tectonique superposée. C.R. de la Soc. géol. de Finlande. 20, No. 19.

Swiss Alps (general)

SOCIETE GEOLOGIQUE SUISSE. 1934. Guide géologique de la Suisse.

COLLET, L.W. 1935. The Structure of the Alps. Edward Arnold.

BAILEY, E.B. 1935. Tectonic Essays: Mainly Alpine. Oxford

Pre-Alps

SCHARDT, Hans. 1898. Les régions exotiques du versant nord des Alpes Suisses (Pré-Alpes du Chablais et du Stockhorn et les Klippes). Bull. Soc. vaudoise des sc. nat. 34, p. 113.

________ 1899. Les Pré-Alpes Romandes (Zone du Stockhorn - Chablais). Inaugural lecture, Neuchâtel, 4th June 1897. Bull. Soc. neuchâteloise de Géographie. 11.

LUGEON, Maurice and Elie GAGNEBIN. 1941. Observations et vues nouvelles sur la géologie des Pré-Alpes romandes. Bull. Labor. géol. Lausanne. No. 72.

High Calcareous Alps

LUGEON, Maurice. 1901. Les grandes nappes de recouvrement des Alpes du Chablais et de la Suisse. Bull. Soc. géol. de France. 4e sér. t.1, p. 723.

Simplon /

Simplon

LUGEON, Maurice. 1902. Sur la coupe géologique du massif du Simplon. C.R.S. de l'Acad. des Sc. Paris. 24th March.

SCHARDT, Hans. 1903. Note sur le profil géologique et la tectonique du massif du Simplon comparés aux travaux antérieurs. Eclogae geologicae Helvetiae. 8, No. 2.

________ 1905. Les résultats scientifiques du percement du tunnel du Simplon. Bull. technique de la Suisse romande, for 1905.

Pennines

ARGAND, Emile. 1911. Les nappes de recouvrement des Alpes Pennines et leurs prolongements structuraux. Mat. pour la carte géol. de la Suisse. New Series. 31.

Ancient Chains

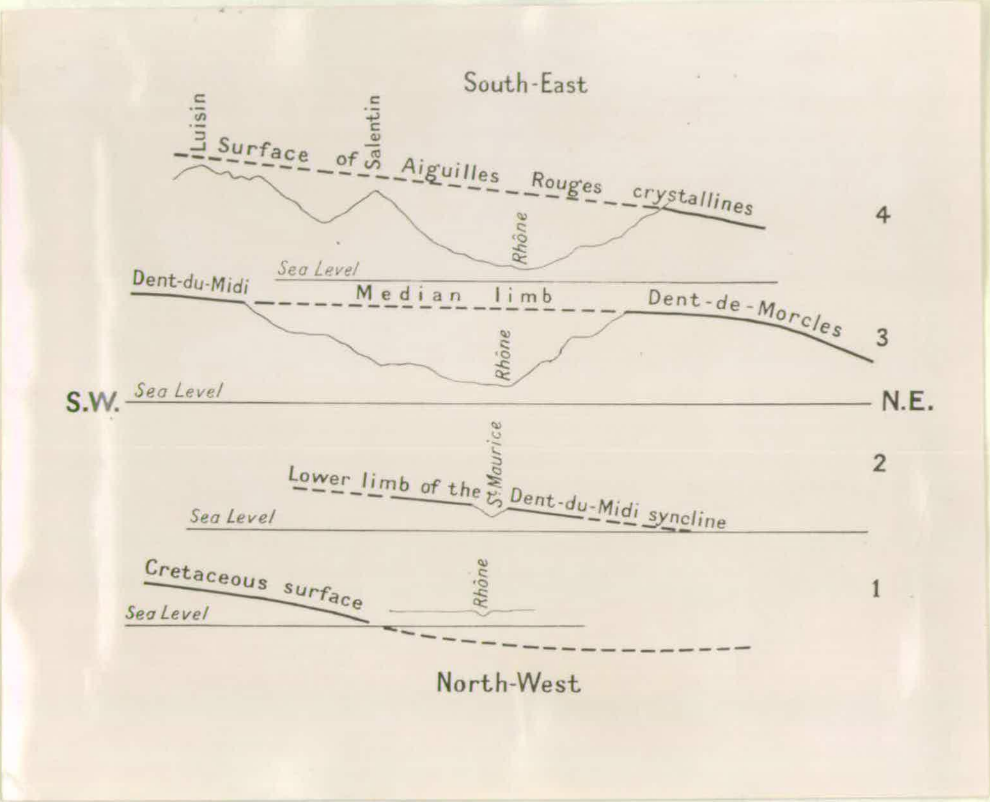
WEGMANN, Eugène. 1925. Note préliminaire sur le profil en long de la chaîne calédonienne scandinave. C.R.S. de la Soc. géol. de France. p. 225, 7th December.

________ 1927. Uber alpine Tektonik und ihre Anwendung auf das Grundgebirge Finnlands. C.R. de la Soc. géol. de Finlande. 6th October.

________ 1928. Uber die Tektonik der Jüngeren Faltung in Ostfinnland. Fennia. 50, No. 16.

________ 1929. Beispiele Tektonischer Analysen des Grundgebirges in Finnland. Bull. Com. géol. de Finlande. 87, No. 8.

________ 1938. Geological Investigations in Southern Greenland. Part I. On the Structural Divisions of Southern Greenland. Meddelelser om Grønland. 113, No. 2.

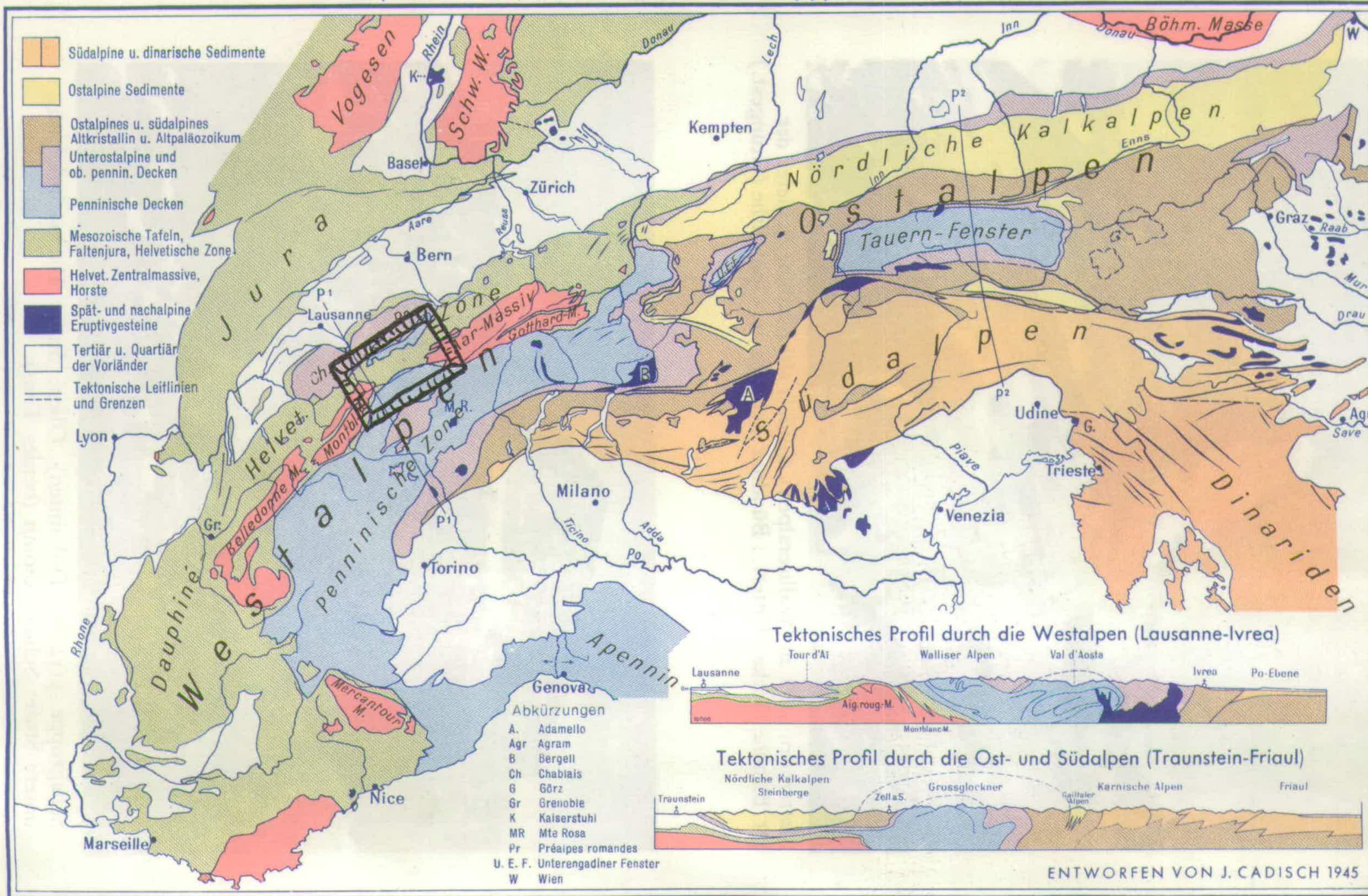


Longitudinal sections across the Rhone north of Martigny.

Re-drawn after Lugeon.

Index. Figs. II, 1, 2, 7.

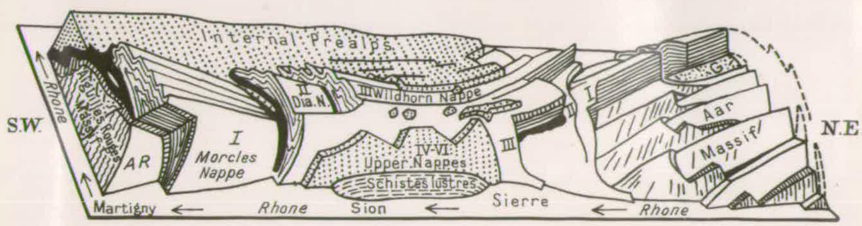
ALPEN, TEKTONISCHE KARTE 1:4 550 000 U. PROFILE



ALPEN, TEKTONISCHE KARTE 1:4 550 000 U. PROFILE

Encyclios Verlag

Kümmerly & Frey, Bern



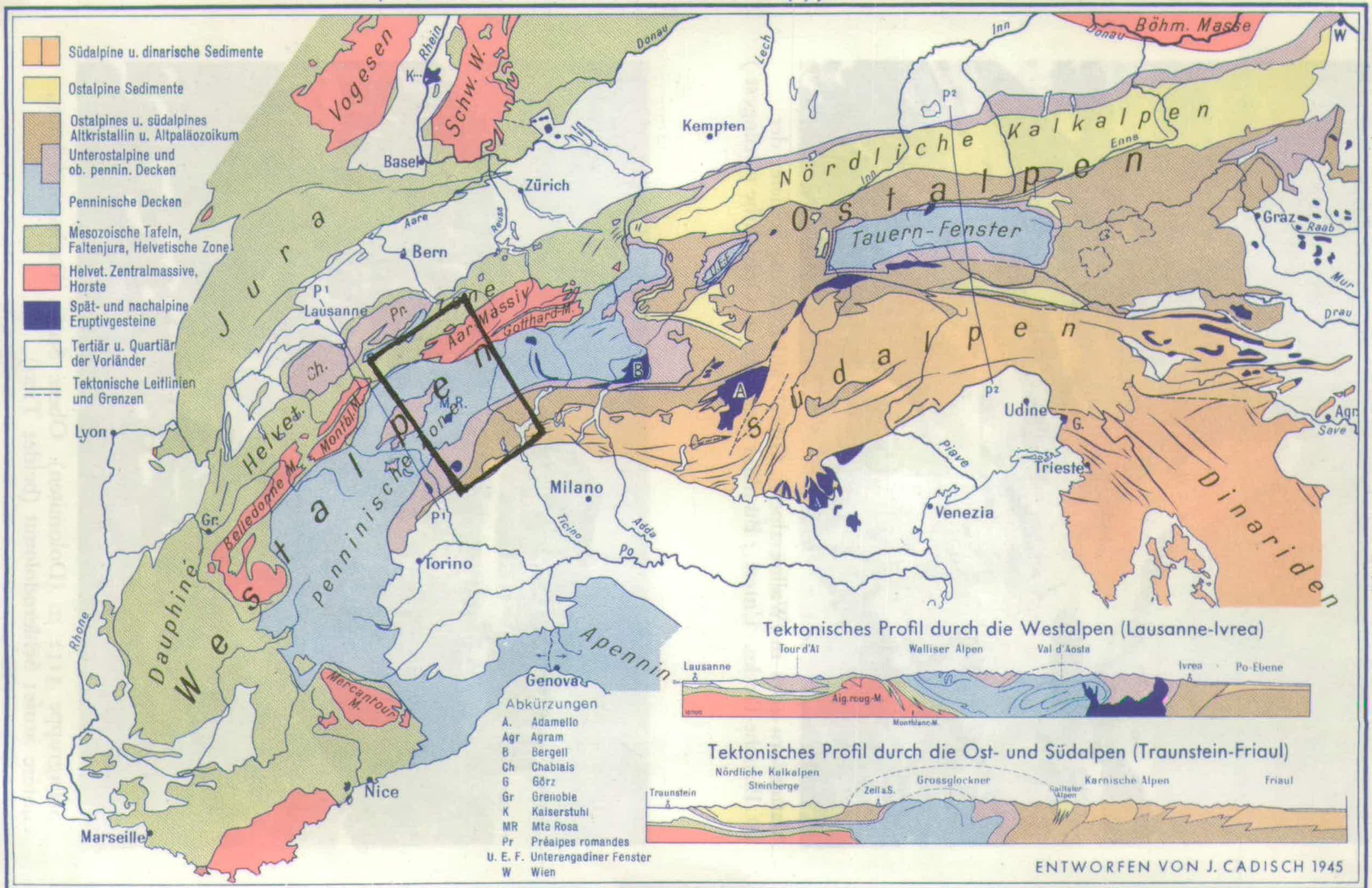
Nappes of the High Calcareous Alps.

Re-drawn from Arbenz

(after Lugeon).

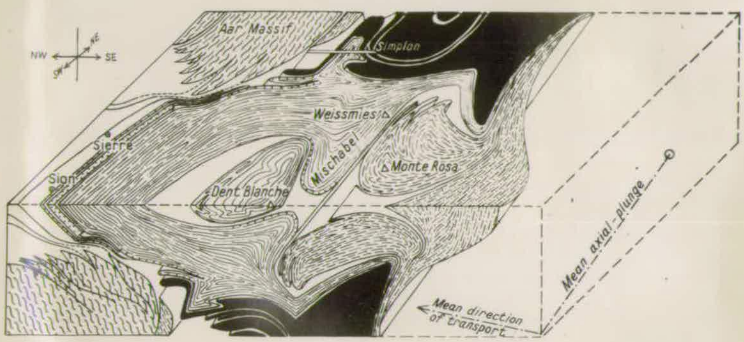
Index. Fig. II. 3.

ALPEN, TEKTONISCHE KARTE 1:4550000 U. PROFILE



ALPEN, TEKTONISCHE KARTE 1:4550000 U. PROFILE

Encyclios Verlag
Kümmerly & Frey, Bern



Block diagram of Pennine Alps.

Re-drawn after E. Argand (1911).

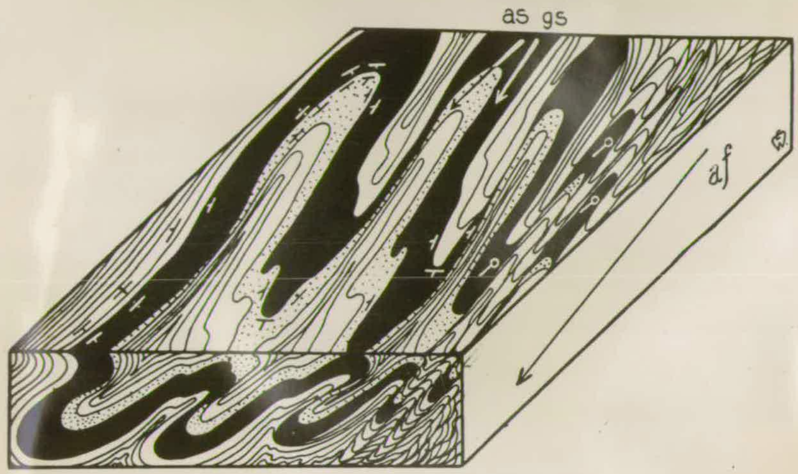


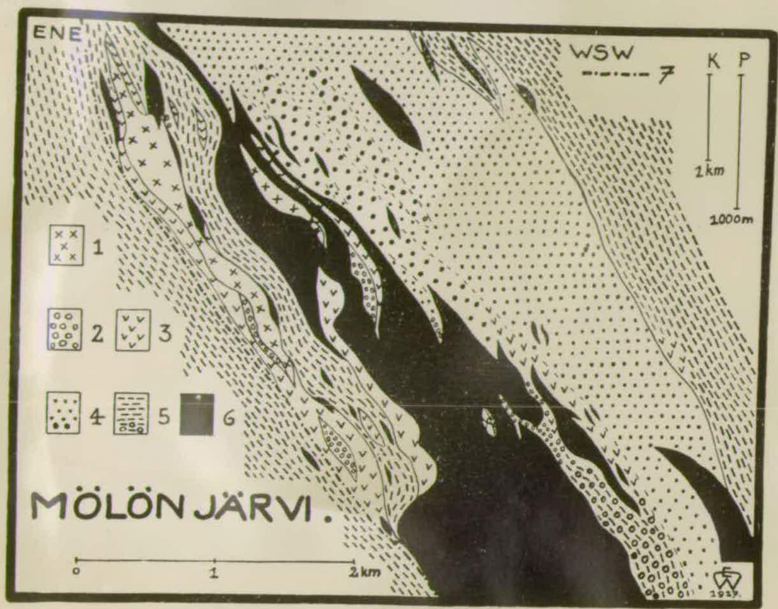
Fig. 4. Schematisches Blockstereogramm.

After Wegmann (1929).

af - axial-plunge.

as - axial-trend.

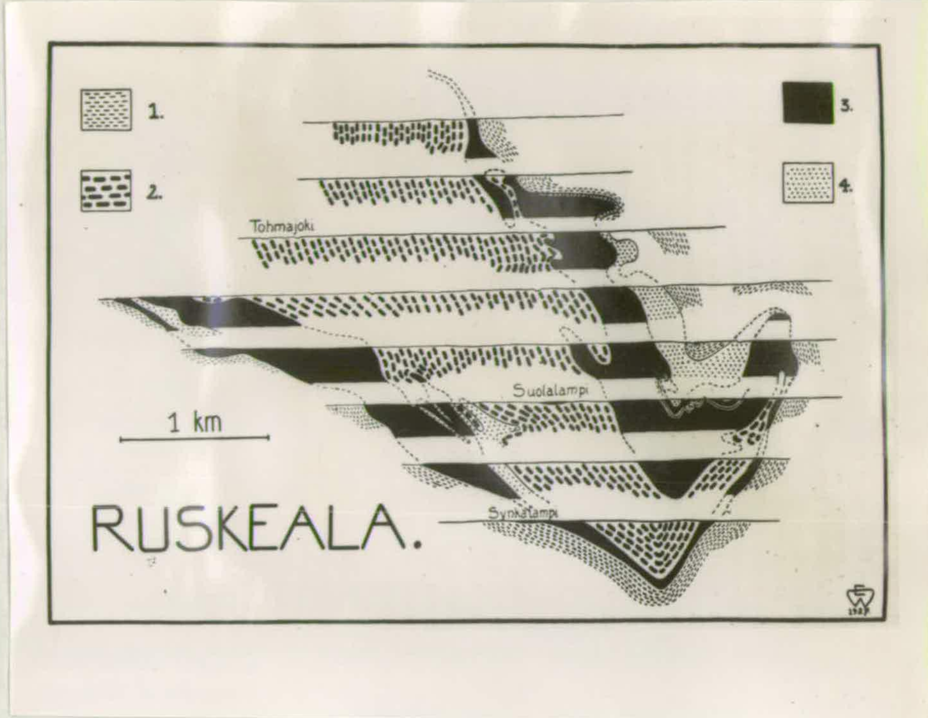
gs - general strike.



~~Fig. 1.~~ Profil der Gegend von Mölönjärvi.

Profile of the Mölönjärvi district (Finland), after E. Wegmann (1929).

1. Crystallines
2. Conglomerate
3. Augen gneiss
4. Quartzite
5. Mica schist
6. Ophiolite
7. Tectonic contact.



Coulisse sections of the Ruskeala district (Finland).

After Eugène Wegmann (1929).

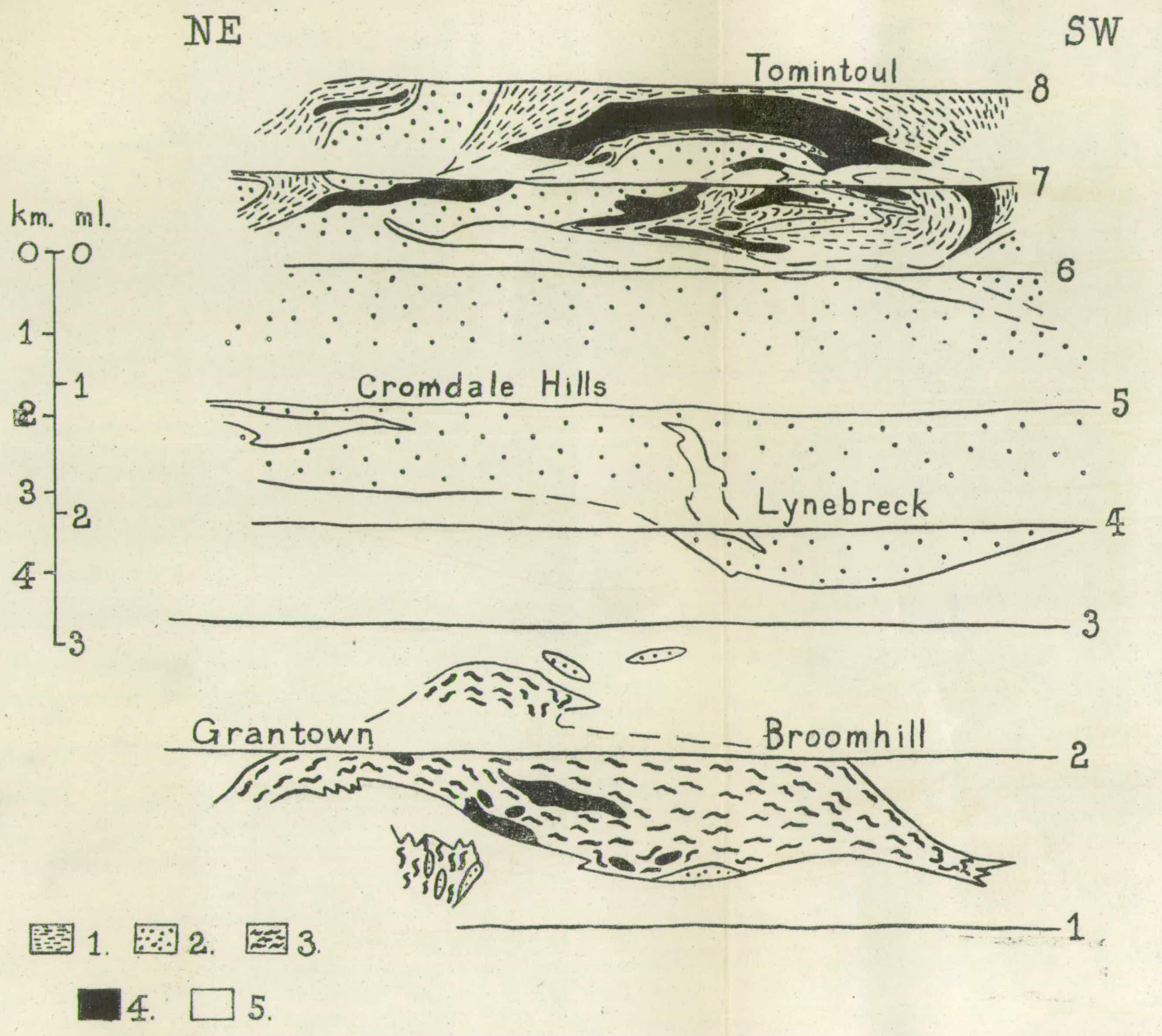
1. Mica schist   2. Amphibolite

3. Marble   4. Dolomite

Superposition of the three great nappes of the High Calcareous Alps: Morcles, Diablerets, and Wildhorn (Mt Gond).

Simplified from the coulisse-sections of Maurice Lugeon (1901).

"Section B-B has been raised because the nappes plunge away from the observer." (Lugeon).



Mid-Strathspey: Grantown-Tomintoul.

III. THE CONCEPT OF FOLD-AXIS IN TECTONIC ANALYSIS: an outline of a method of investigation.

A. GENERAL

Tectonic investigation of deformed rocks should begin with analysis of the present forms of the bodies concerned. Thus the first problem is one of descriptive geometry; the object is to define the actual shapes of the objects. Once this has been achieved one attempts to deduce the sequence of movements that produced the observed forms. At this stage the discussion is in terms of pure kinematics, i.e. dynamics must be rigorously excluded. Forces, pushes, and energies cannot be observed by geological methods. The same movement can result from an infinite variety of combinations of forces, and the choice between the possible forces is always arbitrary. An anticline may develop either by vertical upthrust or by lateral compression. In the past elaborate mechanisms have been postulated for "double systems of folding" which do not exist, and for folds directed at right angles to those actually present.

In general folds are elongate structures, and the tendency for one dimension to predominate becomes more marked as the degree of deformation increases. Where deformation is intense, the folds approximate to ideal cylindroidal surfaces. From /

From the point of view of descriptive geometry, such surfaces are generated by a line, the fold-axis, moving parallel to itself in space. Thus, in highly folded regions, an element of relative simplicity is introduced without which it would not be possible to determine the geometry.

In dealing with folds of this type, random exposure-surfaces must be treated as sections whose obliquity to the fold-axis is to be determined. Once the obliquity is known, the profile, or true cross-section at right angles to the fold-axis, may be constructed from the oblique section, or may be seen directly by observing the surface in the direction of the fold-axis. Although there is a tendency for a system of important joints to be nearly perpendicular to the fold-axis, the trend and plunge of the latter must be determined in every example. Maps are simply random sections of immense magnitude, and they can be treated like any other oblique section. If the space orientation of the fold-axis is known, the profile can be constructed from the map.

One of the initial objects of tectonic work in any region is the delineation of homo-axial units, i.e. the limits of area and scale within which the tectonic axes are unique. The order of magnitude of such units varies from that of a single crystal to those of nappe-complexes and tectonic inclusions of immense /

immense volume, and even up to the dimensions of a whole orogenic belt. Each need be homo-axial only between certain limits of scale; close examination may show that the internal structure is complex, and that the component parts are not parallel; or, again, the tectonic axes of the unit considered may not be parallel to those of its environment.

The study of folded rocks can begin by investigation of tectonic units on any of these varied orders of magnitude. The approximate trends of the principal orogenic belts are now known, and therefore one usually works on some smaller scale. As a general rule, to which there are exceptions, it is more profitable to work from larger to smaller scales rather than the reverse. Thus one's first task in the tectonic investigation of an area is to determine the direction and form of the major folds, i.e. the tectonic setting of the minor structures.

B. GEOMETRIC ANALYSIS

(i) Direct Observation

In well-dissected regions, the major structures can be observed directly. Among the classic examples are the Jura Mountains, the High Calcareous Alps, and the Pennine Alps. A striking instance is the backward folding of the Mischabel

(Nappe /

(Nappe of the Grand St. Bernard) underneath the Dent Blanche Nappe (see Collet, 1935, Plate 6). But the tectonic thickness which can be examined is not necessarily limited by the topographic relief: e.g. Argand has demonstrated how it is possible to examine in the Pennine Alps a tectonic thickness of some 15 miles.

"How is it that we can see a pile of folds some 20-30 km thick in mountains whose height is less than 5,000 m? The very simple reason is that the nappes do not rest on a flat base, but are inclined; because of this, their edges outcrop at varied angles at the topographic surface which erosion has cut through the mass; one can therefore see these edges, count them, and measure them, but it need not be left even at that. To be more precise: a recumbent fold with digitations, or a bundle of such folds, is, at first approximation, comparable to a family of cylindroidal surfaces: in the space occupied by these objects, there is thus a privileged direction, namely that of the generatrix; in tectonics this direction is called the axial direction. Terrain composed of recumbent folds is really a bundle of cylindroidal bodies excavated to great depths by erosion: what is now the topographic surface was formerly a deep tectonic level; that is why you see on the ground, without any veil other than the discontinuous superficial deposits, that /

that deep level itself. Go still further: what happens when the generatrix of these highly recumbent, cylindroidal surfaces is horizontal in one case, and inclined in another? If the generatrix is horizontal it will obviously be impossible to determine a section through the nappes that is thicker than the summits are high. But if the generatrix is inclined, then the entire bundle of recumbent folds, with an immense thickness far exceeding the difference in altitude, emerges obliquely at the surface. An observer in the air, at a very great distance in the upward prolongation of the generatrix, not only would <u>discover</u> the nappes, but would <u>see</u> their true forms, their true amplitudes, their true thicknesses, their true internal arrangement as shown by their hinges, their true relations; he would see, in effect, their true profile. Because his line of sight would coincide with the generatrix, he would see all the objects in all their relations and without any distortion. In its highest form, the art of discovering great recumbent folds is the art of posing and solving, by direct intuition <u>prior to any construction</u>, this problem of descriptive geometry; the art of recreating the movement comes later". (E. Argand, 1923, pp. 9-10.)

In this way, by direct observation, the major structures of the Western Alps have been determined. The classic syntheses /

syntheses are Lugeon's (1901) for the High Calcareous Alps, and Argand's (1911) for the Pennines. The general trend thus demonstrated is approximately east-west, and the sense of movement was towards the north. The correctness of the general picture painted by Lugeon and Argand has never been questioned.

(ii) Structure Contours

It may be possible to determine the form of the major structures from the data on a good map. In particular the technique of constructing "stratum" or "sub-surface" contours may be employed where the topographic relief is sufficient. As the tectonician is interested as much in the forms once present in the air as in those still buried underground, the contours drawn are not always "sub-surface"; for this reason the term "structure contour" is adopted here..

Details of the preparation of structure contour maps may be found in the text-books of structural geology. Only a brief outline is given here. Structure contours are strike lines drawn on a particular structural surface, and spaced at a convenient difference in altitude. They are therefore lines of equal altitude drawn on the surface chosen, and are drawn in the same way that topographic contours are drawn with reference to a series of spot-heights. For the method to be applied successfully /

successfully, the terrain must have considerable topographic relief, or else much sub-surface data must be available.

The construction must not be mechanical; between the control points the contours must be modified in accordance with all known data, e.g. dips and strikes, axial-plunge, &c. The general trend and plunge of the axis will be evident from the structure map of any well chosen horizon; but important additional data will usually be obtained when the structure maps of two or more carefully selected horizons are superimposed.

Two examples of structure contour maps are given here (Plates 1 and 2). The first represents the base of the Dent Blanche gneiss, Pennine Alps; the second illustrates the form of the base of the Hauptrogenstein and its relation to the main thrust, in the Hauenstein region of the Jura.

(iii) Determination of the Fold-Axis

Where the topographic relief is sufficient, and the form of the folds is suitable, the trend and plunge of the fold-axis may be estimated directly from the relation of outcrops to topography. This procedure necessitates accurate mapping both of the geology and of the topographic contours. If, for example, it is possible to determine the location of the highest point (emergence of the crest line) of an anticline in two adjacent /

adjacent valleys, a first approximation to the space orientation of the fold-axis may be obtained immediately. Moreover, if sufficient data of this type are available, the determination may be made more accurate, and variations both in trend and in plunge may be detected.

With such information it is then possible to project all the data on the map on to a suitable plane. The latter may be either vertical, or inclined so that it is normal to the fold-axis, depending on the object of the investigation. If possible the orientation of the fold-axis should be determined independently for each horizon shown separately on the map; an idea of the relative mobilities of the different units present may then be obtained.

It is of course impossible to specify the details of the technique; each case must be handled according to the information available, and an attempt should be made to control the projection by means of structure contours, dips and strikes given on the map, and indeed to utilise all the data presented. The construction is relatively simple provided that the three-dimensional nature of the bodies investigated is kept in mind.

Three sections (on vertical planes) constructed in this manner are given in illustration (figs. Plate 3 III. 1-3). They are all from the Jura Mountains, which are well suited to the application /

application of this method. It should be noted that in these sections the traces of the folds are shown in full lines only where they have been projected on to the plane of the section from the data given on the map; it thus is evident at a glance where the traces are adequately determined and where they are merely conjectured. It will be observed that the method is sufficiently delicate to bring out the thickening of the incompetent shale beds at the anticline hinges.

(iv) Significance of Vertical and Horizontal Structures

The special significance of vertical and horizontal beds is frequently overlooked, in spite of the time which has elapsed since the importance of these structural orientations was first realised by Alpine geologists. As the matter is essentially one of geometry, the simplest demonstration is by a diagram designed to bring out the spatial relations of folded strata in plan and in section.

The accompanying diagrams (figs. Plate 4 III. 4-6) illustrate an exercise adopted by the late Professor Emile Argand for his students at Neuchâtel. Beginning with a block diagram on which a geological section and the space orientation of the fold-axis are shown, the students are required to construct the map; in the example given this is supplemented by the construction /

construction of a further section and map at a higher level. The block is in parallel perspective, and, in order to determine the undistorted form of the map, the upper surface of the block is redrawn as the undeformed map. By study of the block diagram the dips and strikes are now added to the map, one symbol being given for each unit square.

The student thus learns that the general strike does not necessarily coincide with the axial-direction, and a statistical study of the strike directions emphasises this fact. The question naturally arising is therefore how it is possible from such a map to determine the axial trend and plunge. If the student has been accurate in his construction he will discover that the axial-trend coincides with the strike of the vertical beds, and the axial-plunge coincides with the minimum dip.

In this way the special significance of vertical and horizontal beds is brought to the student's attention. He learns that he must not record beds as being vertical, or horizontal, unless they are truly so. Unfortunately not all field workers realise this, and therefore one must use vertical strike symbols with caution when attempting to interpret published maps. In general it will be found that the scatter of vertical strikes is greater than should be the case, and this is often due /

due to beds having been mapped as vertical when they are not vertical. Such an error may lead to serious consequences when the axial-plunge is high.

(v) The Stereographic Projection

If the folds are cylindroidal then the normals to the fold-surfaces will describe a plane which is normal to the fold-axis. When plotted on a stereographic projection, the normals will therefore lie on a great circle whose pole is the fold-axis. This fact was first demonstrated by Wegmann (1929) who used it as a means of determining the orientation of the axis from the data (dips and strikes) given on published maps of Fennoscandia.

The importance of the method lies in the fact that a statistical smoothing of errors gives a remarkably accurate determination of the fold-axis. Moreover, should any dip and strike measurement be obviously far from the constructed great-circle, it is evident that the area where that measurement was made deserves further investigation. The method thus provides a means for determining the tactics to be employed in the revision of earlier field-work. As the method can be used in the field, the attention of the mapper can be directed to critical exposures while he is still in the field.

The closer the fold-surfaces approximate to the ideal cylindroidal /

cylindroidal form, the nearer will the plots of the normals be to the great-circle. Indeed the dispersion from the mean great-circle is an important guide to the style of the tectonics. There are several possible reasons for departure from the cylindroidal form; the folding may not have been sufficiently intense to develop a uniform generatrix, or the deformation may have been sufficient to mobilise the beds. The conditions necessary to cause mobilisation differ in different rocks; in plutonic tectonics the rise of the migmatite front is a common cause. It is often found that the dispersion from the great-circle increases as the granitisation of the rocks becomes more intense.

The accompanying figures illustrate British and Swiss examples of stereographic plots (figs. III. 7-19).

(vi) Small Folds and b-lineations

Small folds are not necessarily parallel to the large structures; with extensive deformation, tectonic inclusions may be rotated so that their internal structure is no longer parallel to the structure of the surroundings. Thus, the internal structures may belong to an earlier phase of movement than that which produced the external structures. It is obvious that extrapolation from the very small scale to the very large /

large may lead to serious error if not controlled by other means.

In spite of this it seems that in many cases the small scale folds are indeed parallel to the major structures. It is obvious that before we can put the matter to the test we must know the orientations both of the small and of the large structures. It is, of course, a simple matter to determine the axial-trend and plunge of small scale folds, for even in country of low relief these structures are directly observable. There are, on the other hand, relatively few regions where the trend of the large scale structures is undisputed. In the Scottish Highlands, for example, there are areas where different workers would orient the major structures at right angles.

It is unlikely, however, that anyone would seriously dispute the facts that the general trend of the major structures in the Swiss Alps is approximately east-west, and that the sense of the movement was towards the north. For this reason the writer made a large number of measurements of the orientation of small scale structures in the Pennine and High Calcareous Alps, in order to determine whether or not these macroscopic structures were parallel to the major structures.

The route followed by the writer is shown on the map (fig. III.20). It is a traverse from east to west across the axial depression in the Rhone valley between the Simplon and the /

the Aiguilles Rouges and Mont Blanc massives near Martigny. The measurements made are grouped in five stereograms (upper hemisphere projections): Brigue to Turtmann; Louèche-la-ville to Lens, via Louèche-les-bains, Salgesch, and Sierre; Icogne to Sion, via Ayent; Ardon to Saillon; and the neighbourhood of Saxon (figs. III. 21-25). The data thus recorded show clearly that the small scale folds in this important region are b structures, and that their trend and axial-plunge are closely parallel to the trend and plunge of the nappes themselves.

Owing to the high topographic relief in the neighbourhood of the Rhone valley, a further control is possible. Several of the horizons mapped by Lugeon (1937) have been contoured, and the normals to bedding-orientations thus determined are plotted on the stereogram, fig. III.26. These values were found in the neighbourhood of the peak Haut de Cry, immediately to the north-west of the traverse from Ardon to Saillon mentioned above. It will be observed that the poles lie on a great circle, the normal to which coincides with the axis of the small folds measured in the field by the writer and recorded on fig. III.24.

In many parts of the Scottish Highlands the topographic relief is sufficient to enable the major contacts to be contoured. By plotting the results, as on the Haut de Cry, the /

the axis of the major structures can be determined. It is obvious that the accuracy of the determination cannot be as great in the Highlands as it is in the Alps; the relief is not so marked, and the exposures are not usually so continuous. Nevertheless, in all cases so far studied, in particular in the neighbourhoods of Beinn Laoigh (Lui), Kincraig, ~~and~~ Beinn Dronaig, and in the Fannich Forest, the small scale folds have been found to be parallel to the major structures.

The utility of this coincidence of large and small scale structures is obvious, and the importance of measuring the macroscopic structures during the field-mapping hardly needs stressing. In addition to the axes of small scale folds, other b-structures may be present. Most of the various types of lineation and rodding which have been described in Highland rocks are parallel to the trend and plunge of the fold-axes, and their orientations should always be recorded.

(vii) Profiles and Coulisse-sections

The procedure usually adopted in drawing a section across a geological map is based on extrapolation in the direction of the dip. Where the structures approximate to the ideal cylindroidal form it is more logical to extrapolate in the direction of the axis. Thus the sections should be oriented with /

with respect to the axis; except in special cases, only longitudinal and transverse sections are required.

Longitudinal sections show variation in axial-plunge; such sections are usually rather simple in aspect, the structures appearing as broad anticlines and synclines (axial culminations and depressions). If there are abrupt folds or overfolds in longitudinal section, then the sequence of movements has been complex.

The true cross-section of a cylindroidal structure is perpendicular to the fold-axis; such a section is referred to as a profile. A vertical section cannot be truly transverse unless the axis happens to be horizontal; in all other cases the profile must be inclined from the vertical position.

Where an area is strictly homo-axial, construction of the profile is without difficulty. The map is covered with a sheet of tracing paper on which are ruled a series of equally spaced, parallel lines oriented at right angles to the trend of the fold axis. The profile plane is likewise ruled with parallel lines at appropriate spacing. The map dimensions can then be rapidly transferred to the profile plane, due allowance being made for topographic relief. If the axial-trend varies over the area, then the guide-lines drawn on the map will no longer be straight, and if the plunge varies they will be unequally spaced /

spaced. Once the orientation of the guide-lines is determined, the profile may be completed quickly.

Where k is a longitudinal dimension on the map and α is the amount of axial-plunge, the corresponding dimension on the profile is equal to $k.\sin\alpha$. On the other hand, if a vertical section is to be constructed normal to the axial-trend, the corresponding dimension on the section is equal to $k.\tan\alpha$ which is, of course, slightly larger than the profile dimension.

It is sometimes desirable to relate the structure to particular points on the ground. This may be done by constructing a series of coulisse-sections. A series of sections on vertical planes (or possibly surfaces) normal to the axial-trend are constructed by projecting the data on the map in the direction of the axial-plunge. The base level of each section is then raised an appropriate amount so that the axial descent is balanced by the successively higher base-levels.

C. KINEMATIC ANALYSIS

Irrespective of scale, once a profile has been constructed the general kinematic features will usually be apparent. The direction of overfolding, the extent of tectonic thickening and thinning, in a word the style of the geometry often has obvious /

obvious kinematic implications. The nature of the longitudinal section will also give an indication of the movements; e.g. the width of the sheaf of fold-axes (fig. III.27) measured in the inclusions within the Beinn Mhor granite, near Grantown, indicates a degree of mobility in excess of that normally found in the schists of Strathspey. Again, differential flowage in differing tectonic levels may be indicated by change in orientation of the fold-axes in the zones in question (fig. III. 28, 29).

Fold-axes are in general normal to the direction of tectonic transport. Thus a map showing the orientation of fold-axes can easily be converted to a kinematic map. Argand (1924, figs. 9, 10, 20) attempted to do this on a continental scale, but the principle may also be usefully applied on much smaller scales.

In the field, features of tectonic significance should always be recorded; e.g. deformation of fossils (Rutsch, 1949); the direction of overfolding; the sense of movement indicated by a system of fracture cleavages (G. Wilson, 1946); the sense of drag on thrusts, slides, and other movement planes; &c. Where the style is such that slickensides have been produced, these give very useful kinematic data. In the two Jurassic examples of slickenside studies by the writer (figs. III. 30, 31) the /

the relationship between the slickenside-movements and folding is obvious.

Few areas have been studied in sufficient geometric detail to permit a kinematic analysis to be undertaken. The above remarks are intended merely to indicate some of the ways in which this analysis may be carried out. Due to lack of data, dynamic analysis is almost an unknown science.

D. LIST OF WORKS TO WHICH REFERENCE IS MADE

ARGAND, Emile. 1911. Les nappes de recouvrement des Alpes Pennines et leurs prolongements structuraux. Mat. pour la carte géol. de la Suisse. New Series. 31.

_________ 1923. La géologie des environs de Zermatt. Actes de la Soc. Helvétique des Sciences nat. IIe partie, pp. 96-110.

_________ 1924. La tectonique de l'Asie. Internat. Geol. Congress, 13th Session. Brussels 1922. Comptes rendus, vol. 1, pp. 333, 341, 343 & 355.

COLLET, L.-W. 1935. The structure of the Alps. Edward Arnold.

LUGEON, M. 1901. Les grandes nappes de recouvrement des Alpes du Chablais et de la Suisse. Bull. Soc. géol. de France. 4 e sér. t.1, pp. 723-825.

_________ 1937. Atlas geol. de la Suisse. 1:25,000 Feuille 485. Saxon-Morcles.

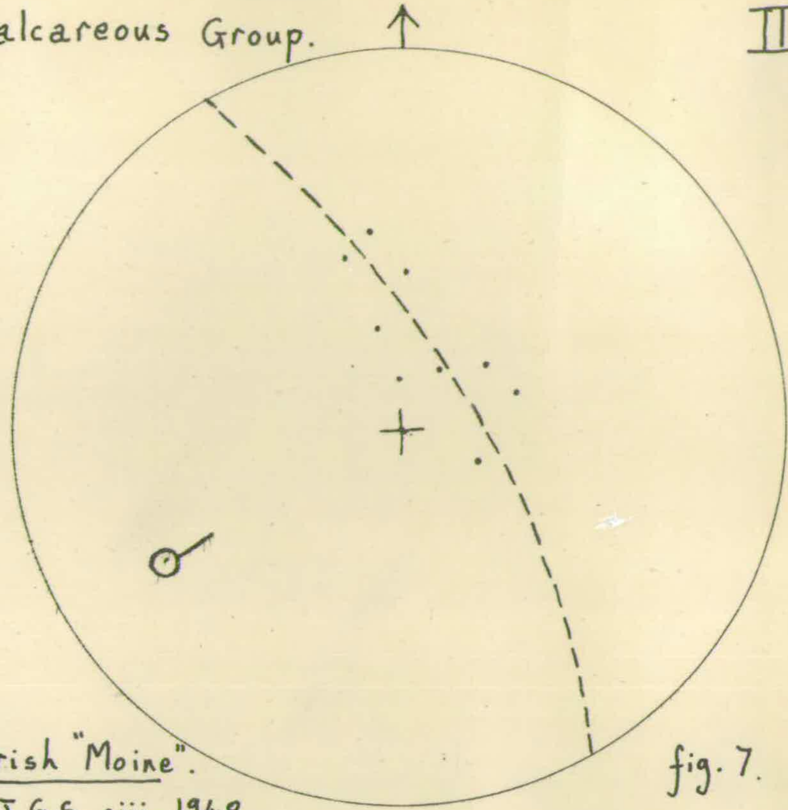
RUTSCH, R.F. 1949. Die Bedeutung der Fossil-Deformation. Bull. d. Ver. Schweiz. Petroleumgeol. und -Ing. Vol. 15, No. 49, pp. 5-18.

WEGMANN /

WEGMANN, Eugene. 1929. Beispiele Tektonischer Analysen des Grundgebirges in Finnland. Bull. Comm. geol. de Finlande. 87, No. 8.

WILSON, G. 1946. The relationship of slaty cleavage and kindred structures to tectonics. Proc. Geol. Assoc., Vol. 57, pp. 263-302.

Calcareous Group. III



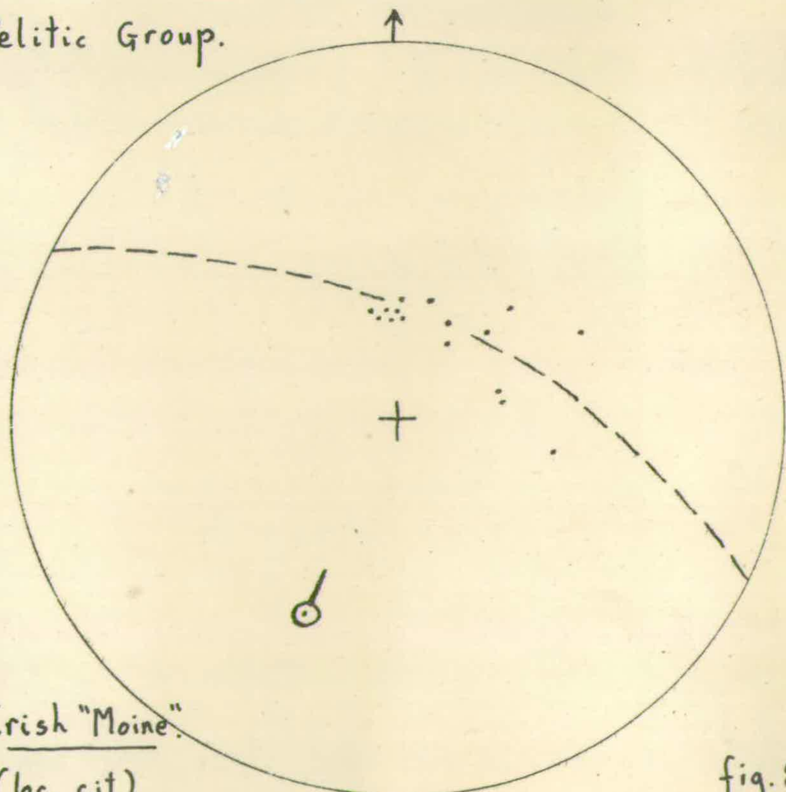
Irish "Moine".

Q.J.G.S. ciii. 1948.

(Normals to s-surfaces recorded on map.)

fig. 7.

Pelitic Group.



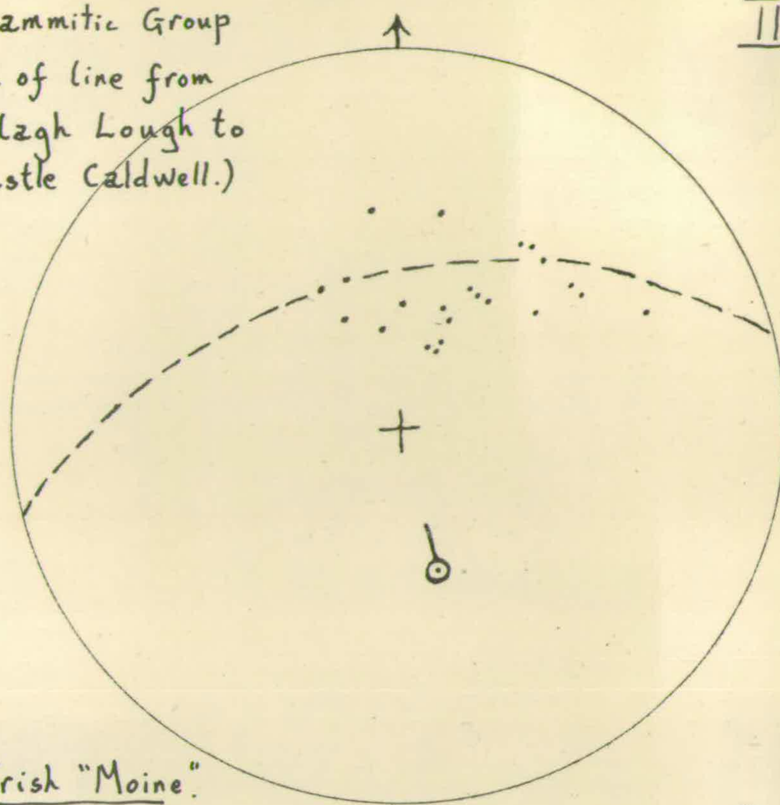
Irish "Moine".

(loc. cit.)

fig. 8.

III

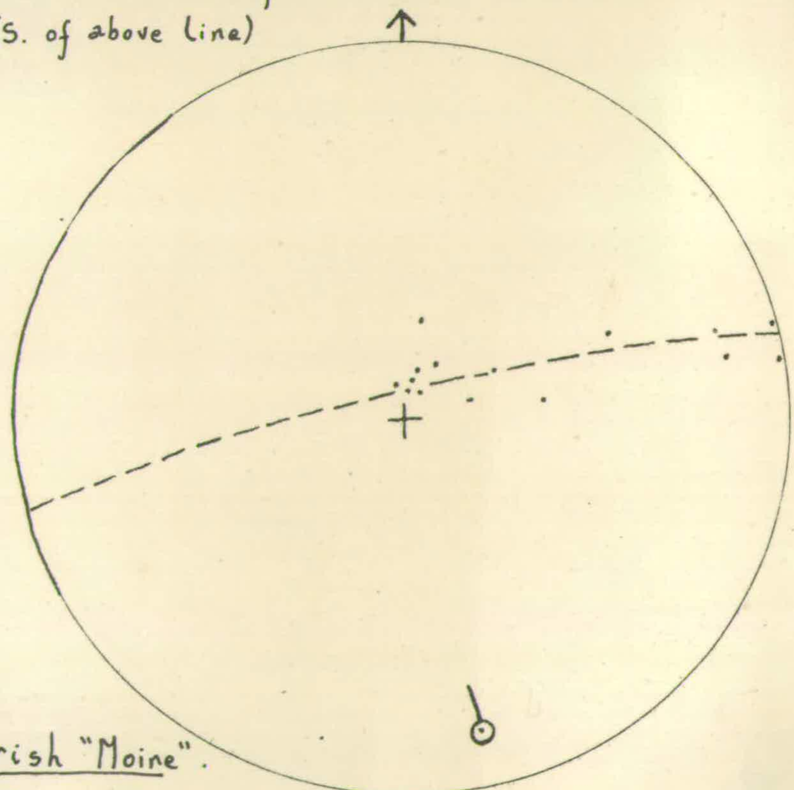
Psammitic Group
(N. of line from
Golagh Lough to
Castle Caldwell.)



Irish "Moine".
(loc. cit.)

fig. 9.

Psammitic Group
(S. of above line)

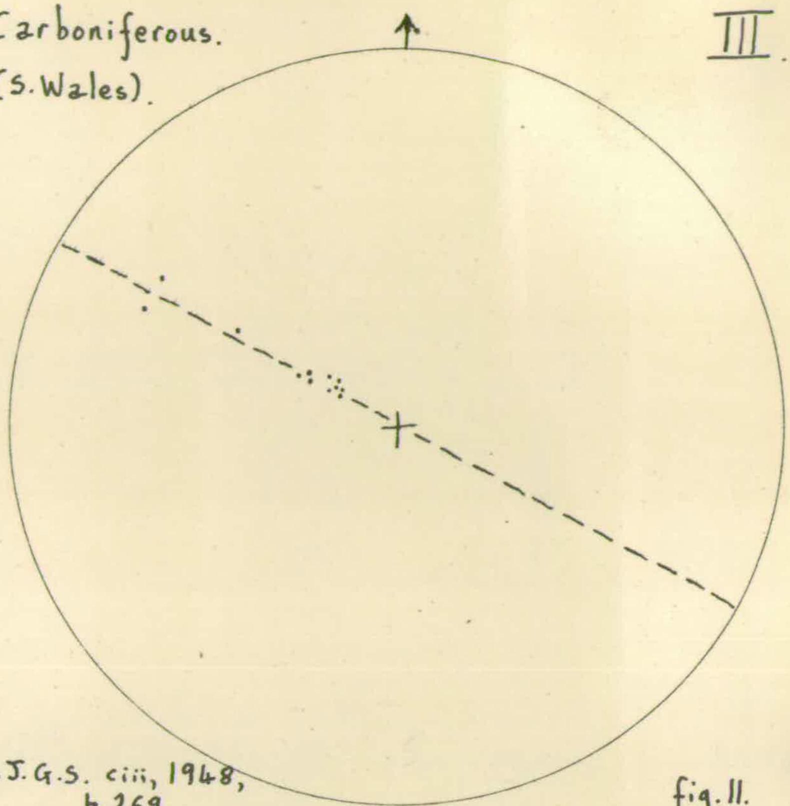


Irish "Moine".
(loc. cit.)

fig. 10.

Carboniferous.
(S. Wales).

III.

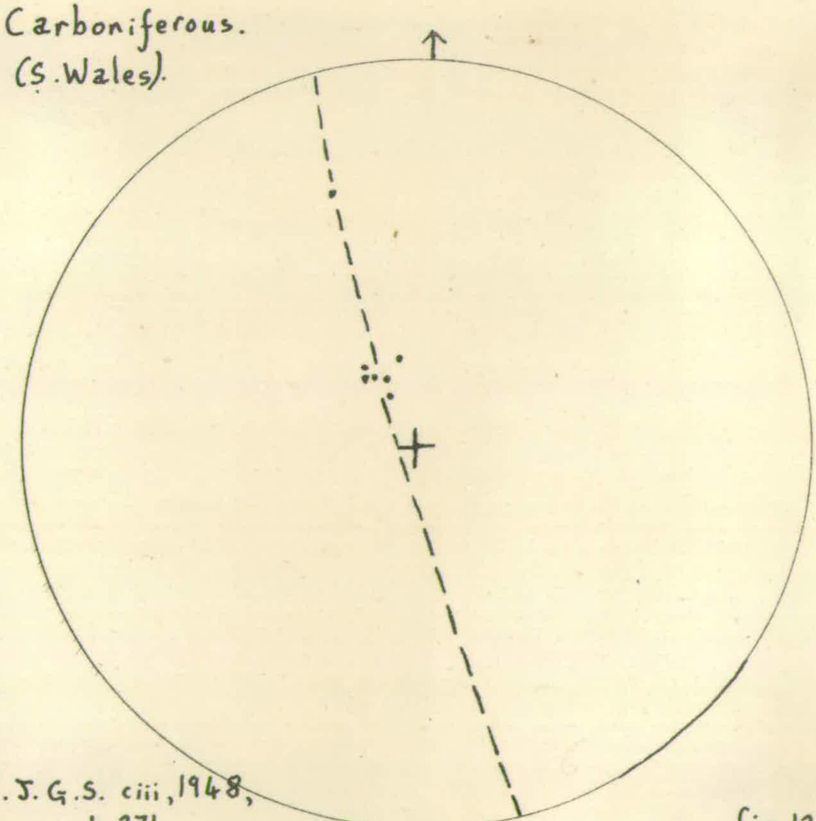


Q.J.G.S. ciii, 1948,
p. 269.

fig. 11.

(normals to bedding given on map.)

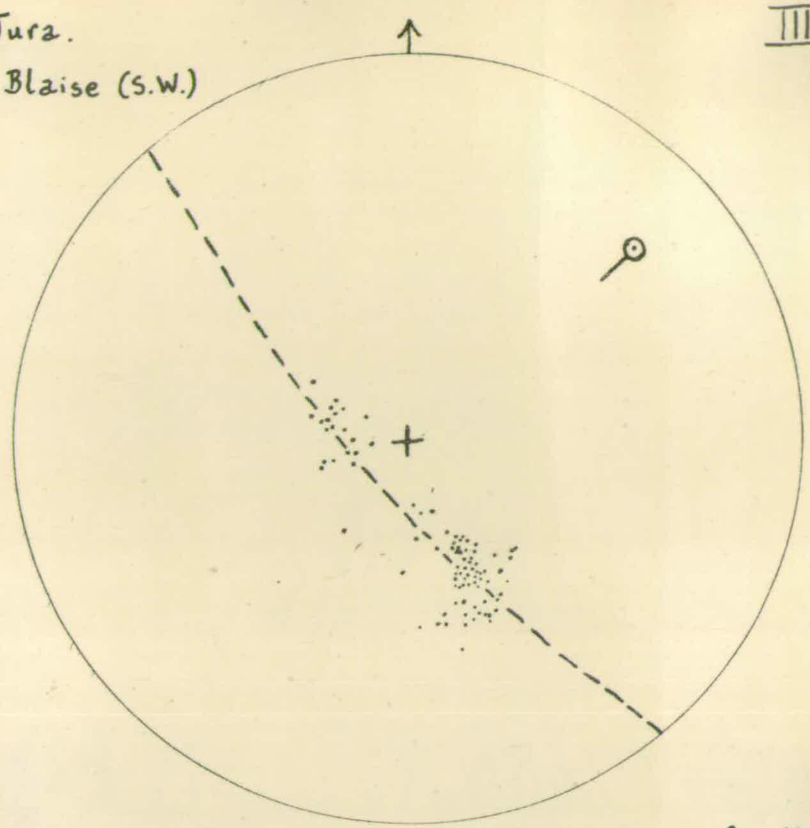
Carboniferous.
(S. Wales).



Q.J.G.S. ciii, 1948,
p. 271.

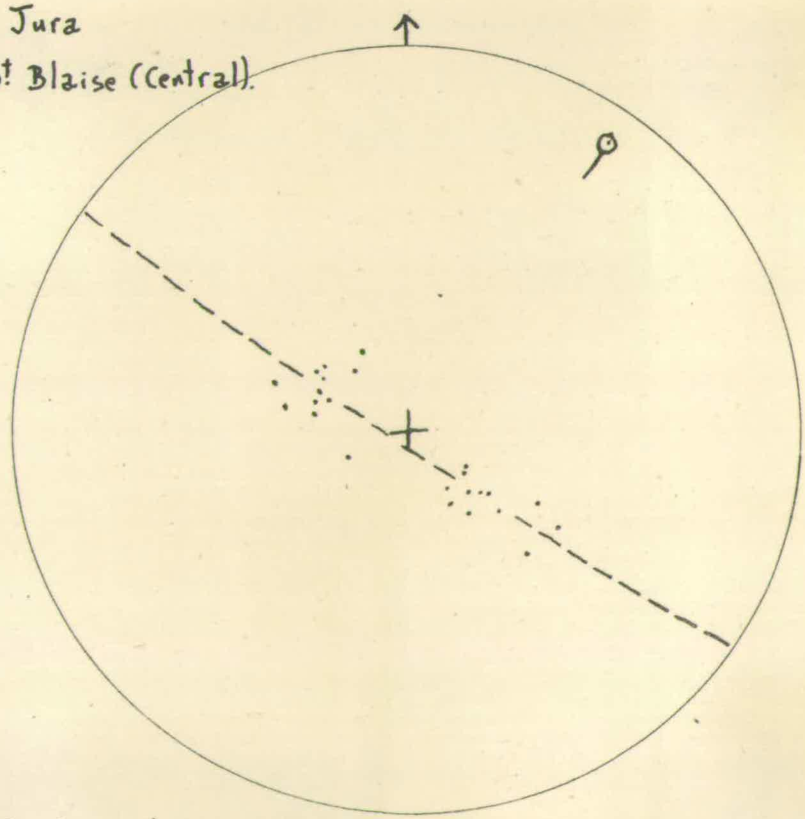
fig. 12.

Jura.
St Blaise (S.W.)



(Author's data) fig. 13.

Jura
St Blaise (Central).



(Author's data) fig. 14.

III.

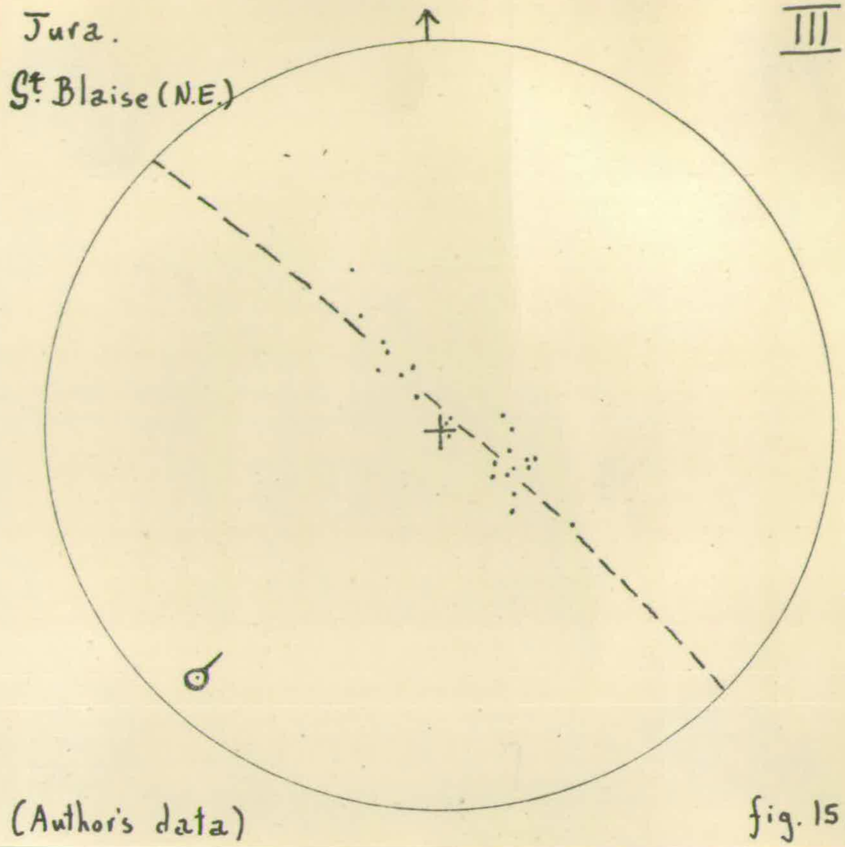


fig. 15.

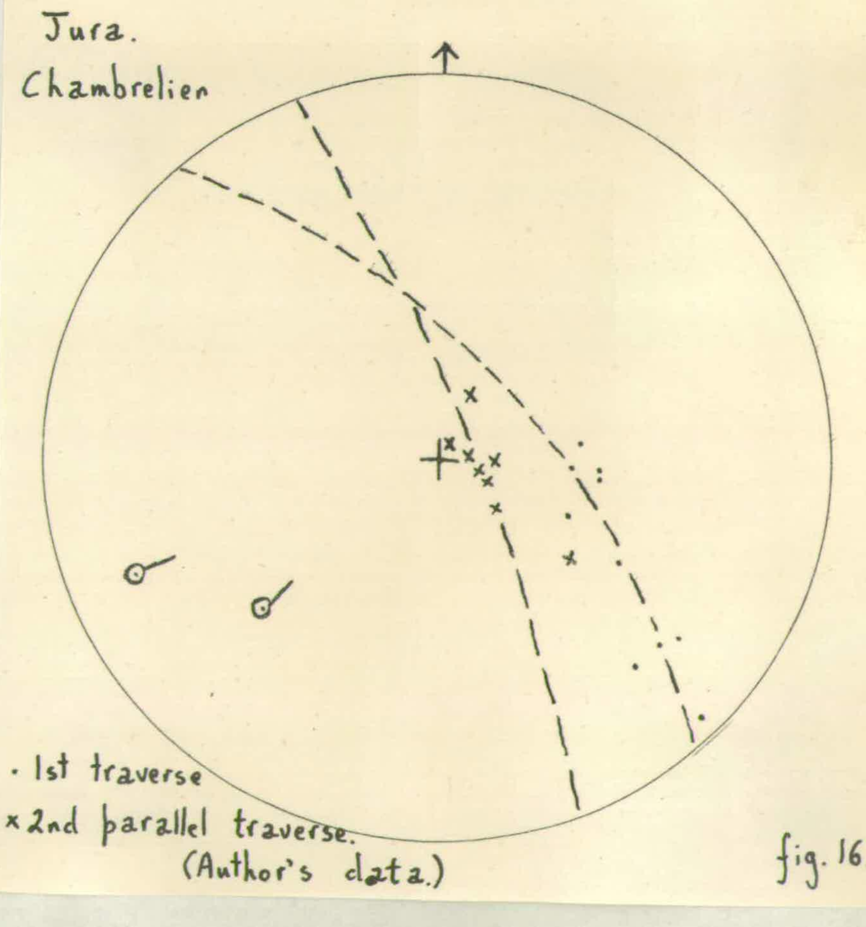
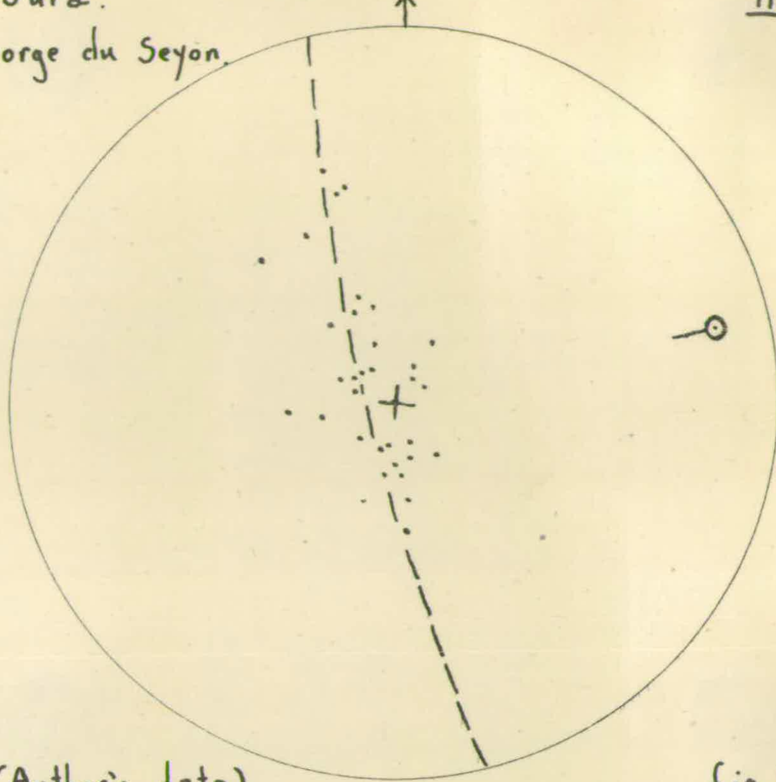


fig. 16.

Jura.

III.

Gorge du Seyon.

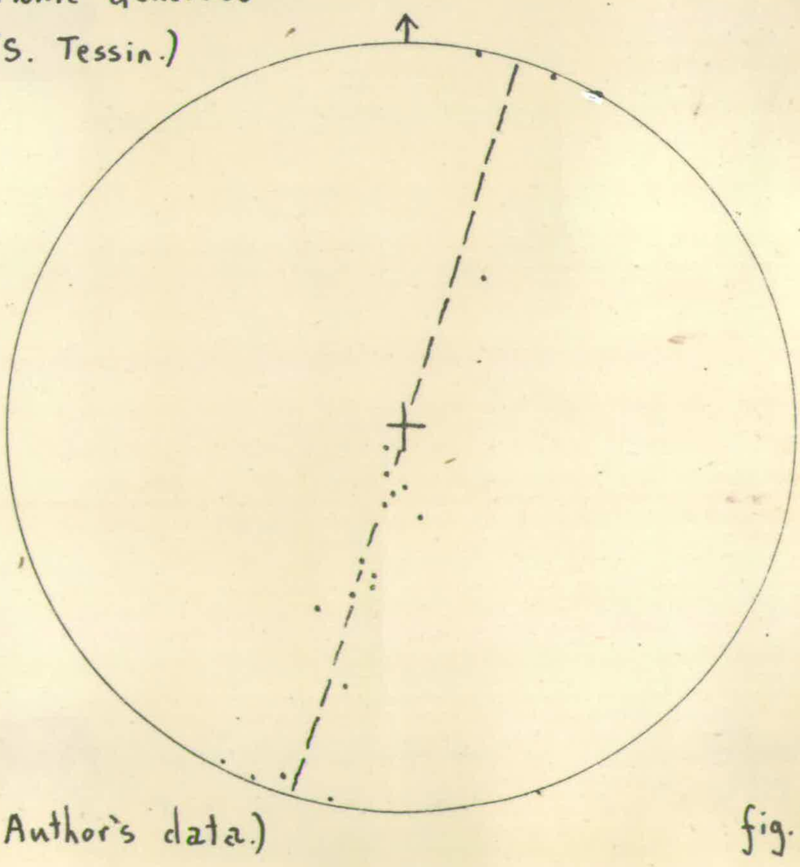


(Author's data)

fig. 17.

Monte Generoso

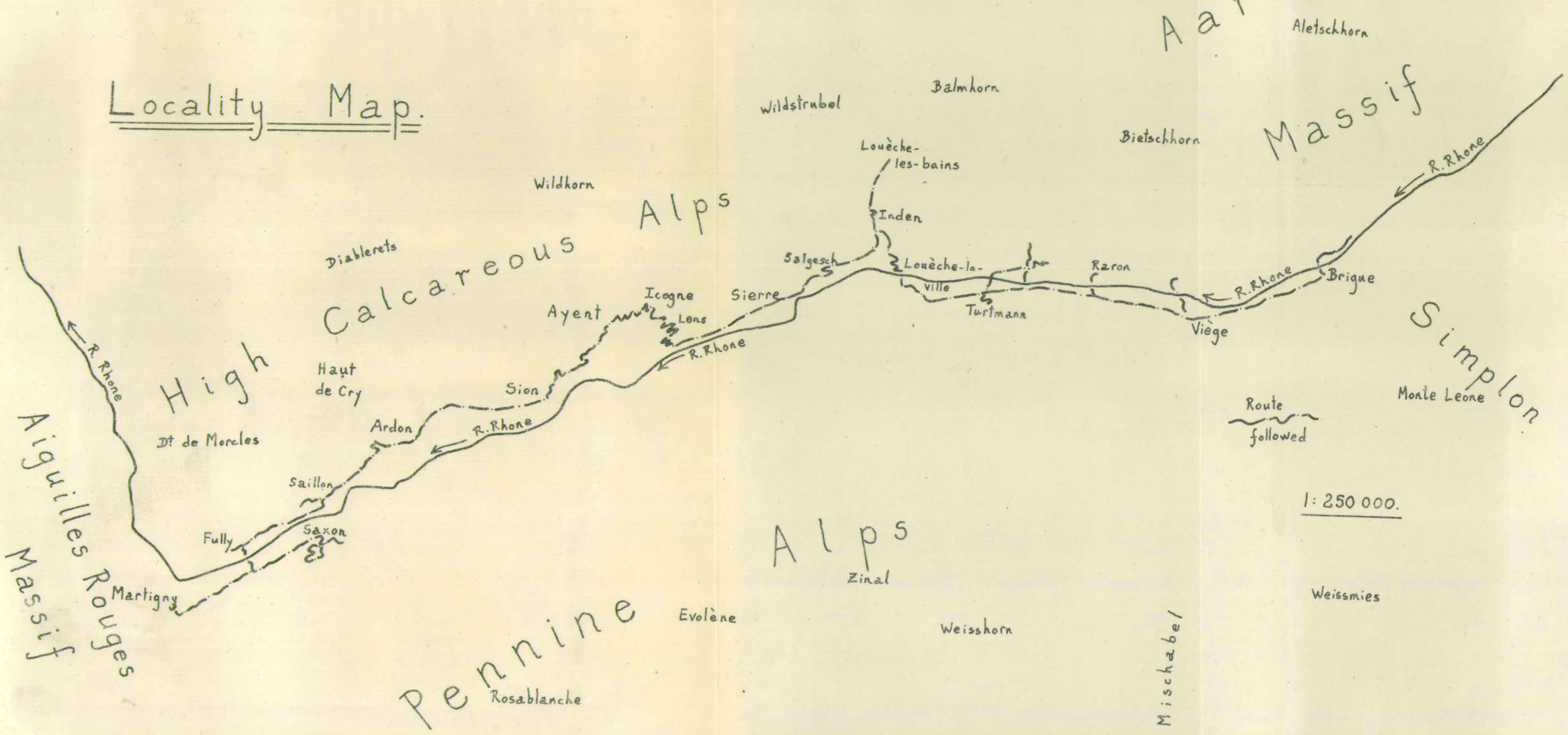
(S. Tessin.)



(Author's data.)

fig. 18.

fig. III, 20


Locality Map.
Aar Massif
Aletschhorn
Balmhorn
Wildstrubel
Bietschhorn
Louèche-les-bains
Wildhorn
High Calcareous Alps
Diablerets
Inden
Salgesch
Louèche-la-ville
Raron
Brigue
Icogne
Sierre
Lens
Ayent
Turtmann
Viège
R. Rhone
Simplon
Haut de Cry
Sion
Monte Leone
Route followed
Ardon
Dt de Morcles
Aiguilles Rouges Massif
Saillon
1: 250 000.
Fully
Saxon
Alps
Zinal
Martigny
Pennine
Evolène
Weissmies
Weisshorn
Mischabel
Rosablanche

III.

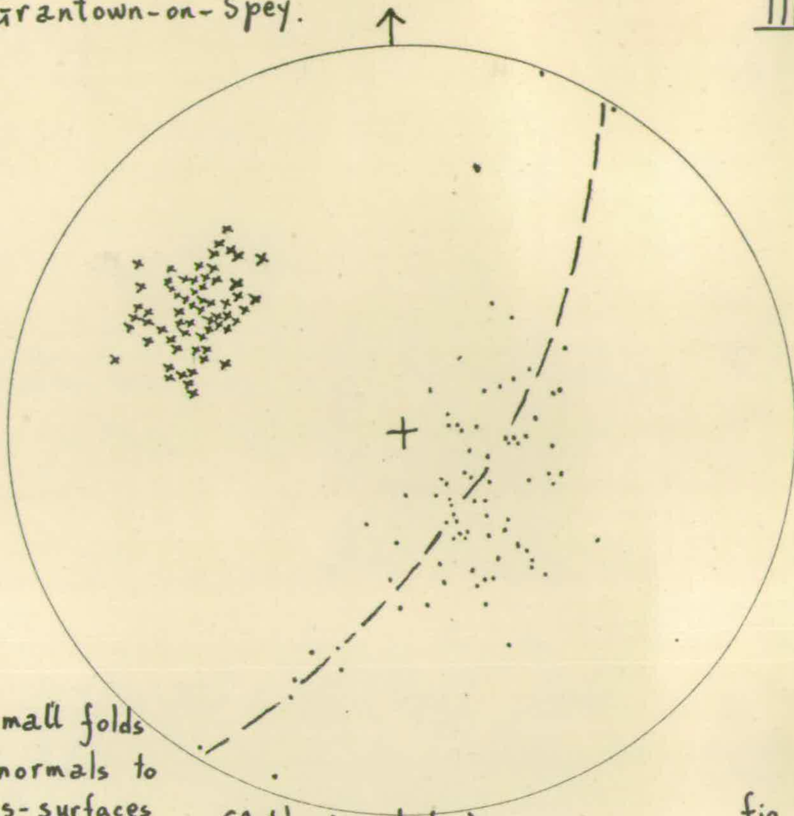


fig. 19.

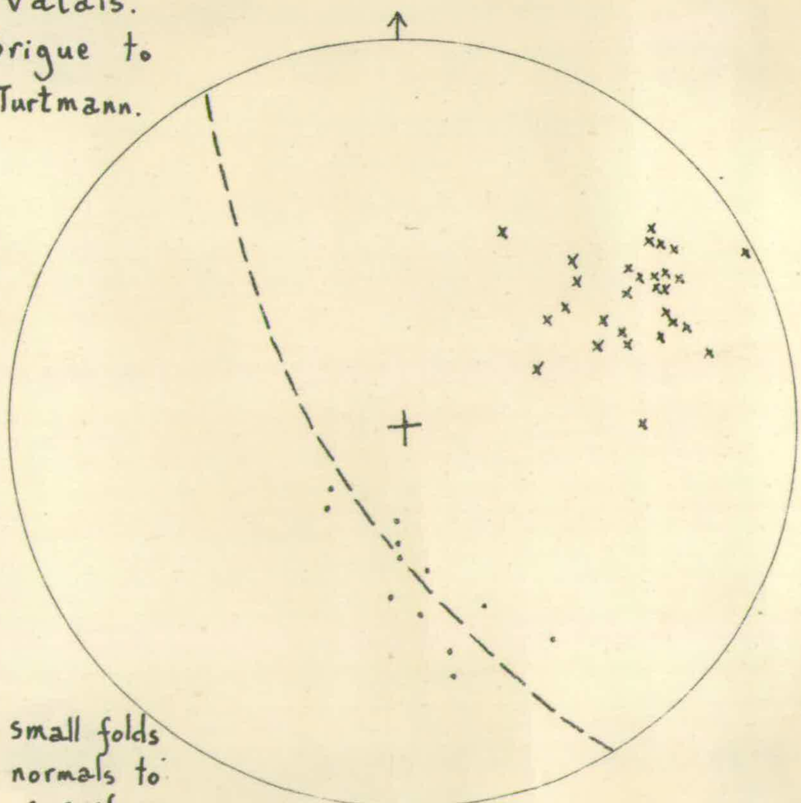


fig. 21.

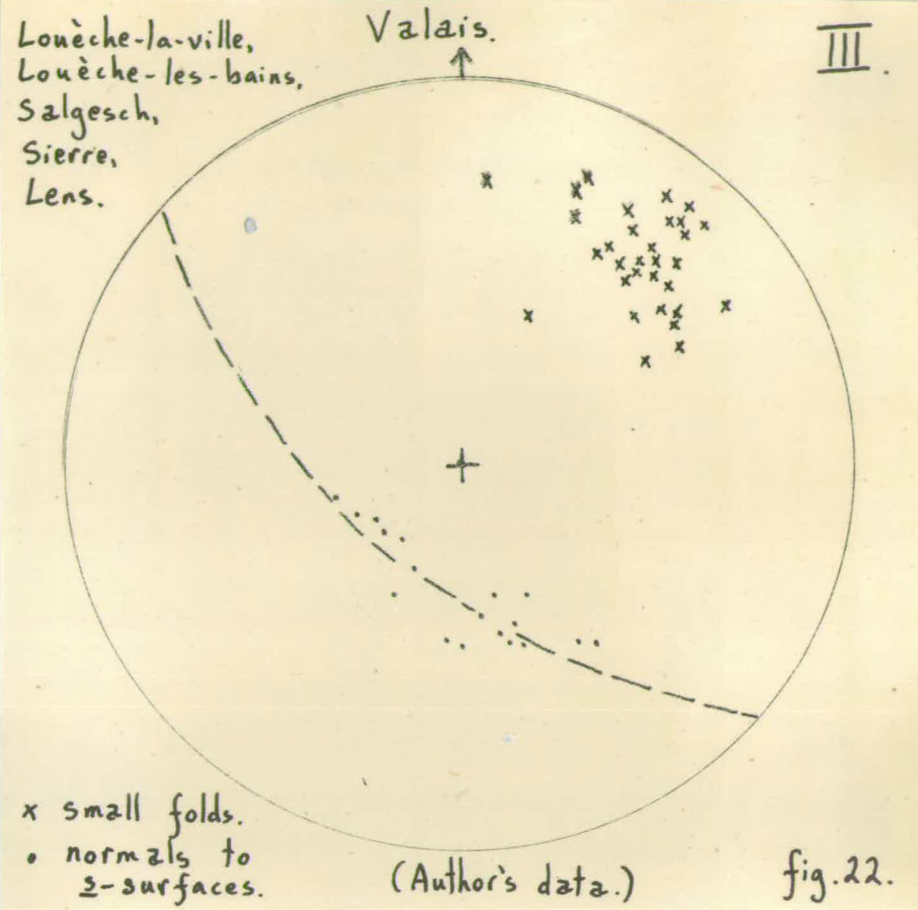

Louèche-la-ville,
Louèche-les-bains,
Salgesch,
Sierre,
Lens.
Valais.
x small folds.
• normals to s-surfaces.
(Author's data.)

fig. 22.

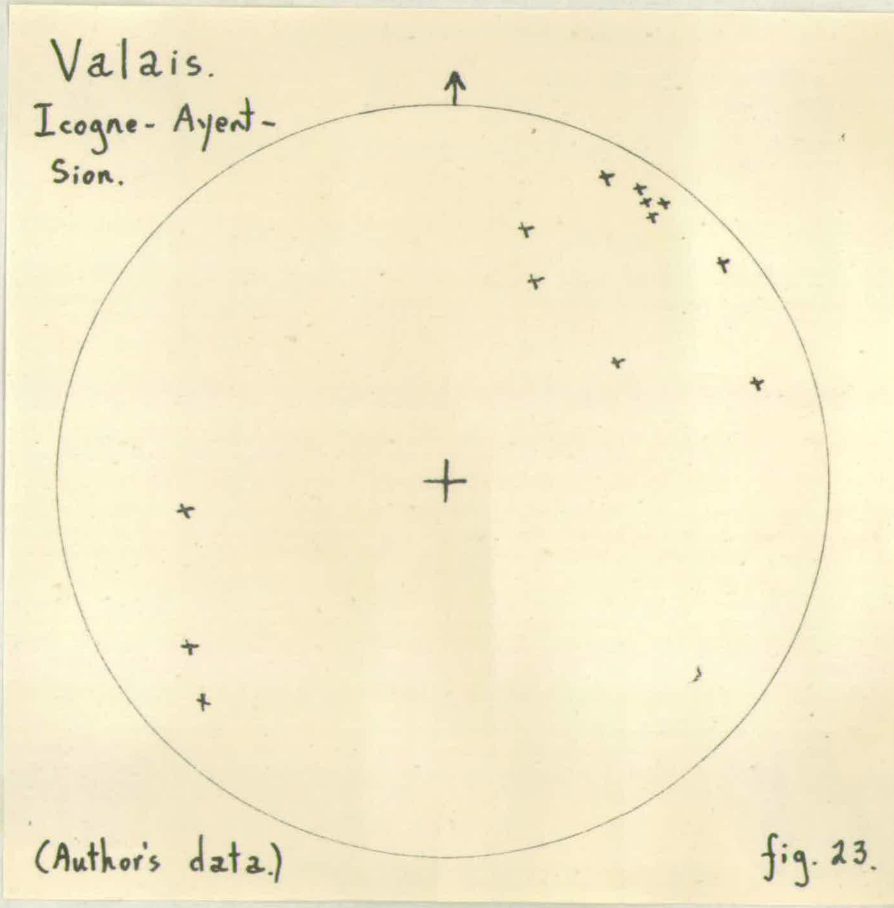
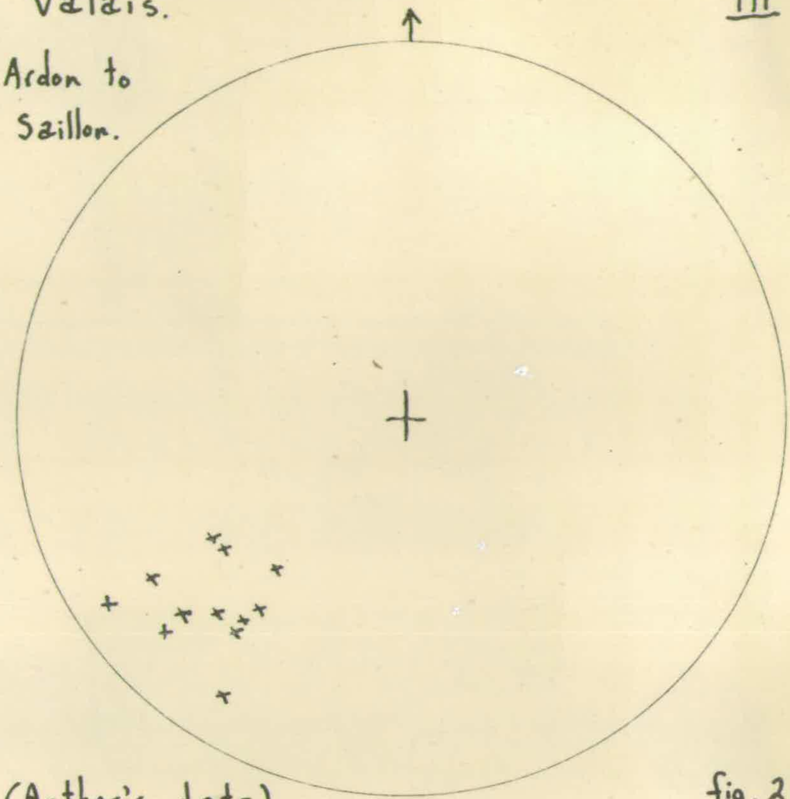

Valais.
Icogne-Ayent-Sion.
(Author's data.)

fig. 23.

Valais. III

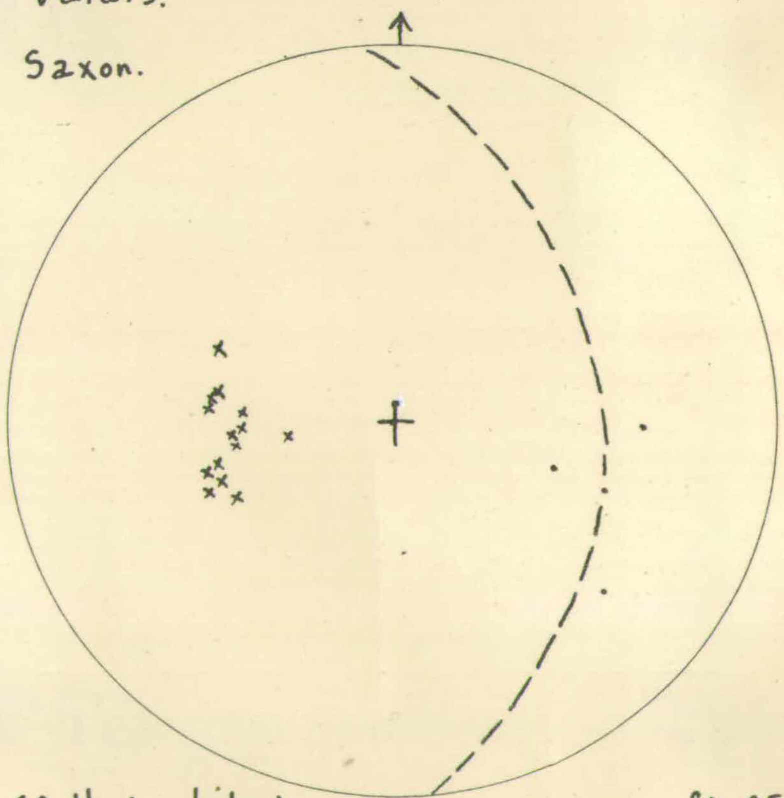
Ardon to Saillon.



(Author's data.) fig. 24.

Valais.

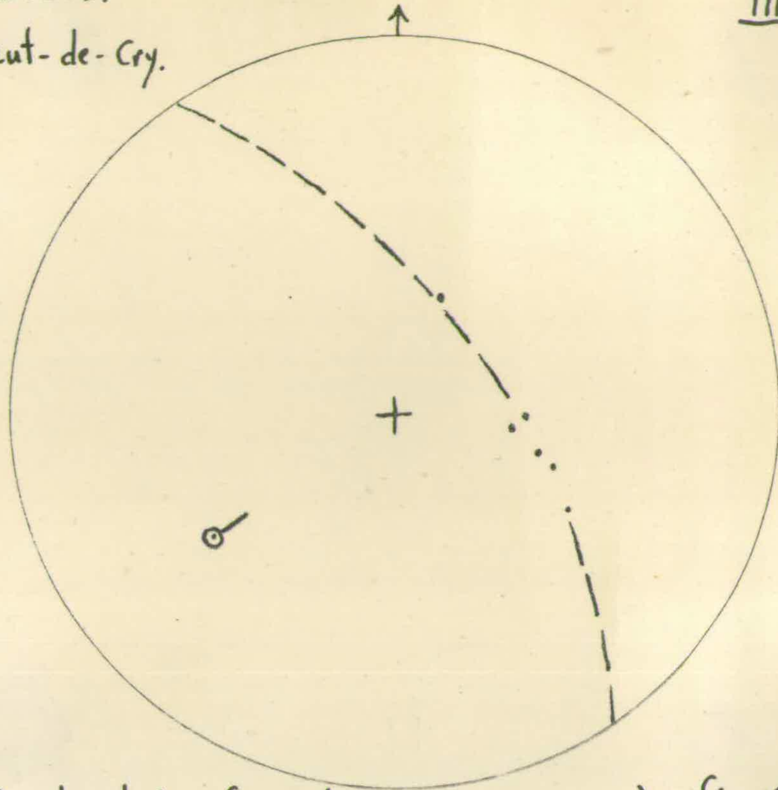
Saxon.



(Author's data.) fig. 25.

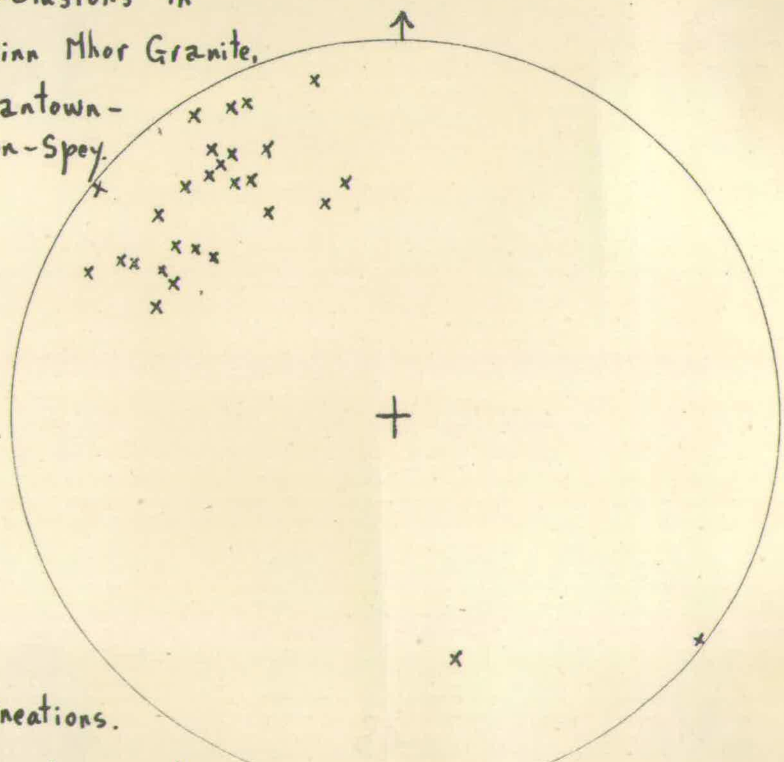
Valais.

Haut-de-Cry.



(Constructed from Lugeon's mapping.) fig. 26.

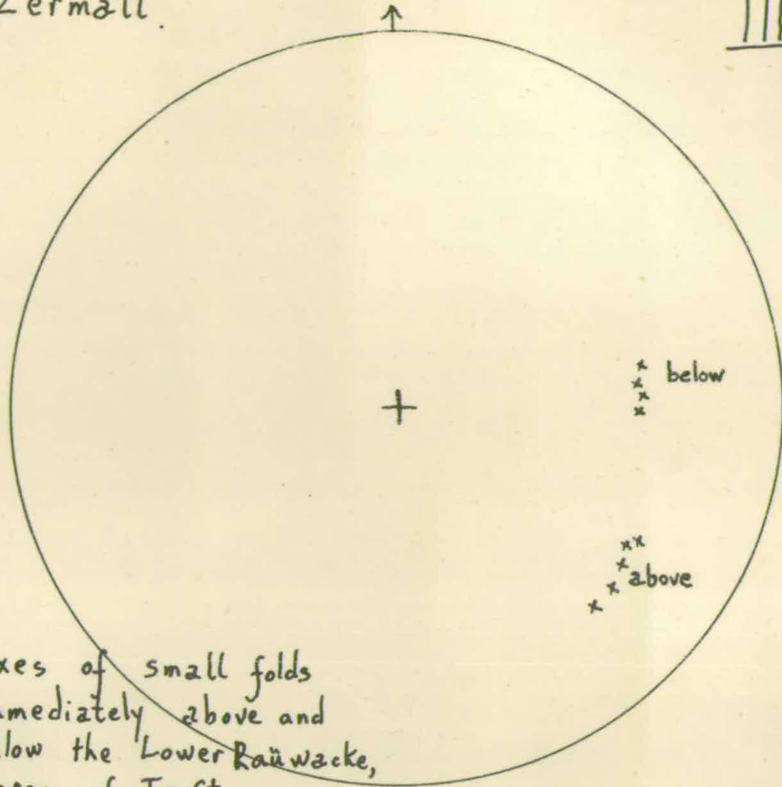
Inclusions in Beinn Mhor Granite, Grantown-on-Spey.



x lineations.

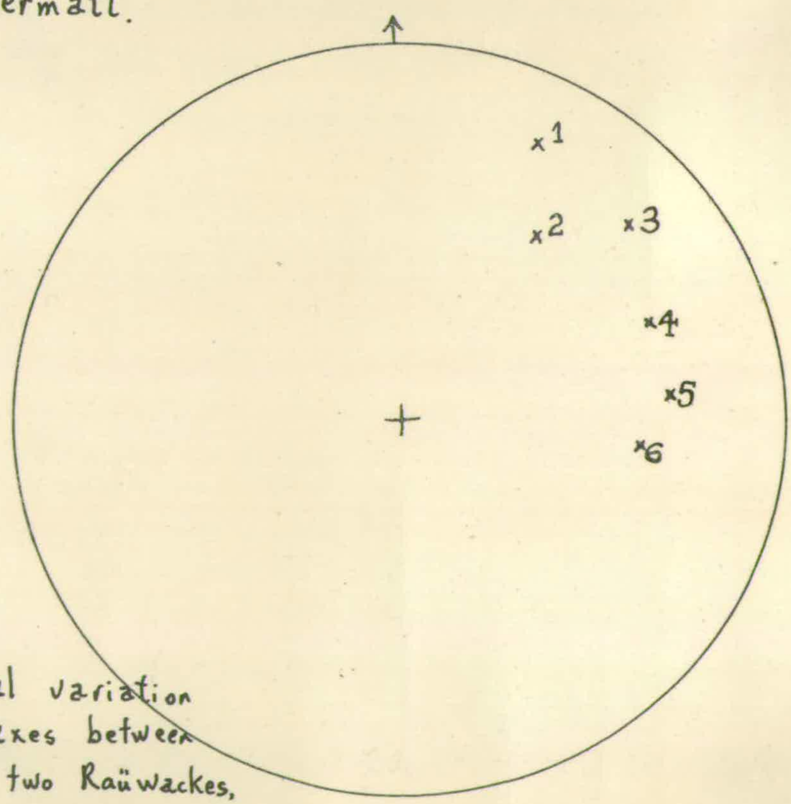
(Author's data.) fig. 27.

Zermatt. III.



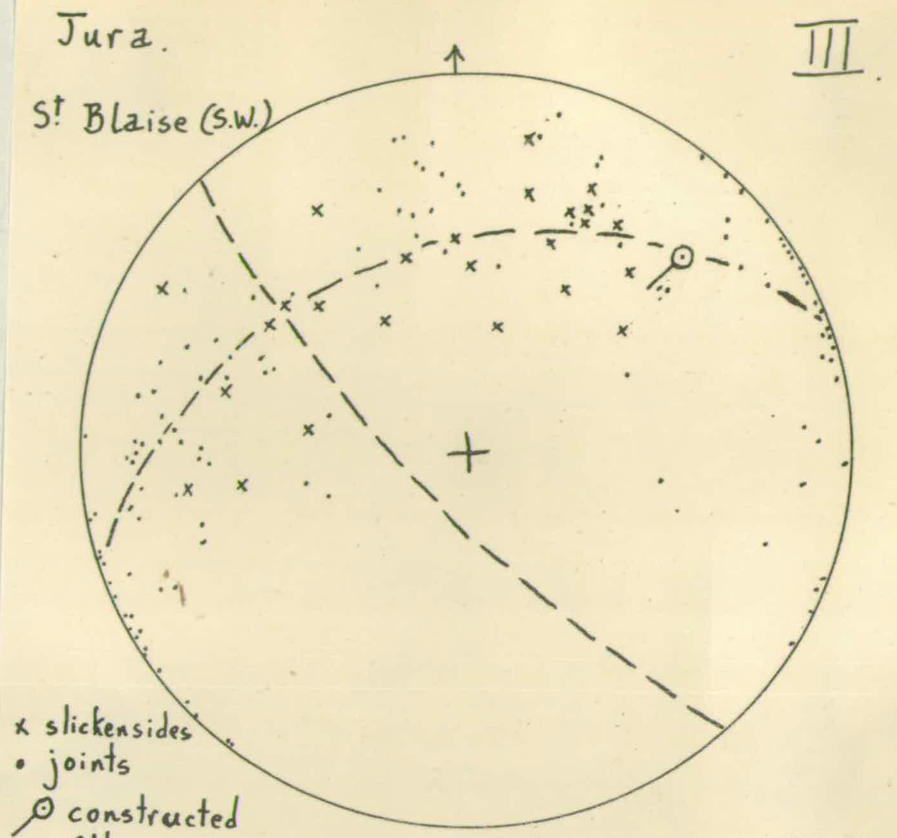
Axes of small folds immediately above and below the Lower Raüwacke, Gorge of Trift. (Author's data.) fig. 28.

Zermatt.

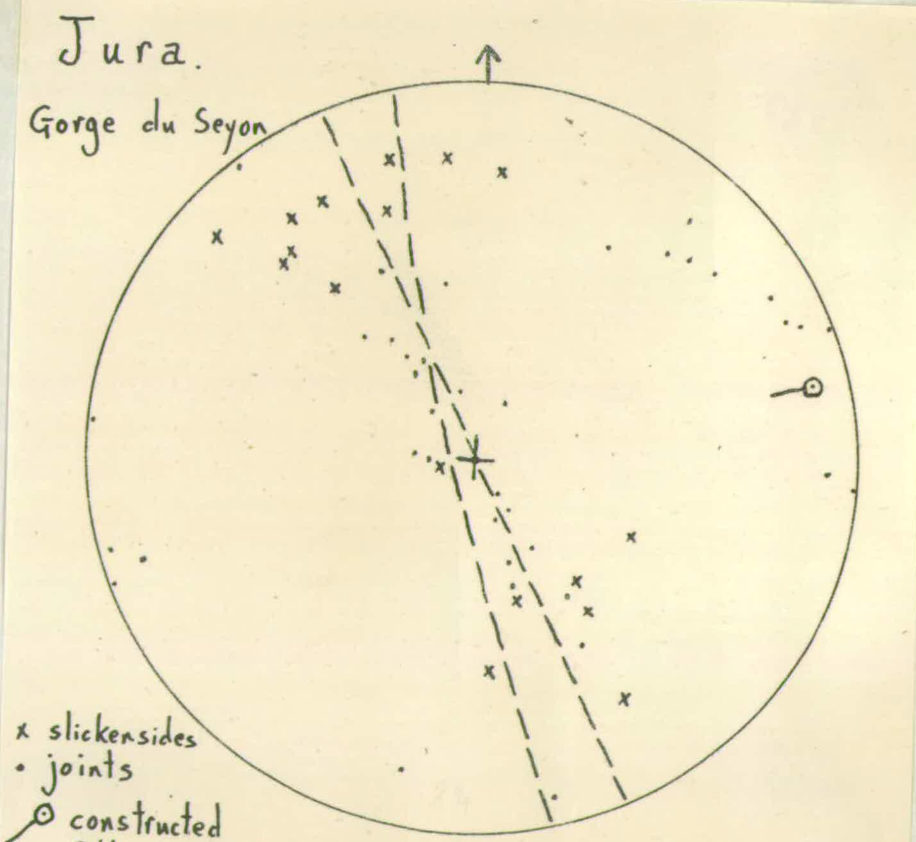


Serial variation of axes between the two Raüwackes, N. of Trift Gorge. (Author's data.) fig. 29.

III



fold-axis (cf. fig. III, 13) (Author's data.) fig. 30.



fold-axis (cf. fig. III, 17). (Author's data.) fig. 31.

IV. NOMENCLATURE: ON THE USE OF THE TERMS PITCH AND PLUNGE

Jointly with R. H. CLARK

To be published in the American Journal of Science

ABSTRACT

Attention is called to the fact that "pitch" and "plunge" are used in varied senses by different authors. "Pitch" appears to have been used originally as a measure of the obliquity of ore-shoots in the plane of the vein. Since 1908, "plunge" has been used as an angular measure in a vertical plane. Tectonicians are today seeking terms for concepts whose nomenclature was standardised by mining engineers forty years ago. It is highly desirable that the established usage should be continued in this new sphere. Application of the terms to igneous and granitic bodies is briefly dealt with; the nomenclature of folds is discussed in more detail.

A. GENERAL

Whereas the orientation of a coal-seam is given by its dip and strike alone, in metal mining, not only is the position of the vein to be defined, but the obliquity of the ore-shoot on the plane of the vein is also to be determined. The direction of maximum elongation, or "pitch-length", of an an ore-shoot may be defined, independently from the vein in which it is contained, by /

by means of two co-ordinates: viz. (i) the bearing of the projection of the pitch-length on a horizontal plane, and (ii) the vertical angle between the pitch-length and the horizontal. These co-ordinates, however, are not normally employed by mining engineers. The underground worker naturally refers all data to the plane of the vein in which the ore-shoot lies; e.g. in a vein striking north-south, an ore-shoot is said to "pitch" either north or south, whatever either its obliquity to the strike, or the dip of the vein may be. In short, the obliquity of the shoot is measured from the horizontal, in the plane of the vein.

As early as 1868, G.H. Cook noted that the term "pitch" had come into use among those engaged in iron mining to denote the obliquity of the long axis of elongated iron-ore bodies with reference to the bedding. Unfortunately his definition is inconsistent and there are certain ambiguities in his diagrams. It is clear, however, that he was endeavouring to describe linear structure lying on a plane. The strike of the plane (N 45° E) can be estimated from the sketch map, and its dip (55° to the south-east) from the "cross-section" at right angles to the strike. Further, a "section", the inclination of which was not stated, was included to show the angle of "pitch" (35° to the north-east). As this "section" contains both /

both the lineation and the strike of the plane, it follows that Cook measured "pitch" on an inclined plane. Thus, in Cook's example, the co-ordinates (mentioned above) of the linear structure are, (i) N 65° E, and (ii) 28° to the north-east. Elsewhere, however, thesame author used "pitch" for a measurement in a vertical plane. The need for separate terms for these two different angles did not emerge until forty years later.

In 1908, Professor H. Louis of Armstrong College, Newcastle, called attention (see Raymond et al, 1908) to the absence of any recognised English term for the vertical angle between the pitch-length and the horizontal, and proposed that "pitch" should be used for this. R.W. Raymond, of New York, objected to this proposal (1908). According to Raymond, the "practically universal" usage of American mining engineers was to measure "pitch" on the plane of the vein. He had himself used "pitch" in this sense for forty years prior to 1908, and he believed that there was no instance to the contrary in the twenty-seven volumes of the Transactions of the American Institute of Mining Engineers that he had edited. In the discussion which followed, all contributors agreed that Raymond's usage had been standard practice for many years amongst American mining engineers.

It was obvious, however, that it had become necessary

to /

to have two terms; one was required for each of the two angles in question. "It is evident", wrote Raymond, "that if Professor Louis's definition of 'pitch' were accepted, what I call 'pitch' would need a new name - and vice versa; and it is probable that the question which pitch should hereafter be the standard pitch would be largely affected by the extent of the present intelligent usage". While Louis naturally preferred his own use of the term, he wrote, "I do not think that it matters very greatly which definition of pitch we adopt; the essential thing is that we shall definitely decide upon one, and keep to it".

The man most keenly interest in pitch was the practising engineer engaged in metal mining, and, for him, Raymond's angle, measured in the plane of the vein, was more convenient than Louis', measured in the vertical plane containing the pitch-length. For this reason, as is now a historical fact, the following usage has become standard (see Lindgren, 1933, pp. 155-156; Bateman, 1942, p. 133):-

With reference to a linear structure contained in a plane,

Pitch is the angle between the lineation and the horizontal, as measured in the plane (angle DAC in text-fig.).

Plunge (the term for Louis' angle suggested by H.L. Smyth in 1908) is the vertical angle between the lineation and the horizontal (angle ACE in text-fig.). In a certain sense it may be said that plunge is thus the special case in which pitch is measured in a vertical plane.

Trend /

<u>Trend</u> is the strike of the vertical plane containing the lineation (CE in text-fig.).

Structural geology is a young science. Even in 1937, R. Balk, in a specialised memoir, found it necessary to devote several pages to demonstrate that a preferred orientation of crystals, seen on a random surface, might represent the trace of either a planar or a linear arrangement in the rock. In fact, in endeavouring to define the position of either a lineation on an <u>s</u>-surface, or a trace on a random plane, we encounter today precisely the same requirements in nomenclature as did our mining colleagues over forty years ago. It seems clear that we should recall Louis' advice and act on it. Having definitely decided upon our nomenclature, it is essential that we should keep to it.

With reference to a particular type of lineation, mining engineers, for more than eighty years, have used "pitch" for an angle measured in a plane, vertical only in a particular case. Now that the need to define other types of lineation has arisen, it would be folly to restrict "pitch" to angles measured solely in this special case. It is always somewhat perilous, as Raymond pointed out in 1908, to restrict the meaning of a term previously used in a wider sense. Moreover, if "pitch" were thus restricted, a new term would be required. The term "pitch" cannot, of course, be used in different senses when applied to different types of lineation. There is here no dilemma; the terms /

terms established by mining engineers in the course of nearly a century of practice fit our requirements perfectly. Either we take advantage of the experience of our mining colleagues, or we invent a parallel set of completely new terms with the same definitions. Any other course will lead to chaos. To invent new terms for angles already carefully defined will serve no useful purpose, and, indeed, many leading tectonicians in the English-speaking world have already adopted the definitions given above (e.g. Billings, Bucher, Nevin and others).

B. APPLICATION TO FOLDS

Although folds are three-dimensional structures, they have, in most cases, an important linear aspect. In any highly folded region, and in particular in a segment of a geosynclinal chain, the folds are found to be conspicuously elongate. The direction in space of this elongation is referred to as the axis of the fold or system of folds. Its determination is a primary requisite for tectonic analysis.

For the tectonician, the most useful definition of fold-axis is that given by Wegmann (1929), based as it is on the usage of the Alpine structural geologists (especially Lugeon and Argand) since the 1890's. The axis of a fold is defined as the nearest approximation to the line, which, moved parallel to /

to itself in space, generates the folds. The utility of this definition lies in the fact that many complex folds maintain remarkably constant profiles (sections at right angles to the axis) even when the sections are spaced at distances many times greater than the amplitude.

A fold-axis is a linear structure, and, in defining its orientation, our terminology must conform to that used for all other linear structures. Thus, the pitch of a fold-axis has meaning only when related to the plane on which it has been measured. In practice the plunge of a fold-axis is usually measured directly, but, on occasion, it is more convenient to measure the pitch of the axis on some inclined plane, the dip and strike of which must, of course, be specified.

Definitions of fold-axis, other than that given above, will be found in most of the current text-books. The majority of these definitions conform, in principle, to one of three different types:-

1. The fold-axis is sometimes defined as "the median line of the fold, along the top of an anticline or the bottom of a syncline". The trend and plunge thus determined are the same as those found when using Wegmann's definition. But, whereas Wegmann's axis is a line with orientation alone, the definition just cited fixes position as well as orientation. This is analagous /

analagous to requiring that a crystallographic axis must pass through the centre of the crystal; the restriction is unnecessar and is, indeed, a disadvantage.

2. For some geologists, "an axis of a fold is the line in which any bed intersects the axial plane". The obvious difficulty with regard to this definition is that it is first necessary to define the term "axial plane". Most attempts to do this either have been too vague, or have been so worded that strict application is not possible when the fold-axis (of Wegmann) plunges.

Bonté (1945, p. 35), following Haug and others, defines the <u>axial surface</u> as the locus of the hinges of all beds forming the fold. This appears to be the only sound definition and if employed it automatically ceases to be necessary to use axial surface in defining fold-axis. The latter then becomes synonomous with "hinge", i.e. with the locus of points of maximum curvature of the cylindroidal surface constituting the fold. Thus, the fold-axis would be fixed in a position which is nearly, but, in the general case, not quite coincident with the median line, i.e. with the apex-line or arete.

3. The axis of a fold has been defined as "the line of intersection of the axial surface with the topographic surface". Even if "horizontal surface" were to be substituted for "topographic /

"topographic surface", this definition would remain unsatisfactory. (i) There would be no way of indicating the plunge of the fold-axis in Wegmann's sense; (ii) except in a special case, a curved axial surface would necessitate a curved "fold-axis", even although the form of the fold were ideally cylindroidal, and (iii) as Argand (1911) and Wegmann (1929) have emphasised, general strike and axial trend, in the sense of Wegmann, coincide only in a limiting case.

It seems clear that Wegmann's concept and definition of the axis as the generatrix of the fold is the most logical proposed. It is a linear structure and the terms pitch and plunge with reference to it must be used in the same way as for all other linear structures.

To the proposals made here it may be objected that the term "plunging" has already been used to denote downward closure at the hinge of a recumbent anticline. Bailey and McCallien (1937, fig. 1), and Bailey (1939, fig. 51) have published a diagram in which this use of the term is implied. Although no definition is given by these authors in their texts, it appears inherent in their diagram that, for them, an anticline is said to be "plunging" where it is a synform. Thus, before the term may be applied to a specific fold, it is necessary to establish that it is in fact an anticline (<u>sensu stricto</u> of Bailey and McCallien). /

McCallien). The term is apparently limited to terrains where the stratigraphy is unravelled.

For more than half a century, Alpine geologists have recognised examples, not only of recumbent folds, but of folds whose axial surfaces (see definition above) have, locally been rotated through more than a right angle from their presumably vertical, original positions. These folds are the "false anticlines" and "false synclines" of Lugeon, Haug, and others. Perhaps the best known illustration is Lugeon's diagrammatic stereogram of the structural units of the Tatra (1903, fig. 1). The use in French of the adjective "plongeant" for such folds, may have influenced the choice of the term "plunge" by British geologists. It should, however, be realised that, in French, the same term may apply, not only to the "plunging anticline" of Bailey and McCallien, but to the dip of a bed, or to the "plunge" of a fold-axis, in our sense. For examples of the latter usage we may cite Lugeon's classic Memoir on the Origin of the Valleys of the Western Alps (1901).

When we refer to the "plunge of a fold-axis" (in our sense), we imply, and in general specifically state, a quantitative measure. On the other hand, Bailey and McCallien, in describing a "plunging anticline" have indicated no way in which the amount of "plunge" is to be measured. The measure which suggests itself is as follows:-

The /

> The amount of "fold-plunge" along any specified line on the axial surface is given by the angle, as measured on the profile plane (i.e. the plane at right angles to the fold-axis) between the horizontal and the tangent to the axial surface along the line specified.

According to this measure, a recumbent fold would have zero "fold-plunge". It would be, of course, possible to determine "fold-plunge" only along a specified hinge-line.

All this, however, exposes the weakness of the term "fold-plunge". Plunge is an angular measure in a vertical plane. Pitch is used when a linear structure is related to the inclined plane on which it is measured. The value of Bailey and McCallien's "plunge" obviously depends on the axial-plunge of the fold, and it is therefore a typical pitch measurement and not a plunge. For this reason it is suggested that, if it is felt necessary to specify Bailey and McCallien's "fold-plunge", it be measured and given as fold-pitch and be stated together with the axial-plunge, without which it has no meaning.

Whereas the concept of Bailey and McCallien refers to the form of the fold in profile (i.e. in transverse section), axial-plunge denotes the inclination of the longitudinal section. There is, therefore, no reason why the two should not be used side by side, and, indeed, they have thus been used in numerous instances in the literature (see for example Lugeon, 1902).

C. APPLICATION TO IGNEOUS AND GRANITIC BODIES

In an igneous or granitic body, a preferred orientation of crystals, observed on a random plane, may represent the intersection with that plane of a linear, a planar, or a cylindroidal arrangement of the crystals within the rock mass, or a combination of these arrangements. It is suggested that the term "trace" is to be preferred to "lineation" or to "apparent lineation" when reference is made to observations on a random plane. The method of distinguishing between the traces of linear and planar structures will be discussed in another publication.

It may sometimes be convenient to measure the plunge of a trace directly. But, as a trace has no meaning except when related to the plane on which it has been observed, it is more logical, and usually more convenient, to record the obliquity of the trace on the plane of the exposure as a pitch.

D. CONCLUSIONS

It is necessary to have separate terms to refer to each of the following:-

1. The angle between a line and the horizontal as measured in some specified plane containing the line.
2. The vertical angle between a line and the horizontal. This case is a limiting example of the first.

Discussion /

Discussion of the different usages of the terms pitch and plunge, due consideration having been given to the question of precedence, has led to the conclusion that the most logical system of nomenclature at the present day is to adopt the former for the first angle and the latter for the second. The following definitions are therefore offered:-

Pitch is the angle, measured in some specified plane, between a lineation, or a trace, and the horizontal.

Plunge is the vertical angle between a lineation, or a trace, and the horizontal.

Trend is the strike of the vertical plane containing a lineation or a trace.

E. LIST OF WORKS TO WHICH REFERENCE IS MADE

ARGAND, E. 1911. Les nappes de recouvrement des Alpes Pennines et leurs prolongements structuraux. Mat. pour la carte géol. de la Suisse, New Series, 31, pp. 25.

BAILEY, E.B. 1939. Introduction to Geology. MacMillan, pp. 498

BAILEY, E.B. and W.J. McCALLIEN. 1937. Perthshire tectonics: Schiehallion to Glen Lyon. Trans. Roy. Soc. Edin., lix - Part 1 - (No. 3)., pp. 79-117.

BALK, R. 1937. Structural Behavior of Igneous Rocks. Mem. 5 Geol. Soc. Amer., pp. 177.

BATEMAN, A.M. 1942. Economic Mineral Deposits. Wiley, pp. 898.

BILLINGS, M.P. 1942. Structural Geology. Prentice-Hall. pp. 473.

BONTE /

BONTE, A. 1945. Introduction a la lecture des cartes géologiques. Masson, pp. 239.

BUCHER, W.H. 1944. The stereographic projection, a handy tool for the practical geologist. Jour. Geol., lii, pp. 191-212.

COOK, G.H. 1868. The Geology of New Jersey. Newark, pp. 899.

LINDGREN, W. 1933. Mineral Deposits. McGraw-Hill, pp. 930.

LUGEON, M. 1901. Récherches sur l'origine des vallées des Alpes occidentales. Ann. de Géographie, x, pp. 295-317; 401-428.

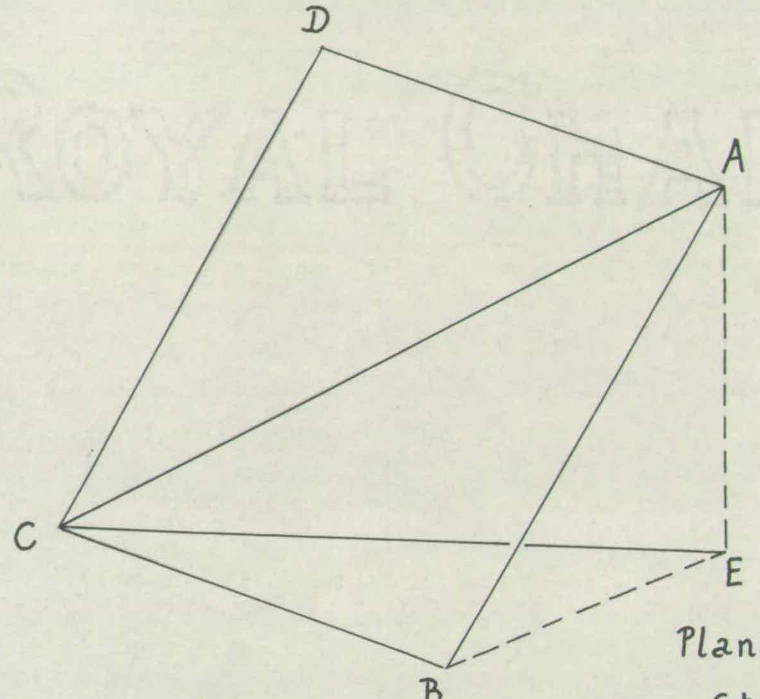
________ 1902. Sur la coupe géologique massif du Simplon. Compte rendu sommaire, Soc. géol. de France, 24th March, pp. 3.

________ 1903. Les nappes de recouvrement de la Tatra et l'origine des Klippes des Carpathes. Bull. de la Soc. vaud. des Sc. naturelles, xxxix, 146, pp. 51.

NEVIN, C.M. 1949. Principles of Structural Geology. Wiley, pp. 410.

RAYMOND, R.W. et al. 1908. Dip and Pitch. Trans. Amer. Inst. Min. Eng., xxxix, 1909, pp. 326-7; 898-916.

WEGMANN, E. 1929. Beispiele Tektonischer Analysen des Grundgebirges in Finnland. Bull. Comm. géol. de Finlande, lxxxvii, No. 8, pp. 98-127.



Plane ABCD
Strike BC ; Dip ∠ABE

Lineation AC :-

Pitch ∠DAC

Plunge ∠ACE

Trend CE

(CE, CB, BE, AD horizontal
AE vertical)

V. APPLICATION OF THE METHOD TO MACROSCOPIC STRUCTURES

A. NOTE ON TWO LINEATED TECTONITES FROM STRATHAVON, BANFFSHIRE

(Geol. Mag. 1950, Vol. 87, pp. 331-6)

ABSTRACT

The principal tectonic terms employed are defined. A specimen of sheared quartzite from Corshellach is described. Shear-planes, drag-folds, and lineation are syngenetic. Their geometric relations show that the lineation is in b. Also described is a specimen of folded marble and graphite schist from Urlarmore. Elongated bodies of graphite schist represent tectonic thickening along the antiform hinges. Their maximum dimension, which is much greater than any other, is parallel to the lineation, but they have not suffered extension in this direction. The form of folds and rotated bodies shows that the lineation is again in b. The sense of the movement was towards the south-west. It is believed that throughout Mid-Strathspey and Strathavon, similar lineations bear the same relations to the kinematic directions.

(i) NOMENCLATURE

To avoid creating unnecessary difficulties by the use of ambiguous terminology, the writer will use the following definitions:-

The /

The <u>fabric</u> of any object is defined by the spatial arrangement of all the microscopic and macroscopic structural elements which it contains. A <u>deformation fabric</u> is one produced by the operation of stress.

<u>Componental movements</u> are those displacements and rotations which take place in a deformed body without destroying intergranular cohesion. A <u>tectonite</u> is a rock which has undergone componental movements.

An <u>s-surface</u> is any structural surface in a deformation fabric.

<u>Lineation</u> (<u>l</u>) is a nongenetic term for any kind of linear structure within or on a rock.

The <u>axis</u> of a fold, or of an <u>s</u>-surface, is the nearest approximation to the line which, moved parallel to itself, generates that surface.

The <u>profile</u> of a fold, or of an <u>s</u>-surface, is the trace of that surface on a plane perpendicular to the axis.

The <u>a-axis</u> is the direction of movement. The <u>b-axis</u> is the axis of rotation. In most cases it coincides with the fold-axis, and it is usually perpendicular to the <u>a</u>-axis. The <u>c-axis</u> is normal to the <u>a-b</u> plane. The <u>a-b</u> plane is the movement plane or principal fabric plane. The <u>a-c</u> plane is usually a symmetry plane.

The definitions of <u>axis</u> and <u>profile</u> follow the usage of /

of Wegmann (1929) and the alpine tectonicians (Lugeon, Argand). The remainder are based on those given by Fairbairn (1942), and E. Cloos (1946), and follow in broad lines the original usage of Sander.

(ii) SPECIMEN OF SHEARED QUARTZITE FROM CORSHELLACH, GLEN TERVIE.

The Cromdale Hills separate the valley of the Spey from that of its tributary, the Avon. Composed of a group of metamorphosed quartzose sediments, they lie between the typical Moine of the Central Highlands and the Dalradian of Banffshire. In 1896 L.W. Hinxman (p. 17) distinguished this group as the "Cromdale Hills Series". In 1902 he included it in the Moine of the Central Highlands (p. 24).

Linear structures were observed in these rocks at a very early date. Hinxman's Map (one-inch sheet 75) published in 1895 has symbols indicating the direction and sense of "striping" or "lines of stretching". "The rock", he wrote (1896, p. 19), "is thoroughly drawn out and often shows beautiful 'mullion-structure'". This area has been studied in detail by the writer, and the results will be published in due course. Macroscopically there is a plane of symmetry perpendicular to the /

the lineation: a-lineation has usually no such plane; slickensides, for example, are smooth one way and rough the other. Hinxman did not state that asymmetry is present; he simply affirmed that the lineation "shows" a north-westerly movement (i.e. parallel to the lineation). It seems that he must have assumed that the a-axis coincided with the lineation and that the sense of movement was up-dip. Present knowledge does not permit such assumptions to be made a priori.

Similar phenomena were found and recorded by Hinxman when he followed the Cromdale Hills Series towards the north (one-inch sheet 85). Where the quartzose members of the group have been sheared, "white mica is developed along the planes of movement". At Corshellach (8 miles south-west of Dufftown), where the shearing is pronounced, "striping produced by the drawing out of the mineral particles in one determinate direction is often well seen, the direction of movement being to the north-west" (1902, p. 25).

The purpose of this section is to describe a specimen from Corshellach, and to demonstrate that its macro-fabric is not in accord with Hinxman's interpretation. Further data on the nature and significance of the lineation in Mid-Strathspey will be given in a forthcoming publication. At Corshellach there is a small quarry, now largely overgrown. The floor is strewn /

strewn with fragments of highly siliceous rock similar to that exposed _in situ_. The specimen described was found loose, and therefore its orientation is unfortunately unknown.

The specimen (fig. V.A.1) is bounded on two sides by _s_-planes (foliation). On one of these there is a well-developed linear arrangement of the crystals; on the other no linear structure is apparent macroscopically. There is a plane of symmetry perpendicular to the lineation. Cutting obliquely across the specimen are two shear-planes, but the rock is so thoroughly welded together that it shows no tendency to split parallel to these planes. The direction of lineation lies on both shear-planes; if projected beyond the limits of the specimen, their intersection would define this direction. Bedding is plainly visible on sections perpendicular to the foliation. If such sections are cut parallel to the lineation, a fine parallel ruling is seen; the bedding and foliation are in the main sub-parallel. In sections cut perpendicular to the lineation, many of the bedding-planes are seen to change direction as they approach the shear-planes. Such a section is illustrated in fig. V.A.2. Close to the shear-planes the dip of the bedding increases and sometimes becomes inverted in the manner usually attributed to drag against a movement-plane. The axis of these drag-folds coincides with the lineation. Where the bedding /

bedding and foliation are not parallel, their intersection would likewise define the lineation-direction.

These geometric relations prove that the shear-planes, the drag-folds, and the lineation on this specimen are genetically related to one another. The direction of movement is clearly perpendicular to the lineation, and not parallel to it as Hinxman assumed. The "striping" is a b-lineation.

(iii) SPECIMEN OF FOLDED MARBLE AND GRAPHITE SCHIST FROM BRIDGE OF AVON, URLARMORE

The specimen (fig. V.A.3) was found in situ in the River Avon below the bridge at Urlarmore ($1\frac{1}{4}$ miles N.N.W. of Tomintoul, and $8\frac{1}{2}$ miles S.S.W. of Corshellach). It consists of alternating marble and graphite schist belonging to the Banffshire Dalradian. The locality is little more than a mile from the outcrop of the Cromdale Hills Series (Moine).

The upper and lower surfaces are of graphite schist. They show the minute puckering which Hinxman carefully described in 1896: "The original bedding-planes, as distinct from the foliation, are generally still recognisable in lines of different sedimentation; while a third set of divisional-planes, arranged at a considerable angle with the foliation, can often be detected

These /

These planes indicate strain-slip cleavage (ausweichungsclivage), and produce a minutely corrugated or puckered structure which is so constant a feature of these rocks, though less recognisable in the more slaty varieties" (p. 11). There is again a plane of symmetry perpendicular to the lineation. At this locality the latter plunges at 30° towards 120-130° E of N.

The rock is broken by joints which are nearly perpendicular to the lineation. The surfaces so exposed show recumbent folds verging towards the south-west (see fig. V.A.4). The fold-axes are very constant and are parallel to the lineation. Successive profiles show little change even though they are spaced at distances measuring many times the amplitude of the folds. Sections cut parallel to the lineation show parallel banding.

In the environment of regional metamorphism, marble and graphite schist flow readily. The profile (fig. V.A.4) shows that the graphite is concentrated along the hinges of the recumbent antiforms. This thickening of the graphitic layers has occasionally caused several of these to coalesce in one, relatively large, graphitic lenticle. An example of the coalescence of at least four layers is illustrated in fig. V.A.4. Such bodies have more or less elliptical profiles and a considerable elongation parallel to the lineation. In the example described /

described, the maximum dimension is <u>at least</u> twenty times the minimum. At first glance, these bodies could easily be erroneously interpreted as due to an <u>extension</u> parallel to the lineation. Indeed, Dr. E.M. Anderson, to whom the writer showed the specimen, was at first inclined to believe that in fact there had been such extension. There is, however, no evidence for extension in that direction. The thickening takes place in three-dimensions, and not in two; the maximum dimension of the body is necessarily parallel to the fold-axis, and this dimension <u>must</u> measure many times the length of the other two.

Of great significance is the orientation of the "feeders" of the elongated graphitic body. Looking south-east, in the direction of axial-plunge, these emerge in a clockwise direction. See fig. V.A.5. Relative to its environment, the body rotated in an anti-clockwise direction; the axis of rotation is parallel to the lineation and to the fold-axis, i.e. the lineation is parallel to the <u>b</u>-axis. As it is unlikely that there was a source of energy within the body, it is convenient to refer to a clockwise rotation of the environment, and to conceive the body as playing a passive role. All movement is relative, and, as we live at the surface of the earth, it is conventional to conceive the surface moving relative to the interior, rather than the equally correct concept of referring all /

all motion to a static exterior. Analysis of the macro-fabric of this specimen thus leads to the conclusion that the a-axis is at right angles to the lineation, and that the sense of the movement was towards the south-west. The form of the folds (fig. V.A.4) supports this conclusion.

(iv) CONCLUSIONS

The lineation in the Corshellach quartzite is typical of that found in the Cromdale Hills Series, and in some of the other Moine rocks of Mid-Strathspey. The lineation in the Urlarmore graphite schist is typical of that in the Dalradian of western Banffshire. In both cases they are b-lineations. It is likely that throughout Mid-Strathspey and Strathavon, similar lineation bears the same relation to the kinematic directions. Further evidence supporting this conclusion will be published in a paper at present in course of preparation.

(v) REFERENCES

CLOOS, E. 1946. Lineation: a critical review .... Mem. 18. Geol. Socl Amer.

FAIRBAIRN, H.W. 1942. Structural Petrology of Deformed Rocks. Addison-Wesley Press.

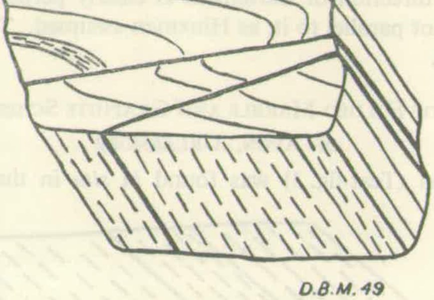
HINXMAN /

HINXMAN, L.W. 1896. Explanation of Sheet 75. Geol. Surv. Scotland.

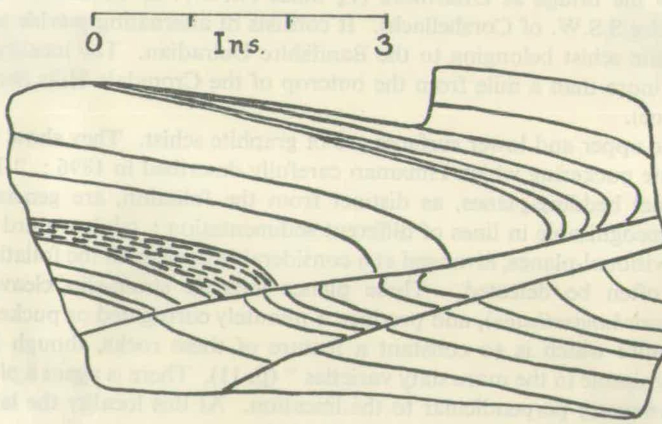
________ 1902. Explanation of Sheet 85. Geol. Surv. Scotland

WEGMANN, C.E. 1929. Beispiele Tektonischer Analysen des Grundgebirges in Finnland. Bull. Comm. géol. Finlande, 87, No. 8.

V A.

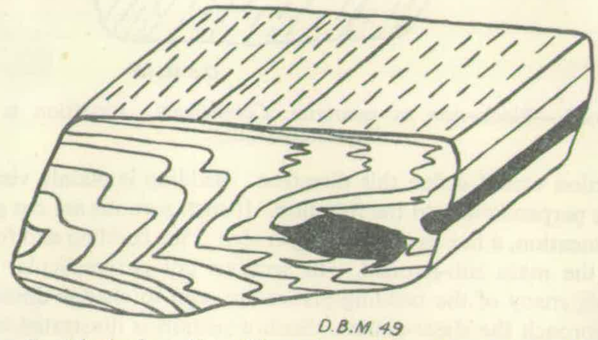


TEXT-FIG. 1.—Block-view of quartzite, Corshellach. Lineation is shown diagrammatically.

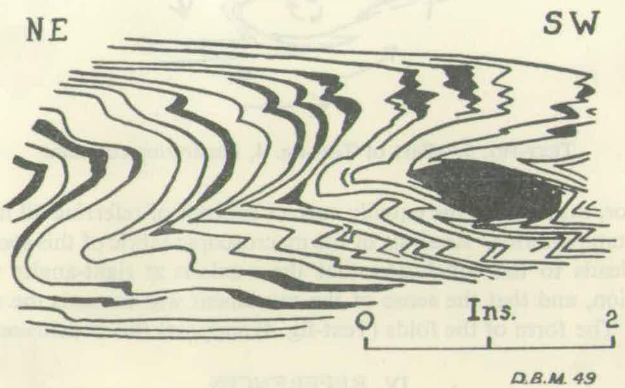


TEXT-FIG. 2.—Profile, perpendicular to lineation.

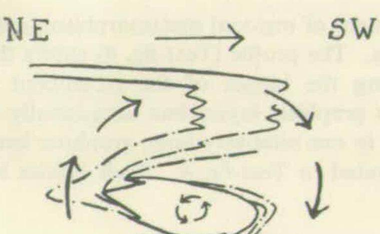
V A.



TEXT-FIG. 3.—Block-view of marble and graphite schist (black), Urlarmore. Lineation is shown diagrammatically.



TEXT-FIG. 4.—Profile, perpendicular to lineation.



TEXT-FIG. 5.—Part of Text-fig. 4, illustrating rotation.

B. NOTE ON LINEATION, BOUDINAGE, AND RECUMBENT-FOLDS IN THE STRUAN FLAGS (MOINE), NEAR DALNACARDOCH, PERTHSHIRE.

(Geol. Mag. 1950, Vol. 87, pp. 427-432)

ABSTRACT

Present knowledge of the tectonics of the Struan area is summarised. Recumbent-folds and incipient boudinage are recorded for the first time in the Struan Flags. The different types of lineation present are described; it is pointed out that all types present are mutually parallel. Simple kinematic analysis of an exposure north-west of Dalnacardoch, demonstrates that the lineations coincide more or less closely with the axis of rolling; they are therefore _b_-lineations. The need for further field-work is stressed, and the type of data required is indicated.

The exposure described is in a roadside quarry nearly 1½ miles north-west of Dalnacardoch, in the valley of the Garry. The surrounding region was described in detail by George Barrow (1904) from whose paper the following description is quoted (p. 401): "Since the days of McCulloch, the River Garry above Struan has been famous for the sections of flag-like rocks which are exposed in its bed and banks, from Struan, almost without interruption, to the summit of the Highland Railway. Its most striking feature is the extraordinary simulation of a normal sequence of enormous thickness, the dip being apparently persistent /

persistent in one direction (the south-east), at an angle of from 20° to 30°."

According to Barrow, the very large outcrop of the Central Highland Granulite (Struan Flags) is due to folding of the rock upon itself, without infolds of other material; it is "really the outcrop of a great sheet formed by the repeated folding of a bed on itself, after the manner of the bellows of a concertina when shut up. This concertina-structure was produced by the first and greatest folding of the Highland rocks, and to it is due the erroneous idea that the latter were of great thickness originally" (1904, p. 443). For Barrow, the grand-scale style was characterised by superposed concertinas. This hypothesis has not been accepted by later workers (see Bailey, 1925, pp. 673-674).

Folds, on any scale, have rarely been noticed in the Struan Flags. However, in the exposures, then newly opened, in the cuttings on the Highland Railway, J.S. Grant Wilson observed folding: "The extreme freshness of the section enables us to see that there are present a series of small folds or buckles, which consist of two parts - first, a longer limb, rising comparatively slowly; and second, a short limb, in which an abrupt fall takes place and counteracts the slow rise. The longer limb is the part of the structure seen everywhere over the whole area, and this can be recognised at least ten times as often /

often as the shorter falling limb. The longer limb, so easily seen, is the part of the structure which gives the mistaken notion of a persistent dip. If now we proceed to examine the other side of the cutting, which has been exposed to weathering for years, it is by no means easy to see the structure referred to. In the bed of the Garry it is still more difficult" (1905, pp. 67-68). Hitherto, no recumbent folds have been found in the Struan Flags.

It cannot be assumed *a priori* that, in a region of apparently uniform dip, the strike of the folds necessarily coincides with the general strike of the beds. Normally, fold-strike coincides with the general strike only if the fold-axis be horizontal or if the beds be vertical. Structures characterised by flat recumbent-folds empiled one on top of the other, often have a general strike nearly at right angles to the true axial-direction. Examples of this apparent anomaly, which is merely an expression of the geometric form, are common in the Alps, in Scandinavia, and in the Scottish Highlands. It is thus obvious that in a region such as the one discussed, determination of the axial-plunge of the major structures is necessary before any discussion of the general structure is possible.

There are a number of ways by which the axial-plunge of the grand-scale elements may be determined in a segment of an orogenic belt.

(i) /

(i) By study of the plunge of intermediate-scale structures. In the Struan Flags, as we have remarked above, small-scale folds have rarely been observed. It is therefore clear that one cannot be optimistic about the use of this method in the region referred to.

(ii) By geometric construction from the orientation of the bedding. This method can be adopted only when the dips are sufficiently diverse, and therefore it would not seem to have application to the Struan Flags. However, vertical bedding is shown at several localities on the published map. Further field-work, with determination of all dips differing from the prevalent dip of the flags, may yield sufficient data to enable this method to be applied.

(iii) By stratum contouring the mappable contacts. This method requires reliable mapping and a considerable degree of topographic relief before it can yield more than very approximate results. The relief in the valley of the Garry is hardly sufficient for this, and no mappable contacts have yet been found within the Struan Flags.

(iv) By use of linear structures parallel to the plunge of the fold-axis. This method would seem to be the most suitable for the region considered, and it will be discussed more fully. Nevertheless, so far as is possible, all methods should be employed.

Whether lineation can be used for the determination of axial-plunge resolves itself into two questions:-

1. Is lineation present in the area? and

2. Is this lineation parallel to the axis?

The answer to the first question can be found in the published literature. Describing the more micaceous gneiss of the Struan area, Barrow stated (1904, p. 408) that "the gneiss is at times 'rodded'[1], that is the micas are all elongated in a definite /

---

1. This is not the usual use of the term.

definite direction". This structure is clearly linear. Moreover, a further possible linear structure is suggested by Barrow's description (1904, p. 403) of cleavage in the "highly-micaceous bands, originally more of the nature of shales, that occur at intervals throughout the whole of the Struan section". "This cleavage", he wrote, "obviously took place prior to any crystallization, and, as a rule, it ends abruptly against the colour-banded rocks, which from their present composition, must have been of a more sandy nature originally, and would not cleave". Intersection of this cleavage with the bedding gives a linear structure. Attention has recently been drawn to the relation between such lineation and axial-plunge (Gilbert Wilson, 1946).

Plate III of the memoir illustrates "the remarkable 'water-pipe' structure in the Moine gneisses west of Cluns in the Garry". Describing this structure in one sentence (1905, p. 68), Grant Wilson explained it as being due to the outcrop of the fold-hinge; that is, he interpreted this linear structure as oriented parallel to the fold-axis. However, this structure is not of common occurrence in the flags.

The section exposed in the quarry north-west of Dalnacardoch affords valuable evidence as to the relations between lineation and fold-axes in the Struan Flags. It is therefore described /

described in detail. The exposure makes a three-dimensional examination of the structures possible. Figure V.B.1 represents the profile (perpendicular to the fold-axis) of part of the quarry face. It will be seen that both boudinage and recumbent folding are present. Details of these are shown in figs. V.B.2 and 3. The axis of the incipient boudins coincides with that of the fold-system. All structures maintain nearly constant profiles for many yards measured in the axial-direction.

The occurrence of both boudinage and recumbent-folds at this locality reminds one of Wegmann's discussion (1932) of the association of these two structures: "In non-granitised terrains, recumbent-folds seem particularly favourable for the development of boudinage. They can evolve by rolling; by the push of a resistant core which provokes backward-folding (en-capuchonnement); or by sliding on parallel surfaces. These diverse types of movement may be combined" (p. 484, translated). Boudinage may be associated with any of these movements.

At this locality lineation takes several forms; these include, (i) the trace, on longitudinal sections, of points of inflexion (due to boudins or to folds) in the profile, (ii) minute folds and puckers parallel to the principal folds, (iii) preferred orientation of the long axes of crystals, and (iv) cleavage-bedding intersections. In all cases, these are mutually parallel.

For /

For geometric analysis of the structure, any of these lineations may be used. The visible folds maintain constant profiles for distances measuring many times their amplitudes. Provided that the major structures show a corresponding continuity in the axial-direction, the profile can be constructed from the map. Unfortunately, in this area it has not proved possible to differentiate any mappable zones, and consequently there are no data to project. For geometric analysis, it is of no consequence whether the lineations described above are parallel to a or to b.

Kinematic analysis is difficult and tentative when the grand-scale structures are unknown, and in this region the absence of mappable zones leaves us in ignorance of structures on that scale. However, kinematic analysis is possible on a small-scale when structures such as those illustrated can be determined. The question which must be asked is, "can this profile be explained by movement parallel to, or perpendicular to the lineation-direction?" It is obviously impossible to explain the structures illustrated by the hypothesis that the lineation is in a. In the recumbent-fold shown in the figures, two points lying on a particular bedding-plane, and once widely separated, have moved towards one another; one has then passed over the other; and the points have then moved apart. This kinematic /

kinematic picture is inherent in the geometric form. It implies that the axis of rolling coincides more or less closely with the lineation-direction. Moreover, the structure of the boudinage is in accord with this movement picture. It follows that the lineations described are b-lineations, similar to those described by the writer from Mid-Strathspey and Strathavon, to the north of the present area.

Attention has been drawn to this exposure because it indicates the type of data which must be accumulated before knowledge of either the geometry or the kinematics of this region can be acquired. Such lineations must be systematically searched for and mapped, and the style and orientation of the observable structures must be carefully recorded. Not until this has been carried out, will we be in a position to discuss the tectonics of the Struan Flags.

REFERENCES

BAILEY, E.B. 1925. Perthshire Tectonics: Loch Tummel, Blair Atholl, and Glen Shee. Trans. Roy. Soc. Edinburgh, 53, pp. 671-698.

BARROW, G. 1904. On the Moine Gneisses of the East-Central Highlands and their position in the Highland Sequence. Q.J.G.S., 60, pp. 400-449.

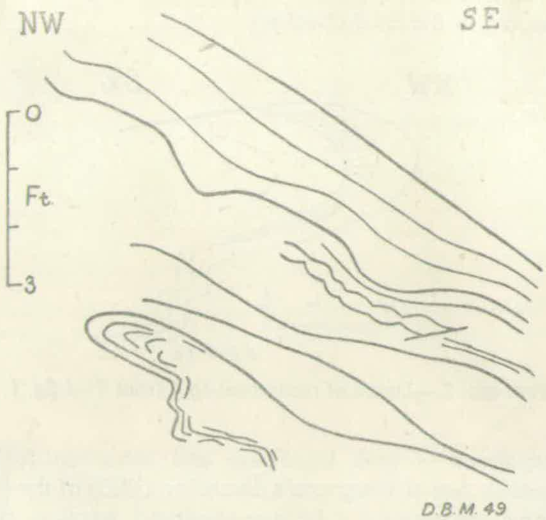
GRANT WILSON, J.S. 1905. In, The Geology of the Country round Blair Atholl, Pitlochry, and Aberfeldy. Geol. Surv. Scotland.

McINTYRE, D.B. 1950. Note on two lineated tectonites from Strathavon, Banffshire. Geol. Mag., 1950, 87, pp. 331-336.

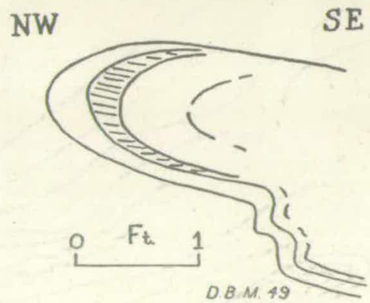
WEGMANN, C.E. 1932. Note sur le boudinage. Bull. Soc. géol. de France, 5e sér., t.2, pp. 477-491.

WILSON, Gilbert. 1946. The Relationship of Slaty Cleavage and Kindred Structures to Tectonics. Proc. Geol. Assoc., 57, pp. 263-302.

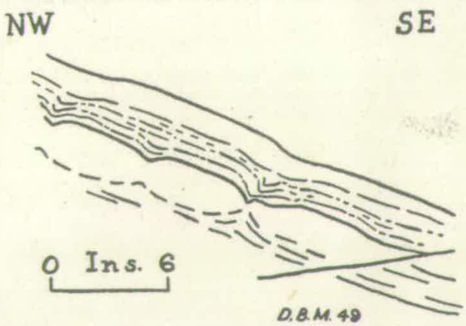
V B



TEXT-FIG. 1.—General profile of exposure near Dalnacardoch.



TEXT-FIG. 2.—Detail of recumbent-fold from Text-fig. 1.



TEXT-FIG. 3.—Detail of boudinage from Text-fig. 1.

C. NOTE ON THE TECTONIC STYLE OF THE ORD BAN QUARTZITES, MID-STRATHSPEY.

(To be published in the Geological Magazine)
(Geol. Mag. 1951. 88. pp. 50-54.)

ABSTRACT

Study of profiles, perpendicular to the fold-axes, shows that the folding is disharmonic. Nearly every s-surface is one of décollement. In some exposures the quartzites are reduplicated by superposed recumbent-folds without infolds of other material. The contacts are tectonic and not stratigraphic Incipient boudinage is frequent, and nearly all surfaces show well-developed b-lineation.

(i) SETTING

Siliceous and semi-pelitic granulites are widely developed in Mid-Strathspey. They belong to the Moine of the Central Highlands. Near Grantown these granulites enclose a group of pelitic, sometimes graphitic schists and gneisses with associated marbles and quartzites. Although the rocks of the Grantown Series are at a higher grade of metamorphism, they resemble the graphite-schist - marble assemblage of the Banffshire Dalradian, ten miles to the east. On the basis of this resemblance, E.M. Anderson suggested that the Grantown Series might be either an outlier or an inlier of Dalradian in the Moine (1915 p. /

p. 30). The present writer proposes to show in another paper that the Grantown Series is a gigantic tectonic inclusion enclosed in the Moine granulites. Thus added interest is given to Dr. Anderson's suggestion.

South of Grantown, in the Spey valley about Kincraig, a similar group of pelitic gneisses with associated marbles and quartzites is exposed. This group will be referred to as the Kincraig Series. It has not only the same lithological characters as the Grantown Series, but the same form and structural position. It is clear that both play a similar tectonic role. The relations and general characters of the two Series will be discussed elsewhere. The purpose of the present note is to record certain significant features of the tectonics of the Kincraig Series.

(ii) FOLDING AND DECOLLEMENT

Excellent exposures of the rocks of the Kincraig Series can be seen on the slopes of Ord Ban above Loch an Eilan, near Aviemore. Many of these are at right-angles to the fold-axes, and are very suitable for the study of the style. Bands of white quartzite are rather common, and the degree of their folding is spectacular. The plunge of the fold-axis is remarkably /

remarkably constant, but it does not coincide with that of the schists or of the marbles except where the latter are closely associated with the quartzites. A totally false impression of the style is obtained if sections oblique to the fold-axis are taken. It is important that the sections be true profiles, exactly perpendicular to the fold-axis.

Disharmonic folding can be seen on most profiles (see fig. V.C.1). The reason for its prevalence is the close association of competent quartzite and incompetent mica-schist. Disharmonic folding implies at least a certain amount of décollement ("becoming unstuck"), and where it is abundant the contacts must be tectonic. Indeed the mica-schist is sometimes intrusive.

Many of the siliceous layers are discontinuous in profile (figs. V.C.2 and 3). This is a natural consequence of the differing behaviour of quartzite and mica-schist under deformation. Even more obviously than disharmonic folding, the discontinuity of the layers in profile shows that the majority, if not all of the contacts are tectonic.

Undoubtedly the most striking aspect of the style is the occurrence of superposed recumbent-folds in pure quartzite (fig. V.C.4). It is evident that quartzite can fold in this manner only if the quartz crystals are able to grow during the deformation /

deformation. As Ellenberger has pointed out (1948, pp. 38, 62 &c.), recrystallisation would give an effective plasticity to the mass as a whole. Where a thin band of mica-schist has been folded with the quartzite, the folding is conspicuous. But where the quartzite has been folded upon itself without infolds of other material, the complexity of the structure can easily be overlooked.

Superposed folds of this type cannot be produced without _décollement_ and disharmonic folding. The contacts of the quartzite are tectonic and not stratigraphic. Indeed the structure is reminiscent of George Barrow's "concertina-folding" (1904, p. 443). In the style envisaged by Barrow, each tectonic unit consisted of beds, folded upon themselves without infolds of other material, in a series of compressed isoclinal folds. Thus the whole was made up of a series of superposed concertinas separated one from the other by tectonic contacts. The essential difference between the style of the Ord Ban quartzites and that of Barrow's concertinas, is that the close-packed folds are not vertical but recumbent.

The _décollement_ is syngenetic with the folds themselves. These surfaces are therefore controlled by the same tectonic axes as the folds and there is no mylonite associated with them. Each surface is a miniature "slide" (Bailey, 1910, p. 593; 1909, pp. 53-54).

(iii) LINEATION

The Ord Ban quartzites show well-developed lineation. It is sometimes due to incipient boudinage (fig. V.C.4), but more frequently to regular ribbing (fig. V.C.5). There are indeed few surfaces without good lineation. The ribs appear to be formed by the crests of small folds. They plunge with great regularity parallel to the axis of the principal folds.

The style of the folding shows that the fold-axis coincides with the b-kinematic-axis. The hypothesis which affirms that the folds are elongated parallel to the direction of transport (a), cannot account for either contraction or extension perpendicular to this direction. The piling up of recumbent folds on one hand, and boudinage and discontinuity of the beds in profile on the other, are just such cases. Relative movement has taken place on almost all s-surfaces, and its direction is perpendicular to the axis of the folds and to the lineation. On the scale considered, the lineation is thus in b.

(iv) LITERATURE REFERRED TO

ANDERSON, E.M. 1915. In, Explanation of Sheet 74. Geol. Surv. Scotland.

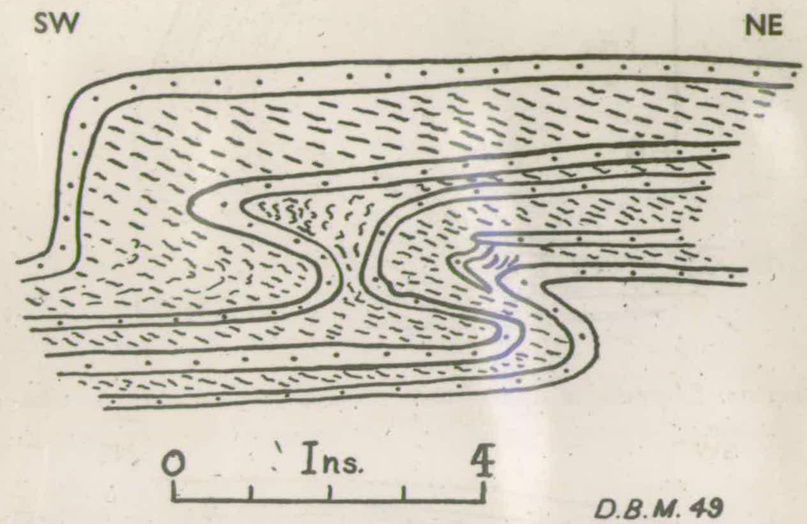
BAILEY /

BAILEY, E.B. 1909. In, Summary of Progress for 1908. Geol. Surv. Great Britain.

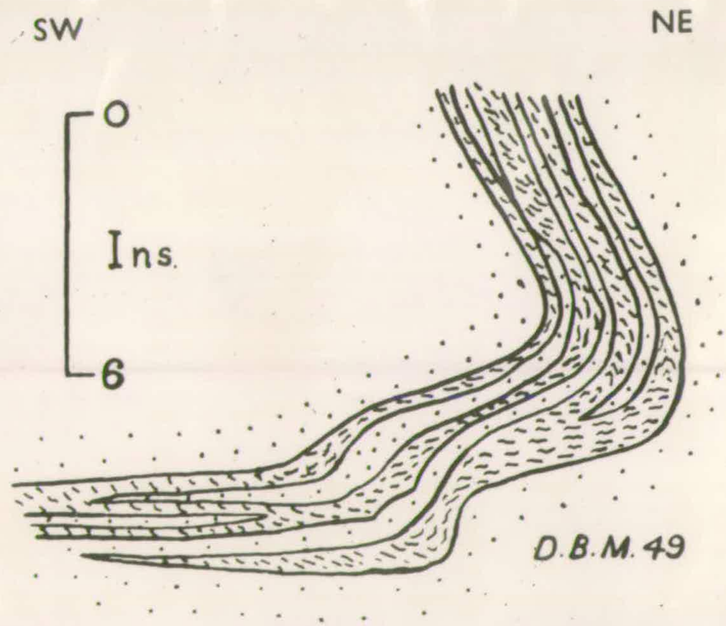
________ 1910. Recumbent folds in the schists of the Scottish Highlands. Q.J.G.S., 66, p. 586.

BARROW, G. 1904. On the Moine gneisses of the East-Central Highlands and their position in the Highland sequence. Q.J.G.S., 60, p. 400.

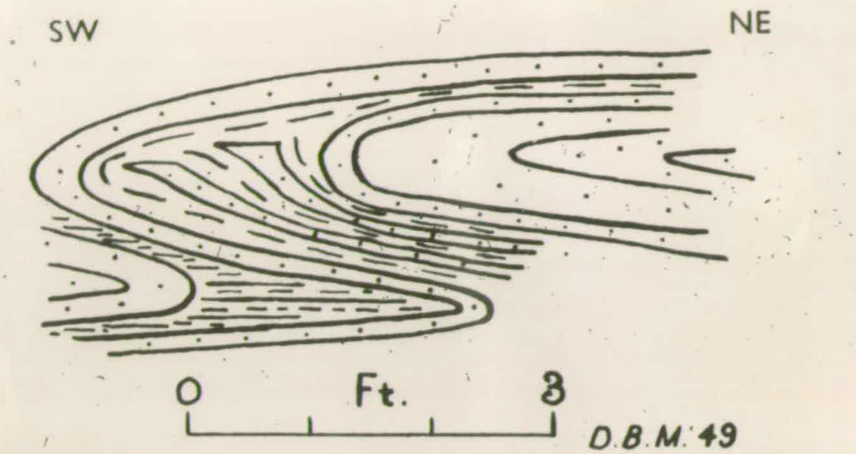
ELLENBERGER, F., and Collaborators. 1948. Métamorphisme, Silicifications et Pédogénèse en Bohême Méridionale. Ann. Sci. de Franche-Comté.



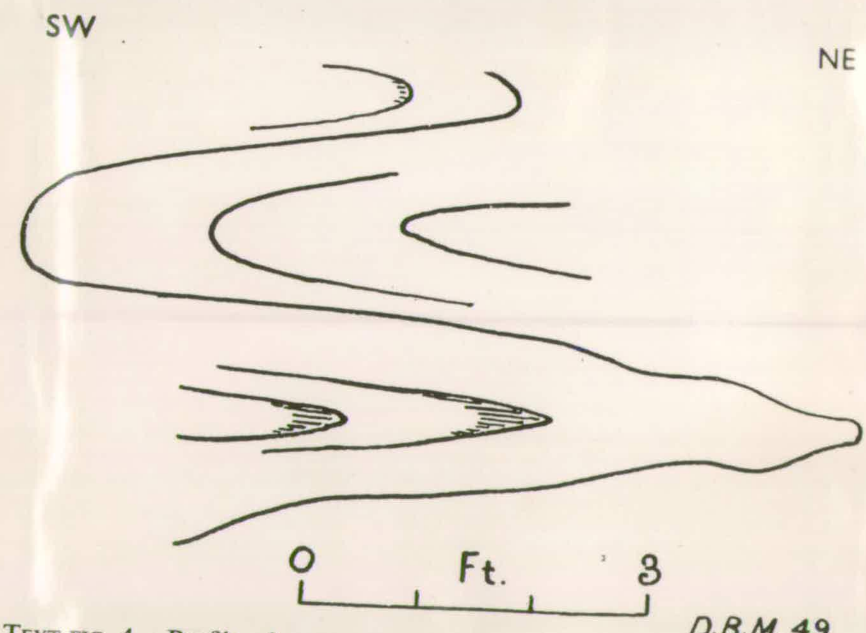
TEXT-FIG. 1.—Profile of disharmonic folding of siliceous granulite (dots) and mica-schist, Ord Ban.



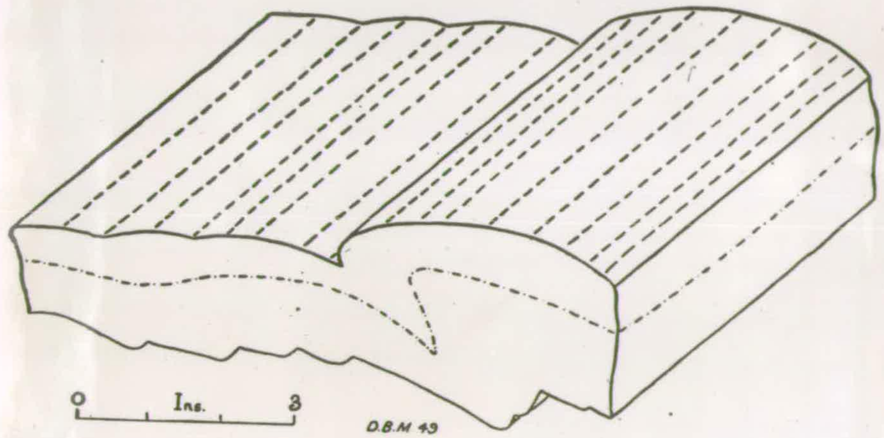
TEXT-FIG. 2.—Profile of discontinuous siliceous granulite (dots) in mica-schist, Ord Ban.



TEXT-FIG. 3.—Profile of discontinuous quartzite (dots) in mica-schist, Ord Ban.



TEXT-FIG. 4.—Profile of superposed recumbent-folds in quartzite, Ord Ban.



Folding and lineation. Quartzite.

Ord Ban.

Lineation is shown greatly simplified.

D. DECOLLEMENT IN THE SOUTHERN UPLANDS: a reconnaissance of the Berwickshire coast between St. Abb's Head and Fast Castle.

(1) Previous Work

The exposures in the Southern Uplands of Scotland are usually much too incomplete to afford a direct insight into the tectonics of the highly folded rocks composing that belt. For this reason the magnificent continuous exposures along the coast of Berwickshire near St. Abb's Head are of the greatest importance. This was appreciated at an early stage in the history of Scottish geology. In his classic paper published in 1815, Sir James Hall wrote: "In the inland part of this range, the rock appears so partially, shewing itself only in river-courses, or in quarries, that it is difficult to obtain any correct information as to the position of the strata, which frequently exhibit great seeming irregularity, and which cannot be described without making use of language which at first sight bears an appearance of contradiction in terms. . . . . On the shore of the sea, however, where these rocks are bare and exposed in such a manner, that our view can embrace at once a considerable extent of the mass, the general structure becomes apparent, and we /

we are enabled to give a rational account of these seeming anomalies. This opportunity of observation, occurs with peculiar advantage on the coast of Berwickshire, where the lofty cliffs which extend from Fast Castle eastward to Gun's Green near Eyemouth, present to view a cross section of these strata, by which their position is seen to possess much more method and regularity than the inland rocks would have led us to expect. The strata here exhibit a succession of regular bendings, and powerful undulations, reaching from top to bottom of the cliffs, two or three hundred feet in height".

In the course of about six miles, Sir James Hall recognised sixteen "distinct bendings, each of the largest size and reaching from top to bottom of the cliffs". He described these as being successively concave and convex upwards. The value of Sir James Hall's description is greatly enhanced by his inclusion of a number of detailed drawings of the folded beds.

Sir James Hall conducted a party consisting of Murchison, Sedgwick, and Sir Archibald Alison, by boat along the foot of the cliffs, and a sketch by the latter was included in the 3rd edition of Murchison's Siluria (p. 166). A more complete sketch by Archibald Geikie of the whole line of cliffs from St. Abb's Head to Fast Castle was included as frontispiece to the Memoir /

Memoir on Eastern Berwickshire (1863). Geikie described the cliffs in the following characteristic prose: "Standing on the western verge of the precipices of St. Abb's Head, the observer sees before him one of the wildest cliff-lines on the east of Scotland. The Silurian strata are there thrown into vast folds which in oft-changing curves jut out, headland after headland, here worn into dim twilight creeks, there standing up as tangle-covered reefs and skerries, or grey sea-stacks, round which the gull, and the awk, and the Solan goose are wheeling above; while the surge is ever breaking into foam below. His eye can trace the stratification of the cliffs as the sun-light falls on each successive promontory, now on an arch that has been half removed by the ocean; now on a trough that descends deep into the precipice, until these details are lost in the blue distance, as the coast-line bends away by the rocks of Fast Castle".

The axis of the folds, as pointed out by Geikie, trends north-east to south-west, or N.N.E.-S.S.W. "As the general trend of the coast line is from N.W. to S.E. it crosses the strike of the beds, and hence the section thus laid bare represents pretty nearly the true relative proportions of the curves, not much distorted, as they would be by any marked deflection from a line transverse at a right angle to the axis of plication. With a sinuous outline, there are of course numerous parts /

parts of the coast where the cliff exhibits a more or less oblique section, but the same indented character enables us to correct such distortion, by constantly presenting coves and creaks where the true direction of the beds is shown".

In the Memoir (1864), Geikie gave a detailed account of the successive anticlines and synclines between Burnmouth in the south, and Siccar Point in the north. This description is further illustrated by sketches of some of the folds. Geikie rightly emphasised that his measurements were not made along the curving outline of the cliffs, but at right angles across the strike of the beds. Even at this early date he appreciated the need to distinguish between oblique and true cross-sections.

(ii) Present Work

In view of the excellence of the exposures along this coast-section, it is indeed surprising that no serious examination of the tectonics has been attempted since 1864. As a result of the detailed stratigraphical and palaeontological work which has since been done on the inland rocks, numerous horizontal sections across the Southern Uplands have been published. The style of many of these bears little or no resemblance to that illustrated by Hall and Geikie as the result of their investigations of the Berwickshire coast-section.

The /

The writer has made a reconnaissance of the coast between St Abb's Head and Fast Castle with a view to determining the style of the structures more precisely. It is hoped to make a detailed study of the whole section from Siccar Point to Burnmouth at a later date, but even this preliminary work has brought to light a new aspect of the tectonics of the Southern Uplands that may be of general importance.

Although highly deformed, the rocks show no sign of cleavage. This fact was recorded by Geikie (1864, p. 19). The original planes of stratification are usually well-preserved, and may be followed with ease as they follow round the successive folds. As would be expected, a-c joints (i.e. joints normal to the fold-axis) are common, and thus profiles of the structures may be observed directly on numerous cliff faces.

In this preliminary work emphasis is laid on the qualitative rather than on the quantitative characters of the structures. Thus the section (fig. V.D.1) illustrates the general style of the folds from Pettico Wick (near St Abb's Head) towards Fast Castle. Comparison with the section given by Geikie shows certain differences in style. Geikie did not recognise the slight but definite amount of overfolding which is present. There is, in fact, a tendency for the axial surfaces to be inclined towards the south-east in this part of the coast.

A /

A feature of more importance is the décollement which occurs in several of the folds. Along certain shale beds, the greywackes have become unstuck and folded separately from the underlying beds. In this way some beds may be duplicated while others may be missing, and false stratigraphic sequences could readily be recorded were the exposures not so excellent. However, in inland exposures, where structure is worked out from fine stratigraphy and much emphasis is laid on "palaeontological gaps in the succession", it may be that tectonic breaks have sometimes been overlooked.

A detail of a cliff-face on which décollement is well shown, is illustrated in fig. V.D.2. It is hoped that future work will enable an estimate to be made of the frequency of these structural breaks.

Bibliography

GEIKIE, Archibald. 1864. The Geology of Eastern Berwickshire. Mem. Geol. Surv., pp. 58.

HALL, Sir James. 1815. On the Vertical Position and Convolutions of Certain Strata, and their Relation with Granite. Trans. Roy. Soc. Edinburgh, Vol. 7, p. 79.

V D.

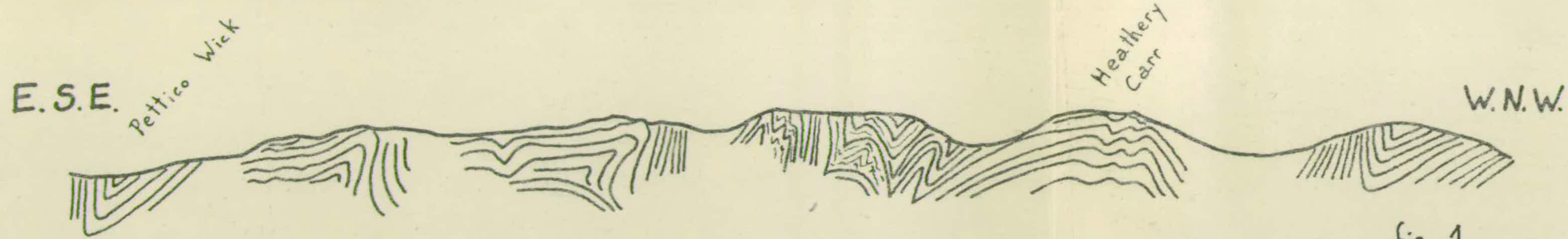


fig. 1.

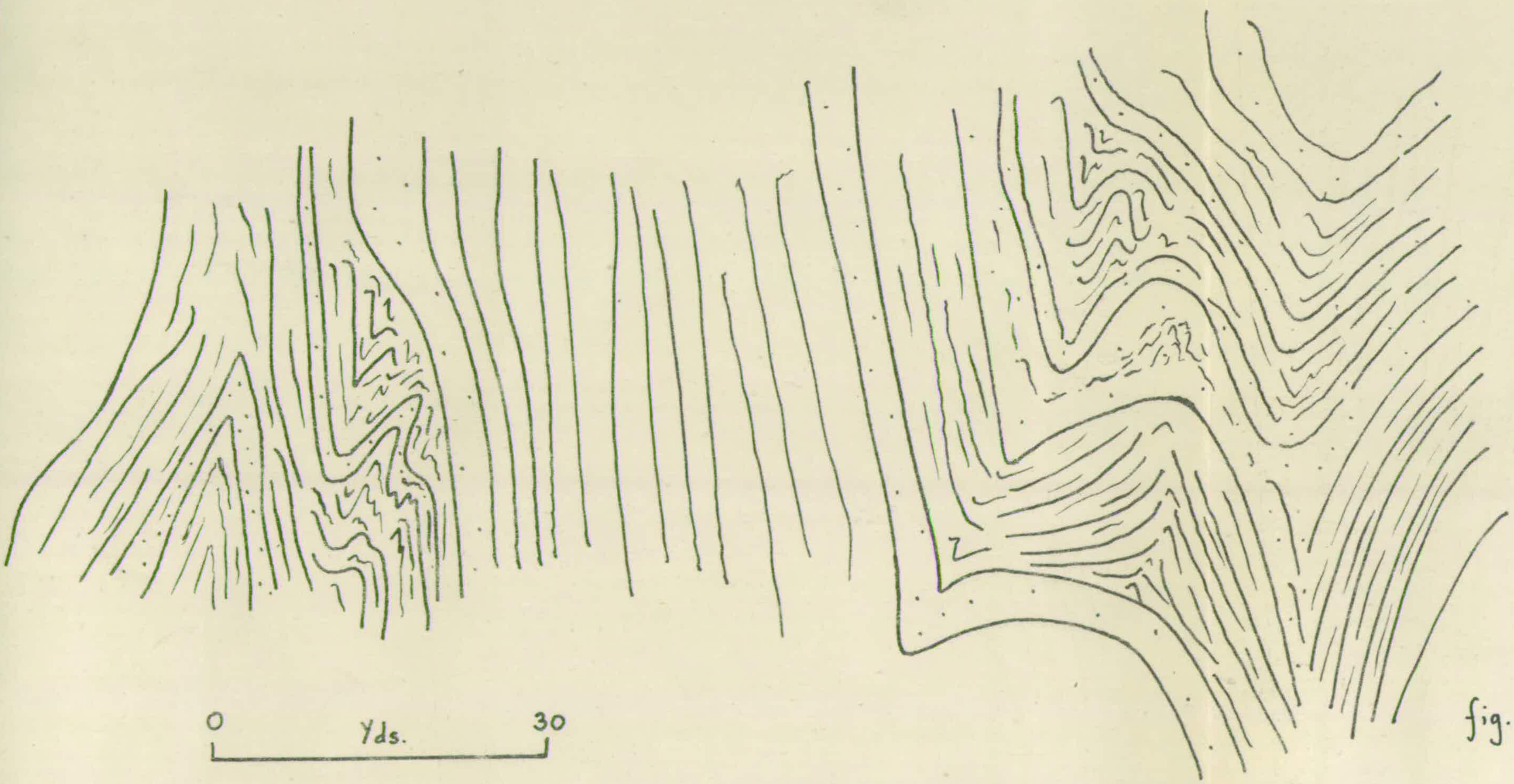


fig. 2.

VI. APPLICATION OF METHOD TO REGIONAL SURVEYS:

A. THE TECTONICS OF THE BEINN DRONAIG AREA, ATTADALE.

ABSTRACT

On Beinn Dronaig are combined not only three stratigraphic zones of the Moine and several "inliers" of "Lewisian", but, apparently, two systems of folding at right angles to one another. Comparison is made between the structures of Beinn Dronaig and the Monte Rosa (Pennine Alps), and the danger of using doubtful stratigraphy to determine structure is pointed out. It is emphasised that the general strike of beds in recumbent structures will, usually be nearly at right angles to the axial-trend. On Beinn Dronaig, even where the strike is N.E.-S.W., the axial-plunge is towards the S.S.E. Thus, in fact, only one system of folding is present, and its trend is nearly at right angles to the strike of the Moine thrust-plane. The "Lewisian inliers" do not root in situ: they are discontinuous bodies in the core of a recumbent fold. "Mullion-structure" and pegmatite eyes are common throughout the area, but are especially characteristic of the fold-hinge.

(i) INTRODUCTION

Beinn Dronaig (2612 feet) is situated in the most inaccessible part of the Attadale deer-forest, near the marches of that forest with Killilan in the south, and West Monar in the north. It is almost equidistant from Achnasheen, Torridon, Strome Ferry, Dornie, and Loch Affric. The area lies in /

in the south-west part of One-inch Sheet 82 (Loch Carron). This map and its explanatory Memoir were published by the Geological Survey in 1913.

The peculiar interest of the Beinn Dronaig area was pointed out by C.B. Crampton (1913, pp. 56-63), and a reduction of the relevant portion of Sheet 82 was reproduced as a text-figure (text-fig. 5) in the Memoir. Not only are the Lewisian inliers and three stratigraphic units of the Moine represented on Beinn Dronaig, but these have apparently been involved in two systems of folding at right angles to one another. "A striking characteristic of the Eastern schists [i.e. the Moine] is presented by the double system of folding which they possess. One system has a N.N.E. and S.S.W. strike, the inclination of the axial planes being E.S.E., thus harmonising with the strike and dip of the Moine thrust-plane and of the divisional planes of the mylonised rocks in association with that displacement. This plication may be regarded as an obvious accompaniment of the movement of the thrust masses in a W.N.W. direction. The other system strikes generally W.N.W. and E.S.E. as if produced by forces acting at right angles to this trend. On looking at an escarpment of Moine-schists, the observer sees the ends of a series of folds, the axes of which run W.N.W. or north-west, lying along the inclined foliation-planes. Hence arises what might /

might be termed 'mullion' structure - that is, the production of a series of rods trending towards W.N.W. or north-west". (Peach and Horne, et al, 1907, p. 601). Thus the Beinn Dronaig area represents in miniature, as it were, a model of the Moine of the Northern Highlands, whether from the point of view of stratigraphy or of tectonics.

(ii) SUMMARY OF PUBLISHED DATA

The pelitic gneiss of the Fannich Forest (Sheet 92) has been traced southwards a distance of 27 miles to its abrupt termination some two miles south of the summit of Beinn Dronaig. This pelitic belt is everywhere bounded by Moine of the normal siliceous type, and a few isolated, lenticular outcrops of pelitic gneiss occur in the surrounding siliceous Moine. In the Beinn Dronaig area (see map, fig. VI.A.1) an important band, and several isolated, lenticular patches of siliceous schist have been found within the outcrop of the pelitic gneiss. On either side of Loch Calavie, and near the summit of Beinn Dronaig the inner siliceous belt surrounds the outcrops of an assemblage of gneisses, which, on lithological grounds, have been referred to the Lewisian.

The ornament on the map (VI.A.1) indicates the generalised strike directions within the pelitic gneiss. North and /

and east of Beinn Dronaig the dip is towards the south-east at 20-40°. South-west of the summit, however, the strike is N.N.W. - S.S.E., and the dip is nearly vertical. On the south slope of the hill the swing-round of the strike direction is very rapid; west of the summit it is rather more gradual. The area of vertical dip and N.N.W.-S.S.E. strike is not confined to the pelitic gneiss, but extends outwards from the summit of Beinn Dronaig to affect a considerable area of the siliceous Moine to the south-west. Within that area, the axes of the small folds plunge to the S.S.E. at approximately the same angle, and with nearly the same trend as the dip of the gneiss lying to the north and east of the summit of the hill. Pegmatite eyes are much more abundant in the region of the vertical dips than they are elsewhere, and "mullion-structure", plunging with the fold-axes, is also well developed.

(iii) SUMMARY OF PUBLISHED INTERPRETATION

The recognition of Lewisian inliers within the pelitic belt provided the basis for interpretation of both stratigraphy and structure. The published interpretation is as follows:- A major "upfold" here has brought the basement complex to the present surface. The general strike of the rocks to the north of /

of the summit of Beinn Dronaig indicates that the axis of this complex anticline is directed N.E. - S.W. As both limbs of the fold dip at nearly constant angle towards the south-east, the axial planes, both of the major anticline and of the small superposed folds, must likewise dip in this direction.

The Beinn Dronaig Anticline is one of the most important structural units in Central Ross-shire. It separates the Carron Syncline to the west, from the Monar Syncline to the east. As in the case of the Beinn Dronaig Anticline, the axial planes of these compound synclines are, in general, inclined towards the south-east. Three horizontal sections across these structures are published in the Sheet Memoir (figs. 6-8). One of these is reproduced by Peach and Horne (1930, fig. 21).

"North of Beinn Dronaig the rocks of this belt of pelitic gneiss are isoclinally overfolded in a general northwest direction, the limbs of the folds lying at low angles and dipping to the south-east. Along a line extending southward from the summit of Beinn Dronaig as far as and beyond the southern margin of this Sheet [82] the country is, however, traversed by belts of vertical folding, the axes of plication striking N.N.W. and S.S.E., i.e. nearly at right angles to the axes of the gently inclined overfolds met with in the rocks to the /

the north-west of the belt of vertical folding. These vertical isoclinal folds pitch S.S.E. nearly in the same direction as the dip of the limbs of the overfolds. The accumulated effect of this vertical folding causes the pelitic gneiss to plunge suddenly to a lower level along this boundary line, which terminates the belt of pelitic gneiss in a manner that simulates the effect of a monoclinal fold. The belt of vertical folding has been followed in the siliceous schists to the south for a distance of over a mile and passes into the adjoining map". (Crampton, 1913, p. 56).

"There are difficulties in explaining this type of structure by a later system of vertical folding imposed upon an earlier system of overfolding. . . . . it seems more probable that the two systems of folds are synchronous and due to the same movement. The vertical plication may have been produced by a differential overfolding movement. During the forward overriding movement the portion of the overfold on one side of the line of drag would remain behind and at a lower level than that on the other. Along the line of drag the beds would be vertically folded, owing to the rocks having to occupy less space in a direction at right angles to the line of forward motion. An overriding of certain sections and a dragging behind of others would thus be necessitated, in order that the lineof advance /

advance might occupy less space. The rocks included within the pelitic band on the north-east side of the vertically folded belt must on the south-west side plunge beneath the surface. They would in this case have dragged behind during an adjustment in the general forward movement". (Crampton, 1913, p. 58)

(iv) ALTERNATIVE INTERPRETATION

According to the published interpretation, outlined in the preceding section, the N.E. - S.W. fold-trend is assumed to be normal, and the area where the fold-axes plunge to the S.S.E. is treated as a local abnormality complicating the general pattern. It may therefore seem strange that, when the writer was shown the map of Beinn Dronaig, the first question he asked was whether there was any evidence for the existence of folds trending N.E. - S.W. To the writer, the whole aspect of the map suggested that only one system of folds was involved, a system with a S.S.E. plunging fold-axis.

(a) The relation of the outcrops to the topography makes it clear that the north-western boundary of the pelitic gneiss dips towards the south-east, while its south-western boundary is nearly vertical. This implies that, on the scale of the map, the plunge of the fold-axis is to the S.S.E. at an angle which is /

is given, approximately, by the dip of the north-western boundary

(b) The dips and strikes recorded by the Survey geologists likewise indicate a S.S.E. plunge for the fold-axis of the structures on an intermediate scale. (cf. E. Wegmann, 1929).

(c) Where the axial-plunge of small folds is given, without exception it is towards the S.S.E. at an angle almost equal to that of the dip of the north-western boundary of the pelitic gneiss.

Thus on all scales, from that of the small outcrop to that of the map, the evidence is that throughout the Beinn Dronaig area the axial-plunge is towards the S.S.E.. The implications of this conclusion are considerable:- (a) The actual fold-trend is at right angles to the assumed "normal" trend; ?(b) the supposed N.W. - S.W. directed folds vanish, and with them disappear the so-called "double system of folding" and the complicated mechanism introduced to explain it; (c) Beinn Dronaig is a mountain without roots; (d) the so-called Lewisian inliers are not an autochthonous upfold of the basement complex, for they do not root in situ; (e) the structure is not an anticline overturned towards the north-west, but a blunt-ended recumbent fold closing towards the south-west, and with a discontinuous core of rocks of Lewisian-type; and (f) the development of "mullion-structure" and of pegmatite eyes is most marked near the hinge of the pelitic gneiss.

The /

The writer has been asked why the pelitic belt closes immediately south of Beinn Dronaig. It does so for the same reason that a simple anticline "closes" upwards; the change in direction of the outcrop of the outer boundary of the pelitic gneiss represents the hinge of the fold, i.e. the junction between its two limbs.

There is here nothing new. The crystalline massifs of the Pennine Alps were likewise first interpreted as upfolds of the basement complex, rooting in situ; but nearly half a century has passed since Lugeon and Argand demonstrated that they were, in fact, recumbent folds obliquely intersecting the present surface. Moreover, the hypothesis that the Monte Rosa was an autochthonous dome necessitated the existence of a double system of folding; the analogy is complete. Argand's remarks with regard to the supposed double folding of the Pennines are appropriate today to the Scottish Highlands:-

"The objections to the existence of the Saint-Bernard and Monte Rosa nappes, are derived from the same source as the hypothesis of transverse folds and the supposed dying out of the Simplon nappes towards the west. A persistent error in diagnosis is through them all. The strike of the beds, i.e. the trace of the folds, has been taken as the direction of the folds themselves. It is easy to show that these elements coincide only if /

if the beds are vertical, and that in all other cases, but especially where recumbent and not simply inclined folds are involved, it is essential to distinguish carefully between the dip relative to the horizontal, given by simple observation, and the inclination of the beds relative to the fold-axis. In committing these errors, a confusion has been perpetuated, which the history of our science shows was completely outmoded ten or twenty years ago. It is a matter of interest to observe, in present-day science, the survival of these methods." (Argand, 1911, p. 10, translated).

(v) THE TEST OF THE HYPOTHESIS

When a new interpretation of certain data has been advanced, one must search for a means of testing it. The usual procedure is to predict, with the aid of the new hypothesis, certain facts which, although previously not known, can be checked by making further observations. The validity of the interpretation is thus determined on the basis of the correctness of the predictions made.

There is, fortunately, a simple means of testing the interpretation advanced here. In general the axes of small folds are parallel to those of the grand-scale structures. Thus /

Thus, if our hypothesis is correct, one would expect the axial-plunge of visible folds to be towards the S.S.E., at nearly constant angle, alike to the north and to the south of the summit of Beinn Dronaig. It is, of course, already known that to the south of the summit the axes do, in fact, plunge in this direction. On the other hand, if the published interpretation (Section iii) is correct, further north the fold-axes should trend N.E. - S.W.

In order to decide between the two possibilities, the writer traversed the ground and made a considerable number of determinations of the plunge of fold-axes, and of parallel linear structures. The results are shown on the map (fig. VI.A.1). It is evident that only one system of folds is involved, viz. one with an axial-plunge averaging some 28° towards N 165° E.

(vi) CONCLUSIONS

The Beinn Dronaig fold is recumbent and closes towards the south-west (fig. VI.A.1). It is therefore improbable that it is genetically related to the Moine Thrust, the movement on which is believed to have been towards the west or north-west. The new interpretation of the tectonics of Beinn Dronaig has an important /

important bearing on the structure of Central Ross-shire.

The so-called Lewisian inliers do not root in situ. Their internal structure is parallel to that of the surrounding Moine. They may be interpreted as either boudins of the basement complex caught up during the Moine folding, or areas where granitisation has taken place in the core of the fold (cf. D.L. Reynolds, 1942, fig. 5).

(vii) ACKNOWLEDGMENTS

The writer wishes to record his gratitude to Sir Edward Bailey for calling his attention to the problem of the "double system of folding" on Beinn Dronaig, and for suggesting that he should attempt to explain it. Colonel W.O. Gibbs of Attadale not only gave the writer the use of Beinn Dronaig Lodge, but permitted him to traverse the area immediately prior to the stalking season. For this courtesy and help the writer is most grateful. The field-work was greatly facilitated by the help of Miss Sheila McIntyre.

(viii) LIST OF WORKS TO WHICH REFERENCE IS MADE

ARGAND, E. 1911. Les nappes de recouvrement des Alpes Pennines et leurs prolongements structuraux. _Mat. pour la carte géol. de la Suisse_, New Series, 31, pp. 25.

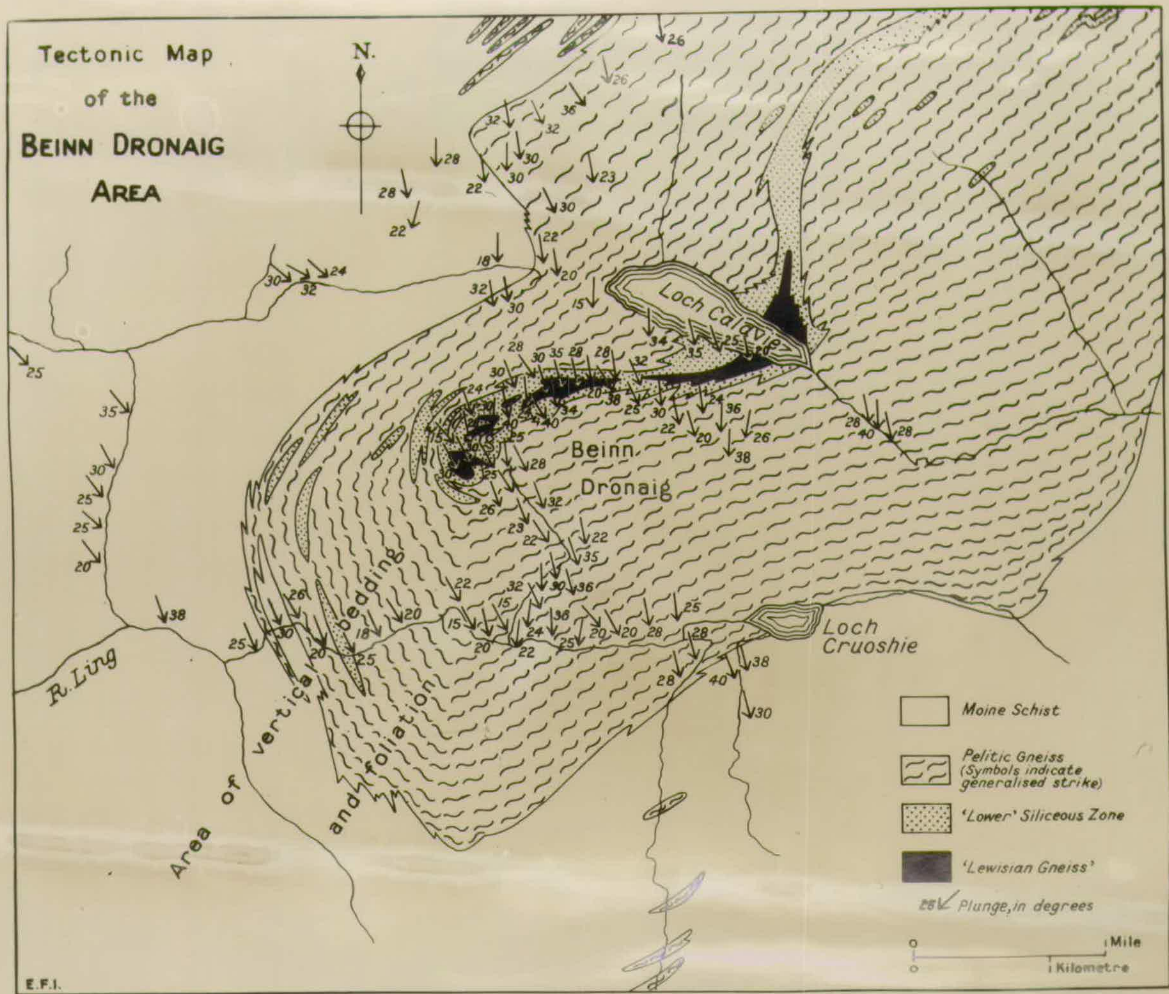
CRAMPTON, C.B. 1913. _In_, Explanation of Sheet 82. _Geol. Surv. Scotland_. pp. 114.

PEACH, B.N. and J. HORNE, _et al._ 1907. The Geological Structure of the North-West Highlands of Scotland. _Geol. Surv. Scotland_. pp. 668.

PEACH, B.N. and J. HORNE. 1930. Chapters on the Geology of Scotland. _Oxford_. pp. 232.

REYNOLDS, D.L. 1942. The Albite-Schists of Antrim and their Petrogenetic Relationship to Caledonian Orogenesis. _Proc. Roy. Irish Acad._, xlviii, B, No. 3, pp. 43-66.

WEGMANN, E. 1929. Beispiele Tektonischer Analysen des Grundgebirges in Finnland. _Bull. Comm. géol. de Finlande_, lxxxvii, No. 8, pp. 98-127.



Tectonic Map
of the
BEINN DRONAIG
AREA
N.
Loch Calavie
Loch Cruoshie
Beinn Dronaig
R. Ling
Area of vertical bedding and foliation
Moine Schist
Pelitic Gneiss (Symbols indicate generalised strike)
'Lower' Siliceous Zone
'Lewisian Gneiss'
Plunge, in degrees
Mile
Kilometre
E.F.I.

B. THE STRUCTURE OF THE FANNICH FOREST

The mountains of the Fannich Forest, like Beinn Dronaig, are built of pelitic schists and gneisses enclosing so-called "Lewisian inliers". These two areas are linked by a narrow belt of pelitic rocks, and the outcrop of the whole pelitic unit, which is nearly thirty miles in length, is surrounded by siliceous Moine granulites. This disposition is reminiscent of the well-known arrangement of the Pennine nappes on either side of the Tessin culmination. The nappes rise from nearly vertical roots and are recumbent, closing towards the north. To the west of the culmination, the axial-plunge is towards the south-west, and therefore the narrow outcrop of the root is succeeded by the wide outcrop of the nappe itself in that direction. On the other hand, towards the east the plunge is reversed and the outcrop pattern is there the mirror-image of that in the Pennine Alps proper (fig. VI.B.1).

Once the writer had discovered the antiform nature of the Beinn Dronaig termination, his attention was quickly directed to the Fannich Forest to determine whether this could be the mirror-image of Beinn Dronaig; i.e. whether the structure of Fannich was that of an antiform with an axial-plunge towards the north-east or north (fig. VI.B.2). If this were so, then the /

the narrow Achnasheen pelitic belt would represent the root of the fold. However a glance at the one-inch maps showed that this was not the case. In the neighbourhood of Glen Docherty (six or seven miles west of Achnasheen) a large number of lineations with N.W.-S.E. trend are recorded. The Survey geologists believed that these were a-lineations, but consideration of the strikes and dips recorded shows that, like the lineations in the Beinn Dronaig area, the Glen Docherty lineations are b-structures, plunging towards the south-east. Moreover the writer had already recorded south-east plunging fold-axes in Glen Carron (eight or nine miles south-west of Achnasheen).

In 1897, W. Gunn described the structure of the northern part of the Fannich Forest as synclinal (p. 17). Inspection of the one-inch map (sheet 92) confirms Gunn's conclusion. The topographic relief is considerable, and whether one takes the relation of the outcrops to topography, or the recorded strikes and dips, the result is the same. Indeed, the synclinal closure at Fannich is as obvious as is the anticlinal closure at Beinn Dronaig. The pelitic belt is continuous between the two areas, and it is evident that the Fannich and Beinn Dronaig structures are very different. Gunn's mapping shows that the axis of the Fannich synform plunges towards the south-east: the structural base of this structure cannot /

cannot re-emerge at the surface to the south of Fannich without closure of the pelitic belt, and we have seen that the belt remains continuous as far as the antiform closure at Beinn Dronaig. Thus the remarkable conclusion is reached that, in the section exposed at the present surface, the whole pelitic unit between Fannich and Beinn Dronaig is closed both upwards and downwards. In profile it must be a tectonic inclusion ("fish") of immense vertical magnitude. This conclusion follows from the published one-inch maps once the writer's interpretation of Beinn Dronaig is accepted.

The vertical thickness of this pelitic unit would, of course, be less than appears at first sight, if there were undulations in the longitudinal section between the two extremities. In the summer of 1950, Dr. Rutledge joined the writer in making many hundreds of determinations of axial-plunge over the whole area between Beinn Dronaig and the Dundonnell road north of Loch a'Bhraoin. The remarkable uniformity of the fold-axis over this considerable area is shown in fig. VI.B.3. Plate 5.

Conclusions: There is no evidence for the fan-fold postulated by the Survey geologists (Peach, Horne, et al, 1913, fig. 6). The structure of the Fannich Forest is that of a large and complex synform in which is contained an annular mass and numerous lenticular units of Lewisian-like rocks. This synform plunges with great uniformity towards the south-east, and /

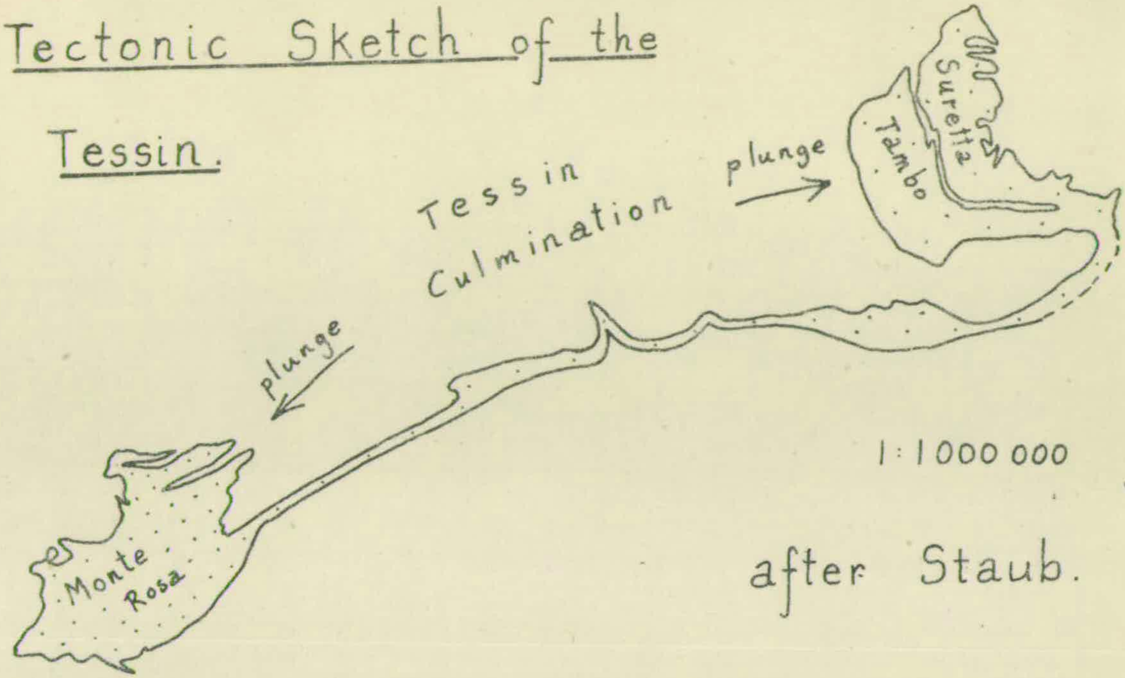
and must be at considerable depth below the Beinn Dronaig antiform. The orientation of this gigantic tectonic inclusion of pelitic rocks, and its great vertical magnitude, suggest that the origin of this remarkable structure had no relation to that of the near-by Moine Thrust. The style of the two structures is very different.

Bibliography

GUNN, W. 1897. Summary of Progress for 1896. Mem. Geol. Surv. Gt. Brit., pp. 17-18.

PEACH, B.N., J. HORNE, et al. 1913. The Geology of the Fannich Mountains &c. Mem. Geol. Surv. Scotland.

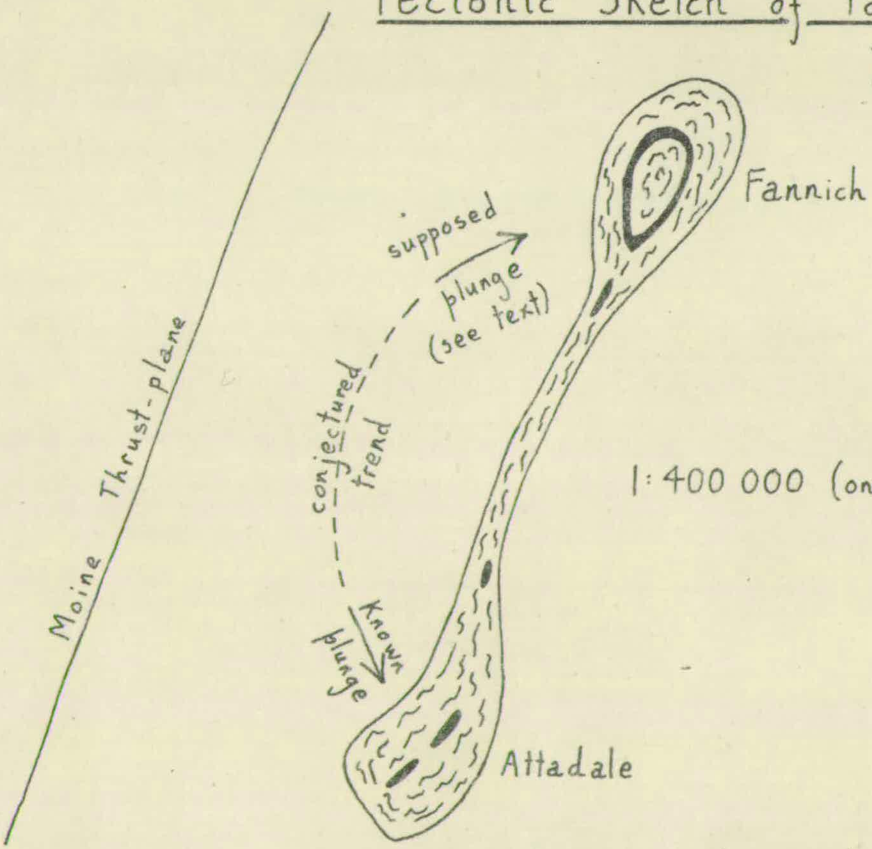
Tectonic Sketch of the Tessin.



1:1000 000 fig. 1.

after Staub.

Tectonic Sketch of Fannich Region.



1:400 000 (only approx.)

(To illustrate hypothesis outlined in the text.)

fig. 2.

C. THE TECTONICS OF THE AREA BETWEEN GRANTOWN AND TOMINTOUL (MID-STRATHSPEY)

(To be published by the Geological Society of London; read 29th November 1950)

ABSTRACT

The region is homo-axial; the plunge of the fold-axes is to the south-east at nearly 30°. A profile nearly seven miles deep has been constructed by the use of the axial-method of tectonic analysis developed by Lugeon, Argand, Wegmann and others. This profile shows the tectonic relations of the Grantown Series, the Moine, and the Dalradian. Given the profile and the plunge, the general dips can be predicted; these coincide with the observed data. Metamorphism grades from phyllites to migmatites from the highest levels to the deepest. The majority, if not all, of the contacts are tectonic. Gigantic tectonic inclusions of Moine swim in the Dalradian; it is possible that similar inclusions of Dalradian occur in the Moine. The Moine and Dalradian suffered the same movement, the sense of which appears to have been towards the south-west. Lineation is perpendicular to this direction.

CONTENTS

I. INTRODUCTION

The region described is shown in fig. VI.C.1. Stretching eastwards from the River Spey at Grantown, across the Cromdale Hills to Tomintoul in the tributary valley of the Avon, it covers approximately eighty square miles. The maximum difference of altitude is about 1,500 feet. There are numerous outcrops, both natural and artificial, but certain parts of the region are obscured by thick drift; the valley of the Spey is filled with fluvio-glacial and recent gravels extending on each side of the river. Fortunately the distribution of exposures is such that, on the scale of an inch to a mile, little difficulty is found in locating the principal contacts. These are shown on the map, Plate 6.

The particular interest of the area is that in it the Moine and the Dalradian are in contact. Moreover, the Moine rocks enclose the outcrop of a group of pelitic gneisses and marbles (the Grantown Series) which, it has been suggested on lithological grounds, may represent either an outlier or an inlier of the Dalradian. In view of these features, it is surprising that so little attention has hitherto been given to the region. The Tomintoul area was mapped for the Geological Survey by L.W. Hinxman. His one-inch map (Sheet 75), one of the most beautiful of Highland maps, was published in 1895, and was followed /

followed in 1896 by his little known but valuable memoir on the area. Hinxman continued the mapping westwards to the Spey; west of the river the mapping was by E.M. Anderson, to whom we owe also the description of most of the Grantown Series. Their memoir was published by the Geological Survey in 1915, and their one-inch map (Sheet 74) in 1917.

The purpose of the present communication is to show that the axial-method of tectonic analysis (Argand, 1911; Wegmann 1927, 1928, 1929) provides the key to the interpretation of Hinxman and Anderson's maps. The region described is homoaxial; the plunge is nearly 30° towards the south-east. Higher tectonic elements are therefore found in that direction. Indeed the traverse from Grantown to Tomintoul is effectively a vertical ascent through a tectonic thickness of six miles. In this immense natural section, which is visible thanks to the oblique intersection of the folds with the present topographic surface, the tectonic relation of the Moine and the Dalradian is clear.

II. THE GRANTOWN SERIES

(i) General

Anderson (1915) pointed out that the Moine Series, which /

which covers such a large part of Sheet 74, is characterised by "a monotony of variation". Because of this he inferred (p. 27) that "where paragneisses of a markedly different type occur surrounded by the [Moine] complex there is a prima facie case for regarding them as belonging to a different group". Such a case is presented by the rocks grouped by him as the Grantown Series. The rocks in question consist chiefly of fine micaceous granulites and coarse micaceous gneisses; they often contain kyanite and sometimes graphite. Associated with these are smaller areas of coarsely crystalline marble, and, more rarely, quartzite.

The quartzite and the finer pelitic granulite "can be closely matched within the Moine Series" (Anderson, 1915, p. 30) On the other hand, "the association of limestone with carbonaceous pelitic sediment reminds one of the similar association of limestone and black schist occurring in Banffshire some ten miles further east. This fact, together with the general difference in type between the rocks here described and the surrounding Moine granulites, suggests that a part of the Grantown complex may be an outlier or an inlier of the Banffshire or Central Highland Series [Dalradian] " (Anderson, 1915, p. 30).

The possibility of differential movement between the typical Moine and the rocks of the Grantown Series was suggested by /

by Anderson. "Everywhere along the western margin of the Grantown complex the siliceous Moine granulites are seen to dip beneath it, but this must not be taken as having any stratigraphical significance. A fact of more importance is the contact of these granulites along this margin with several distinct members of the complex, suggesting a line of break or 'slide' similar to those described by Mr Bailey in the Appin district of Argyllshire. Near Dreggie, however, the Moine granulites are intimately interfolded with the fine pelitic schist suggesting a natural junction at this point" (Anderson, 1915, p. 29). This matter is discussed below (p. 146), but it may be noted here that no evidence of fracturing (mylonite &c.) has been recorded.

The writer has been familiar with this region for some years. Indeed it was here that he was first introduced to geology. However, its peculiar importance was not appreciated until the late summer of 1948 when it was discovered that over the outcrop of the Grantown Series, the axes of the small folds plunge to the south-east at a rather high angle (nearly 30°). Several authors (including Dr. E.M. Anderson, 1948, p. 101) have challenged the hypothesis that the pitch of small folds, and of lineation parallel with their hinges, necessarily gives the plunge /

plunge of the major structures. To prove the validity of the hypothesis for the region discussed in this paper, the Grantown Series was taken as a test-area. A considerable number of dips are given on the published maps, and the approximate dip of the major contacts can, in places, be determined by the relation of the outcrops to the topography. These data have been supplemented by measurements made in the field by the writer. In addition, numerous determinations have been made of the axial-plunge of the visible folds and of other linear structures. These directions have been plotted on a stereographic projection (fig. VI.C.2).

The normals to the bedding and foliation describe a great-circle on the projection. The fold-axes, and parallel linear structures, form a sheaf. Of great significance is the fact that the centre-line of the sheaf coincides with the normal to the mean great-circle. (In fig. VI.C.2 the great-circle drawn is normal to the centre-line of the lineation-sheaf.) This fact proves that the axial-plunge of the small folds coincides with that of the structures on every intermediate scale up to the dimensions of the whole area.

The outcrop of the Grantown Series is enclosed by the Moine granulites, except in the extreme north-west where it is cut off by the Grantown granite. The plunge of both the Grantown /

Grantown Series and the surrounding Moine is constant, except for a few very minor variations. It follows that the Grantown Series is a gigantic tectonic inclusion enclosed in the Moine granulites. It is certainly true, as Anderson suggested, that there has been relative movement of the two series. The style of the movement has been pseudo-viscous in the sense of Argand (1912). Relative movement has taken place on every macroscopic s-plane. The marble outcrops are discontinuous in plan and must be discontinuous on the profile. They represent relatively small and isolated "fish" swimming, as it were, in the pelitic gneiss, just as the whole Grantown Series represents an immense "fish" swimming in the Moine.

We cannot assume a priori that the smaller fish necessarily moved in precisely the same direction as the larger; nor can we assume that the mobility of the marble necessarily equalled that of the gneisses. It is, however, a remarkable fact that the lineation-sheaves of the two rocks are almost identical. The largest systematic variation between a particular marble and its associated pelitic gneiss is only 10°. It seems probable, on the other hand, that the southern termination or "tail" of the Grantown fish has been twisted some 40° relative to the complex as a whole. Unfortunately the lineation is not particularly well developed at this locality, and therefore the suspected /

suspected twist referred to cannot be verified with certainty.

Approximately a mile west of the northern termination of the Grantown Series is the outcrop of the Beinn Mhor Pelitic Group, with its enclosed quartzites. The outcrop is small and is largely cut off by the Grantown granite. The rocks of this group are very similar to those of the Grantown Series. Like the Grantown Series and the Moine granulites of the region, this group plunges to the south-east. It is therefore clear that in vertical section it is separated from the base of the Grantown Series by Moine granulites. Although the plunge of all these tectonic elements is similar, there is a small but systematic difference. Relative to the Grantown Series, the Beinn Mhor Pelitic Group has been rotated some 15° clockwise and downwards.

(ii) Style of Macroscopic Structures

Study of the small-scale structures is essential for elucidation of tectonic style, and for kinematic analysis. The accompanying figures (figs. VI.C. 3-7) have been selected as representative of the style. They are true profiles in which every surface, the trace of which is shown, is approximately at right angles to the profile plane.

The style of the pelitic gneiss at Dulnain Bridge is illustrated by fig. VI.C.3. The gneiss has suffered intense syn-kinematic /

syn-kinematic granitisation, and much of the rock is muscovite-pegmatite. The mica crystals are frequently severely plicated. It is obvious from this figure that differential movement has taken place on every macroscopic s-surface. The sense of movement on the s-surface shown in fig. VI.C.4 is particularly clear. Relative to the lower layers, the upper ones have moved towards the south-west. This movement appears to predominate throughout the Grantown Series. It gives additional proof that the lineation is in b.

It is interesting to notice Hinxman's statement (1896, p. 13) that "the general structure of the country is often completely represented in miniature over a few square feet of rock". Just as tectonic inclusions ("fish") are found on the grand- and intermediate-scales, so they are found also on the macroscopic scale. Three "fish" of garnetiferous quartz-biotite-granulite in a rather more pelitic matrix are shown in fig. VI.C.5. Their maximun elongation (normal to the plane of the figure) is parallel to the general plunge and represents a b-lineation.

The quarry at Broomhill gives excellent exposures of several types of b-lineation. In addition to the lineation given by the long axis of the "fish" just described, we may note /

note the following: parallel trains of biotite; preferred orientation of the long axes of mica crystals; and corrugation of large crystals of mica. However, much more conspicuous than any of these is a well-developed "rod- or mullion-structure" Hinxman used these terms (1896, pp. 10, 19) to describe a structure in the rocks of the Tomintoul area, and published a photograph (1896, fig. 1) illustrating the structure referred to. While it is true that rodding has not previously been recognised in the rocks of the Grantown Series, there can be no doubt of the identity of the Broomhill structure with that described by Hinxman; even their plunge is the same.

The rodding is produced by the intersection, both with each other and with the bedding, of sets of curved joints. These joints are controlled by the same axis as the folding, and hence the elongation of the rods plunges with the folds. The range of scale on which the structure is found is shown in figs. VI.C. 6 and 7. On different occasions during the summer of 1949 the writer visited the classic exposures of rodding in Strath Oykell with Dr. G. Oertel, Dr. Gilbert Wilson, Mr G.C. McCallum, and Mr H. Rutledge. A similar control of the rods by the intersection of curved s-surfaces prevails at Strath Oykell as at Broomhill; at both localities the rods plunge with the small-scale recumbent folds. Thus the mode of formation and /

and the orientation of the lineation in our area are of more than local significance. They appear to provide support for F. Cole Phillips' view (see Phillips, 1949 for references) that the lineation in the Northern Highlands is a b-lineation and is not genetically related to the Moine Thrust.

III. THE MOINE GRANULITES

A large part of Sheet 74 is covered by the outcrop of rocks of Moine type. In the area considered in this paper, the lineation in the Moine is parallel to that in the Grantown Series. This Series is almost completely surrounded, on both map and profile, by the Moine rocks. The dominant variety in this region is the siliceous granulite of Hinxman (1915, p. 13). Quartz and feldspar are the chief constituents, but a certain amount of biotite is always present. Increasing percentage of mica gives the transition to semi-pelitic types. Quartzites are distinguished by the absence of biotite, and usually also by their low percentage of feldspar.

As noted in the memoir (1915), the grade of metamorphism is high, and the granulites are "often permeated with granitic material" (p. 12). In fact the granulites grade into migmatites /

migmatites. Where the granitisation has been observed in proximity to one of the Newer Granites (such as the Grantown granite the authors of the memoir have tended to ascribe the phenomenon to the action of that granite. These granites are post-kinematic; much of the granitisation, on the other hand is syn-kinematic. The crystals which constitute the migmatites are often deformed, and this deformation is geometrically related to the kinematic axes. The authors of the memoir realised that the distribution of the migmatites does not bear a very close relation to that of the Newer Granites. Localised granitisation of rocks close to, or enclosed in one of the granites is doubtless connected with that granite; but the demonstrably syn-kinematic migmatites are older than the Newer Granites.

Migmatites are found as far east as Nethy Bridge. Structurally this locality is at the same depth as the highest part of the Grantown Series. But the most widespread and thorough granitisation is found west of the Grantown Series. It is recorded in the memoir (1915, p. 20) that the granulite is there granitic in character and "can hardly be distinguished from the igneous rock". It is perhaps significant that this zone of syn-kinematic granitisation coincides with the deepest part of our profile.

The migmatites, sometimes in the form of augen gneiss, are /

are well exposed on the Craig Garten ridge, near the southern extremity of the Grantown Series. The dispersion of the fold-axes at this locality is considerably greater than is found in the less altered Moine rocks. It is clear that a greater mobility than normal accompanied the granitisation, and it is possible that the "twist" of this end of the Grantown Series (mentioned above) can be correlated with the excessive mobility of the neighbouring migmatites.

The difference in style between the upper and lower tectonic levels in the Moine of the Grantown area is illustrated by figs. VI.C. 8 and 9. An exposure at Castle Roy. Nethy Bridge is represented by fig. VI.C.8; incipient boudins of siliceous granulite are enclosed in semi-pelitic schist. The long axis of the boudins (perpendicular to the plane of the figure) is parallel to the fold-axis, and is a b-lineation. This exposure represents an early stage in a process which is competent to produce "fish" such as those illustrated in fig. VI.C.5. A migmatite from Duthil, west of the Grantown Series, is illustrated in fig. VI.C.9. It represents a tectonic level some three miles deeper than that represented by fig. VI.C.8.

IV /

IV. THE CROMDALE HILLS SERIES

The Cromdale Hills separate the valley of the Spey from that of its tributary, the Avon. "They consist of an assemblage of schistose quartzite, quartz-schists, mica-schists, quartzose and micaceous flagstones, uniformly holocrystalline and granulitic in structure" (Hinxman, 1896, p. 17). East of the River Avon outcrop the graphite-schist, marble, mica-schist, phyllite, and quartzite of the Banffshire Dalradian. In 1896 Hinxman (p. 17) separated the quartzose series of the Cromdale Hills from the Dalradian quartzites "on account of differences in character and structure that are, as a rule, easily recognisable". The validity of this separation is discussed below (pp. 161-164).

In 1902 Hinxman (p. 24) regarded the "Cromdale Hills Series" as belonging to the Moine of the Central Highlands, and therefore discarded the purely local term. Referring to the rocks of the Cromdale Hills in 1915, he wrote: "At the time when the latter were mapped, their identity with the widespread altered sedimentary rocks of the Moine Series had not been definitely recognised, and they were provisionally given a local name" (p. 12). Nevertheless, Hinxman's map (Sheet 75) shows the contact between the western limit of the quartzose group of the Cromdale Hills and semi-pelitic Moine. Although in his Memoir /

Memoir (1896, p. 19) he makes it clear that this is not a sharp contact, it is evident that the rocks of the Cromdale Hills represent one of the more siliceous groups of Moine that is sufficiently distinct to be shown by a different colour on the one-inch map. It is desirable to have a term to facilitate reference to this group, and therefore Hinxman's old local designation is retained and used as the heading to this section.

Hinxman's description of lineation in the Cromdale Hills Series has recently been quoted, and his interpretation has been discussed (McIntyre, 1950). The writer has attempted to show that the macroscopic fabric of a specimen of sheared quartzite from this Series proves that the lineation on the specimen was _b_-lineation, and not _a_ as Hinxman had assumed. Accordingly Hinxman's symbols showing the direction and sense of "stretching" cannot be accepted without further consideration; they must be taken as descriptive and non-genetic, showing merely the direction of a linear structure in the rock at that locality. _The head on the arrow constituting the symbol does not represent the plunge of the lineation_. The dips of bedding and foliation given on Sheet 75, together with the lineation-directions likewise recorded, are already sufficient to show that the lineation in the Cromdale Hills is _b_-lineation. Further measurements made in the field by the writer confirm this conclusion. The plunge is /

is the same, both in direction and amount, as that in the Grantown Series and in the undifferentiated Moine lying to the west of the Cromdale Hills.

The continuous plunge towards the south-east implies that the Cromdale Hills Series is at a higher structural level than the rocks already described. It is therefore of great interest that both metamorphic grade and intensity of syn-kinematic granitisation increase from the south-east towards the north-west as successively deeper levels appear at the surface. On the eastern slopes of the Cromdale Hills, dark laminae, due to layers exceptionally rich in ilmenite, rutile, and zircon are present; they are believed to represent "the original lamination of a fine-grained sandstone" (Hinxman, 1896, p. 19). The quartzite on the western slopes, on the other hand, is "thoroughly drawn out and often shows beautiful 'mullion structure'" (p. 19). "Passing westwards towards the Spey the schists show signs of further alteration .... In the Haughs of Cromdale, and especially about Ballenluig, where veins of pegmatite first make their appearance, biotite is largely developed, and sometimes entirely replaces the white mica in the schists, which are thoroughly granulitic, gneissose, and sometimes garnetiferous" (p. 19). Comparing the Moine of the Grantown map with the Cromdale Hills Series to the east, Hinxman wrote (1915, p. /

p. 12): "In Sheets 75 and 85, conclusive proof of the sedimentary origin of these crystalline schists was found in the colour-banding due to laminae of heavy residue minerals. In the present area, however, where the rocks are generally in a much higher stage of metamorphism, and often, in addition, permeated with granitic material, such direct evidence is seldom forthcoming".

Reference has already been made to the variety of rock-types in the Cromdale Hills. "The constant variation in the nature of these rocks is to a considerable degree no doubt due to original differences in sedimentation, but may also be attributed to the effects of subsequent mechanical movement" (Hinxman, 1902, p. 24). At many localities Hinxman observed that "where the quartzite is more sheared white mica is developed along the planes of movement" (1902, p. 25). "The amount of shearing and interstitial movement constantly varies, and the rock passes rapidly from a comparatively unmoved and massive quartzite into a thoroughly schistose rock in which white mica is abundantly developed along the planes of movement" (1902, p. 26). Moreover, he has given precise descriptions of the phenomenon as seen at specific exposures: "The crests of the folds can often be seen to be occupied by comparatively unmoved and massive quartzite. Further along the rapidly thinning limbs /

limbs of the fold, where the material has yielded more readily to the increasing strain, the quartzite is converted into a fissile, quartze-felspathic schist, in which white mica is plentifully developed. This structure is a common accompaniment of the folding among the quartzose rocks of this area" (1896, p. 18); "The arches of the minor folds are occupied by lenticular cores of comparatively unmoved quartzite, which passes along either attenuated limb of the fold into a fissile quartzo-felspathic schist, in which white mica has been plentifully developed under the increasing shearing strain. The result of this process, continued throughout the different portions of a set of compressed overfolds, will obviously be the production of a series of rapidly alternating bands of quartzite and quartz-mica-schist, such as we find here and in several other of the stream-sections of the Cromdale Hills" (1902, p. 25). "In the more thoroughly sheared portions, silvery white mica in crystalline plates of uniform size, is the predominating mineral. These mica flakes are not bent where puckering occurs, showing that the crystallisation was later than the movements which produced the puckering" (1896, p. 19). It has been necessary to quote thus substantially because the validity of the criteria used by Hinxman to distinguish the Moine and Dalradian quartzites depends on the interpretation of the phenomenon described in these passages.

Much /

Much of the Cromdale Hills is covered by thick hill-peat. Hinxman has nevertheless been able to map two belts of "fissile mica-schist" within the quartzose series. These appear in profile as "fish" enclosed within the siliceous granulites and schists of the Cromdale Hills, just as the Grantown Series is a "fish" enclosed in the typical siliceous Moine granulites. It is possible that, under the peat, other smaller pelitic "fish" lie between the two recorded by Hinxman. As the lower limit of the Cromdale Hills Series is very poorly defined (if, indeed, it exists at all), the difference between these pelitic "fish" in the Cromdale Hills, and the Grantown Series is probably only a matter of tectonic depth. This conclusion is supported by the fact that the structurally lowest part of the lower of these "fish" is a coarse pelitic gneiss, which closely resembles that of the structurally highest part of the Grantown Series. Finally we may note that Hinxman grouped the Cnoc Feargan - Bridge-of-Brown flagstones ("mica-schist") with the Cromdale Hills Series (1896, p. 18). These flagstones thus represent the highest of the Moine rocks in this area; they represent a very low grade of metamorphism for the Moine.

V. THE DALRADIAN SERIES

This series consists of graphite-schist, mica-schist, slate, phyllite, marble, and quartzite. With the exception of the quartzite, which is discussed below, these rocks contrast markedly with the siliceous Moine granulites of Strathspey; the metamorphism of the Dalradian is much lower in grade than that of the typical Moine. Folding is intense; many measurements of axial-plunge have been made. Lineation is present throughout, but is particularly frequent in the graphite-schist (minute puckering), the marble (preferred orientation of crystals), and in the quartzites (rodding). The writer has already described (1950) a lineated specimen of graphite-schist - marble from this area, and has attempted to show that the lineation is parallel to b. Everywhere in this district the lineation is parallel to the axial-plunge of the small folds (measured directly), and also to that of the large folds (determined by construction). As far east as the outlier of Old Red Sandstone at Tomintoul, the region belongs to the homo-axial area which extends to the north-west and includes the Grantown Series.

The continued plunge towards the south-east brings the highest tectonic elements down to the present topographic surface in this direction. The Dalradian, as a whole, is higher than the Moine. The geometric inter-relations of the members /

members of these two series is shown on the profile (fig. VI.C. 10). A highly complex, recumbent fold closes towards the south-west. Its form is best seen in the shape of the Tomintoul marbles. The Cnoc Lochy quartzite forms the core of the fold and is mantled by the marble and the graphite-schist. The latter has the same flowing style on the grand scale as it has in hand specimen. The flowage of the graphite-schist on a macroscopic scale has been referred to elsewhere (McIntyre, 1950) but the mobility of this rock is often three-dimensional, as the relatively great dispersion of its axes indicates. The marble was competent relative to the graphite-schist. In the latter lie vast tectonic-inclusions ("fish") of marble and of quartzite.

The Cnoc Lochy quartzite shows incipient boudinage on an enormous scale (cf. fig. VI.C.9). The more mobile marble and graphite-schist have flowed into the grooves of the boudins. The Tom Beag - Urlarmore quartzite is obviously the pinched off nose of the quartzite core; it is now completely separated from the Cnoc Lochy quartzite by the marble. This phenomenon is of the greatest importance, for it illustrates the mechanism by which the other tectonic inclusions of quartzite (e.g. that of Carn Liath) may have been formed.

In the Memoir (1902) on Sheet 85, J.S. Grant Wilson wrote (p. 12): "In this Sheet there is no direct evidence that the quartzite rests unconformably on the other members of the Banffshire /

Banffshire series. The indirect evidence is very strong, for a glance at the map shows that the main belt of quartzite ..... is at various places in contact with phyllite, black schist, and limestone. But it should be borne in mind that, throughout the area included in Sheet 85, the quartzite, phyllite, black schist, and limestone have been affected by a common system of folds". In the Tomintoul area, however, it is evident from the profile that the contacts are tectonic and not stratigraphic.

One's views on the detailed style of the Moine-Dalradian contact depend, in considerable measure, on one's interpretation of the relations between the quartzose members of the two Series. Referring to the criteria used by him in mapping Sheet 75, Hinxman wrote (1896, p. 17): "Generally a quartzose series, they [the rocks of the Cromdale Hills Series] have been separated from the Banffshire quartzites to the east on account of differences in character and structure that are, as a rule, easily recognisable. The Banffshire quartzite, as developed in this area, may be regarded as a homogeneous formation deposited under nearly uniform conditions of sedimentation. The sedimentary origin of the rock is clearly apparent to the eye, and even when the structure is more or less granulitic, the original clastic grains are never entirely destroyed. Deformation due to mechanical movement is an infrequent feature and /

and confined to strictly limited areas. The Cromdale Hills Series, on the other hand, represents a set of alternating shales and sandstones which have been converted, chiefly by dynamical metamorphism, into micaceous and siliceous schists and flagstones. These rocks are thoroughly granulitised, and their sedimentary origin is only occasionally to be recognised in the dark laminae which under the microscope are found to be composed of heavy residues such as ilmenite and zircon. In addition to the granulitisation, the original mineral particles are drawn out in one determinate direction, giving a striped appearance to the rock in many places that at once catches the eye".

The essential criterion used by Hinxman in 1896 to differentiate between the two quartzose Series is thus based on the degree of their deformation; the Moine rocks are more deformed than their Dalradian equivalents. His views remained unchanged after he had mapped the sheet to the north (Sheet 85), for, referring to a quartzite from the Cromdale Hills Series of that area, he wrote (1902, p. 25): "This rock is somewhat similar in outward appearance to the quartzite of the Banffshire Series, but a closer examination reveals the presence of black mica disseminated in minute flakes through the rock, while where the quartzite is more sheared white mica is developed along the planes /

planes of movement".

The Dalradian is at a higher tectonic level than the Moine. Just as the metamorphic grade diminishes as the rocks are traced from the deep tectonic level at Grantown to the intermediate level represented by the Cromdale Hills, so a still lower grade prevails in the Dalradian. There are, in fact, gradations between Hinxman's two types; in this area there is no known difference between the quartzose rocks of the Moine and of the Dalradian except the degree of their deformation; the general difference in metamorphic grade of the two series may be correlated with the difference in their tectonic depth.

Reference has already been made to Hinxman's descriptions of the formation of white mica and schistose structures during deformation of the quartzose rocks of the Cromdale Hills. It has also been pointed out that, where deformation has been less intense, the original sedimentary structures are still preserved. The same features are found in the quartzites of the Banffshire Dalradian, but, as has been noted above, the deformation of these has not usually been so intense. The Dalradian quartzites are sometimes considerably deformed over wide areas, and in the same manner as those of the Cromdale Hills. This fact is apparent when the descriptions of the latter (pp. 156-157 above) are compared with the following description /

description by J.S. Grant Wilson of the Dalradian quartzites of Sheet 85 (Memoir, 1902, p. 12): "Over the greater portion of the northern half of the area this rock is felspathic and granulitised, and often passes into a quartzo-felspathic schist with white mica developed along the divisional planes, while towards the south-east the original clastic grains can still be recognised, and in several localities bands of pebbly grit prove the sedimentary origin of the rock".

Even Hinxman's own descriptions of the Dalradian quartzites of the Tomintoul sheet show that here too, the Dalradian is, at least locally, as much deformed as some of the less altered of the Cromdale Hills rocks. "The texture of the rock is often entirely or in great part granulitic .... Felspar and white sericitic micas are present in varying amount, the latter only where the rock is schistose or shows signs of mechanical deformation" (1896, p. 8). In the gorge of the Ailnack, immediately south of our area, "the rocks are for the most part thoroughly sheared, and often pass into fissile quartzo-felspathic schist" (1896, p. 10).

The writer found b-lineation (usually in the form of more or less well developed rodding) in all the principal Dalradian quartzites of the western half of sheet 75; for example, in all three quartzites which cross the Ailnack: in the Muckle Fergie /

Fergie burn; in the Conglass Water south-east of the Tomintoul Old Red Sandstone outlier; in the Cnoc Lochy quartzite; on the Bochel (east of Knockandhu); and near Tomnavoulin and Allanreid in Glen Livet.

Just as a bed of sandstone may project into an intrusive sill, so the Cnoc Lochy quartzite is a gigantic flake of Moine rising into the overlying graphite-schist of the Dalradian. It is true that on the one-inch map (Sheet 75) a contact is drawn between this quartzite and the Cromdale Hills Series, but there is no evidence for this separation. The pinched off nose of the Cnoc Lochy quartzite, namely the Tom Beag - Urlarmore quartzite is interpreted as a tectonic inclusion ("fish") of Moine now entirely enclosed by Dalradian rocks. The Carn Liath quartzite is likewise enclosed by the Dalradian, and is presumably also an inclusion of Moine. Possibly many of the other "Dalradian" quartzites represent similar tectonic inclusions.

VI. THE PROFILE

The profile (fig. VI.C.10) has been constructed from the published maps on the basis of the plunge determined by the writer. The plane of projection strikes 30° east of north and dips at 64° to the north-west. In the resulting profile the effect /

effect of topography is eliminated.

The construction of the profile is based on purely geometric reasoning. On all visible scales, the structures maintain constant profiles over distances, measured in the axial-direction of many times their amplitudes. It is assumed that the major structures show equal continuity in the axial-direction, and evidence is given above in support of this hypothesis. Although it is believed that the axis of projection is the b-axis, no kinematic reasoning is used in the construction of the profile. This is exactly analogous to the procedure used by Lugeon (the High Calcareous Alps and the Simplon region), Argand (the Pennine Alps), and Wegmann(the Pre-Cambrian of Finland). The kinematics are determined from the geometric forms (on all scales) of the structures actually present. The forms alike of the Tomintoul recumbent-fold, and of the macroscopic structures indicate movement towards the south-west. As in the Swiss Alps, the best proof that the lineation present is, in general, parallel to the b-kinematic-axis, is thus based on consideration of the grand-scale structures.

Many examples of recumbent-folds in the Scottish Highlands have previously been described (for references see Read and MacGregor, 1948, Chap. 4). But in Scotland little mention has hitherto been made of large scale tectonic inclusions, although these are well known in Fennoscandia. Thus a new and perhaps /

perhaps important element has been added to our concept of the tectonic style of the Scottish Highlands.

The relations between the Moine and the Dalradian in Strathspey are now known to be much more complex than has hitherto been supposed. There is no evidence for an unconformity between the two, nor, with such a tectonic style, can there be such evidence. In the homo-axial region described, both Series have suffered the same movement; namely N.E.-S.W. in direction, and apparently in general of the upper layers towards the south-west relative to the lower. The relation of this homo-axial region to its general tectonic environment will be discussed in a paper now in the course of preparation.

VII. BIBLIOGRAPHY

ARGAND, E. 1911. Les nappes de recouvrement des Alpes pennines et leurs prolongements structuraux. Mat. Carte géol. Suisse. n.s. 31.

________ 1912. Sur la segmentation tectonique des Alpes occidentales. Bull. Soc. vaudoise sc. nat. 48, pp. 345-356.

ANDERSON, E.M. 1948. On lineation and petrofabric structure and the shearing movement by which they have been produced. Quart. Journ. Geol. Soc., civ., pp. 99-132.

HINXMAN /

HINXMAN, L.W. 1896. Explanation of Sheet 75. Mem. Geol. Surv. Scotland.

________ and J.S. GRANT WILSON. 1902. Explanation of Sheet 85. Mem. Geol. Surv. Scotland.

________ and E.M. ANDERSON, 1915. Explanation of Sheet 74. Mem. Geol. Surv. Scotland.

McINTYRE, D.B. 1950. Note on two lineated tectonites from Strathavon, Banffshire. Geol. Mag., lxxxvii, pp. 331-336.

PHILLIPS, F.C. 1949. Lineation in Moinian and Lewisian Rocks of the Northern Highlands of Scotland. Geol. Mag., 86, pp. 279-287.

READ, H.H. and A.G. MacGREGOR. 1948. The Grampian Highlands. Brit. Reg. Geology.

WEGMANN, E. 1927. Uber alpine Tektonik und ihre Anwendung auf das Grundgebirge Finnlands. C.R. Soc. géol. Finlande, 6th October.

________ 1928. Uber die Tektonik der jüngeren Faltung in Ostfinnland. Fennia. 50, No. 16.

________ 1929. Beispiele tektonischer Analysen des Grundgebirges in Finnland. Bull. Comm. géol. Finlande, 87, No. 8.

1. The tectonics of the area between Grantown and Tomintoul (mid-Strathspey). By Donald B. McIntyre, Ph.D. F.G.S.

The region is homo-axial; the pitch of the fold-axes is to the south-east at nearly 30°. A profile nearly seven miles deep has been constructed by the use of the axial method of tectonic analysis developed by Lugeon, Argand, Wegmann, and others. This profile shows the tectonic relations of the Grantown Series, the Moine, and the Dalradian. Given the profile and the pitch, the general dips can be predicted; these coincide with the observed data. Metamorphism grades from phyllites to migmatites from the highest levels to the deepest. The majority, if not all, of the contacts are tectonic. Gigantic tectonic inclusions of Moine swim in the Dalradian; it is possible that similar inclusions of Dalradian occur in the Moine. The Moine and Dalradian suffered the same movement, the sense of which appears to have been towards the south-west. Lineation is perpendicular to this direction.

Discussion

Professor H. H. Read congratulated the author on two features of his Strathspey work. First, he had paid a tribute to the mapping of L. W. Hinxman, by whom the speaker had had the privilege of being introduced to the Highlands. Highland geology had often been cluttered up with geniuses, a class to which Hinxman repeatedly denied he belonged. Hinxman considered it his duty to make an honest map of the Highlands, completely objective in character. After fifty years, Dr. McIntyre had found his work to be good—an epitaph most fitting for a field geologist. Second, the author had had the courage to release himself from the baleful influence of the Moine Thrust. The great body of superstition, *Aberglaube* and sheer infatuation that had gathered round this structure had greatly retarded the progress of Highland geology. It would be well to forget about the Moine Thrust for ten years and then the Highlands could be dealt with in a proper manner, uninfluenced by any south-east to north-west dogma. This Dr. McIntyre was doing, and the speaker wished him well.

Sir Lewis Fermor said that if he had been a professor of geology, Dr. McIntyre might have been one of his students; for what the author had expounded that evening based on studies in Scotland agreed essentially with his (the speaker's) experience during many years' study of the Archaean rocks of the Central Provinces of India, and especially on the fundamental principle that the pitch of the minor folds and of the striations of the rocks was parallel to the axis of the latest period of folding imposed upon the rocks in which these phenomena were observed.

He (the speaker), as long ago as 1904, during his examination of the manganese-ore deposits of the Central Provinces, observed the grooving and striation of both manganese-ore bodies and associated rocks, a phenomenon to which he had applied the term "slickensides-grooving", not being cognisant of the term "lineation". A fine example of such slickensides-grooving was exposed at Mandri in the Nagpur district, where the footwall of the manganese-ore band was a quartzite cropping out as a number of parallel, striated and grooved prisms (*Mem. Geol. Surv. India*, xxxvii, 1909, p. 935), suggesting logs of fossilized wood, and very similar in aspect to one of Dr. McIntyre's specimens on the table. These striations pitched at from 25° to 40° in the general direction of the contorted ore-band, and the folds of the ore-bed were found to have axes parallel to the groovings. As the ore-body was mined it was found that workings had to follow the direction of the pitch: that is to say, it was the pitch and not the manager of the mine that decided the direction and details of the development.

The magnificent body of manganese ore at Kandri in the same district showed a marked prismatic structure giving rise to grooved prisms of manganese ore pitching at about 30° to the east-south-east (loc. cit. p. 867 and pl. 30). This structure, with its cross-joints, facilitated the extraction of the ore and also controlled the direction of the extension of mining operations; and it was found subsequently that the whole ore-body was pitching to the east-south-east, so that mining operations had perforce to follow suit.

Later (1911 onwards), when he came to survey in detail the Archaean tracts in the Central Provinces, the speaker found that in order to understand the structure it was fundamentally important to take notice of such striations and structures in the gneisses and schists, and he and his party made a practice of inserting on their maps *pitch arrows*, as being as important as dip arrows. The pitch phenomena were found to be parallel to the fold axis of the latest system of folding imposed on the rocks. Moreover, the constituent minerals were aligned in the direction of the pitch.

Sir Lewis said that these pitch phenomena were observable not only when one looked at the rocks close at hand, but were also often to be detected from afar, once one knew what to look for. For the prismatic jointing of the gneisses and schists, parallel to the pitch, was brought out by weathering, so that the general pitch could often be observed from a distance of a mile or more by noticing the general slope of the crude prisms of rock. Last summer, when on holiday at Lochinver in Sutherlandshire, he had noticed that the general pitch of the Lewisian gneisses could in this way also be seen from afar.

Many of the photographs that the author had shown the Society that evening might equally well have been taken in India instead of Scotland: and he was very glad that Dr. McIntyre had brought so convincingly and eloquently to the notice of all, phenomena that were of general importance in any attempt to study the old folded gneisses and schists and associated rocks, including quartzites and crystalline limestones.

Dr. Gilbert Wilson said that, to elucidate the structure of an area in the Highlands in accordance with definite rules of geometrical procedure rather than in conformity with a preconceived tectonic pattern naturally yielded results that at first sight appeared unexpected. The evidence presented by the author showed irrefutably that the various linear structures illustrated and discussed were *b*-structures. In this they agreed with similar phenomena observed by the speaker in the Ross of Mull, Ross-shire, and Sutherland. The mullion structures at Oykell Bridge, mentioned by Dr. McIntyre, the flat folding at Altnaharra, at Borgie, Tongue, and on A'Mhoine itself, all corresponded in general pitch direction and sense of translation with the movements postulated for the structures of Strathspey.

The speaker was, however, somewhat worried as to where this apparently regular south-easterly pitch was going to lead. Dr. McIntyre had demonstrated that the structures at Grantown must lie some six or seven miles below those near the south-eastern edge of his area. He also had clearly demonstrated that migmatization of these rocks increased with tectonic depth, i.e. towards the north-west. The speaker therefore asked Dr. McIntyre whether he had any explanation as to why, if this regional pitch were reasonably constant, the apparently "tectonically abyssal" rocks of the northern Highlands were not much more profoundly altered than they seemed to be?

Professor R. M. SHACKLETON inquired whether there was only one cycle of metamorphism associated with one cycle of movement in the area, and, if so, whether the author thought that this metamorphism was a part of the regional metamorphism of the Highlands, which elsewhere could be shown to be associated with movements at right angles to those inferred in the Grantown–Strathspey area.

Dr. G. M. LEES also spoke.

The following written contributions were received :—

From Dr. E. M. ANDERSON : " Dr. McIntyre is to be complimented as one of the few Scottish investigators at present occupied with the tectonics of Moinian and Dalradian areas : in particular, so far as the present writer is concerned, with regard to his studies of lineation, on which he has spent much time and work.

" The application of the method of 'axial' analysis, devised by Wegmann and his predecessors, appears to be quite legitimate. But does not the method in itself assume an elongation of individual elements parallel to the pitch of the strata, and therefore to the lineation? If so, it would imply that lineation and shearing are parallel, and not transverse, as Dr. McIntyre supposes.

" Apart from this, some new terminology seems to be needed for the description of the more highly altered parts of these Highland rocks. Even before 1923, the writer became convinced that something in the nature of prongs, as well as of folds, must take a part in the relation of the different groups of the Dalradian, e.g. the Schichallion Boulder Bed, and the White Limestone by which it is accompanied (*Q.J.G.S.* lxxix, 1923, pl. xxv). The first simile which occurred to him was that of the teeth of a comb, but the arrangement is perhaps better expressed by the prongs of a fork. In either case these linear structures may be connected with more continuous ones which are perhaps the terminations of recumbent folds. The folds may be supposed to be 'frayed out' in the direction of motion.

" The necessity for such a conception is emphasized when Dr. McIntyre says, 'Gigantic tectonic inclusions of Moine swim in the Dalradian.' Does he mean that these inclusions are disconnected from their roots?

" The writer gladly accepts the conclusion that the rocks of the Grantown Series are an outlier, at a lower tectonic level, of the main mass of the Dalradian Series to the east."

From Mr. H. RUTLEDGE : " I have been acquainted with Dr. McIntyre's work in mid-Strathspey since its inception and have visited the area with him on several occasions. In the field I was greatly impressed by the marked similarity of tectonic style on all scales. On measuring the structural elements present I was struck by the constancy in direction and plunge of the fold-axes in the varied rock types. In all cases the linear structures measured were demonstrably *b*-lineations. Dr. McIntyre's study has thrown new light on the tectonic relations of the Moine and the Dalradian and is in consequence a great advance in the structural field. I would like to congratulate him on the successful application of the Alpine techniques to the structural problems of the Scottish Highlands."

The AUTHOR in his reply said that the greatest compliment that could be paid to a field geologist was to show how his map could be interpreted in the light of later advances in theoretical knowledge. As Professor Read had said, Hinxman had demonstrated the value of honest mapping. His map, published over fifty years ago, had symbols showing the trend of lineation; moreover, the data on the map were sufficient to prove that the lineation was in *b*, and plunged towards the south-east. Modern methods of analysis enabled us to read Hinxman's map; the tectonic style thus determined was very similar to that found by Wegmann in the Pre-Cambrian of Finland. This was a remarkable tribute to Hinxman's mapping.

The author heartily agreed with Professor Read and Dr. Wilson that, in the past, the Moine Thrust had been given a position of unwarranted dominance in Highland geology. It had been supposed that the Moine Thrust held the secret of the whole Highlands. The author pointed out how Clough's early and important work in Cowal had given indirect but strong support to this erroneous view. That area was one in which the folds did indeed have the orthodox north-east to south-west trend, and it was the only area in the Highlands, outside the immediate neighbourhood of the great thrusts, where the author knew of the existence of *a*-lineations. These lineations were recorded by Clough at an early date, and a syngenetic relationship between lineation, folding and thrusting was soon tacitly assumed. Clough's work had a profound influence; many geologists supposed that everywhere in the Highlands the major structures trended north-east to south-west and that the lineation was always in *a*. Mid-Strathspey was a case in point.

The author welcomed the opportunity of paying tribute to Sir Lewis Fermor's early realization of the importance of lineation. Sir Lewis had pointed out that the direction and amount of axial plunge was commonly reflected in the topography, and that a trained observer could often evaluate the axial plunge immediately upon entering an area. The author said that the reason was the common occurrence of *a–c* joints normal to the fold-axis. The geomorphological effect of this was analogous to dip-slope and escarpment in less folded terrain. He regretted that time did not permit him to show lantern-slides to illustrate the application in Strathspey of Sir Lewis Fermor's observation.

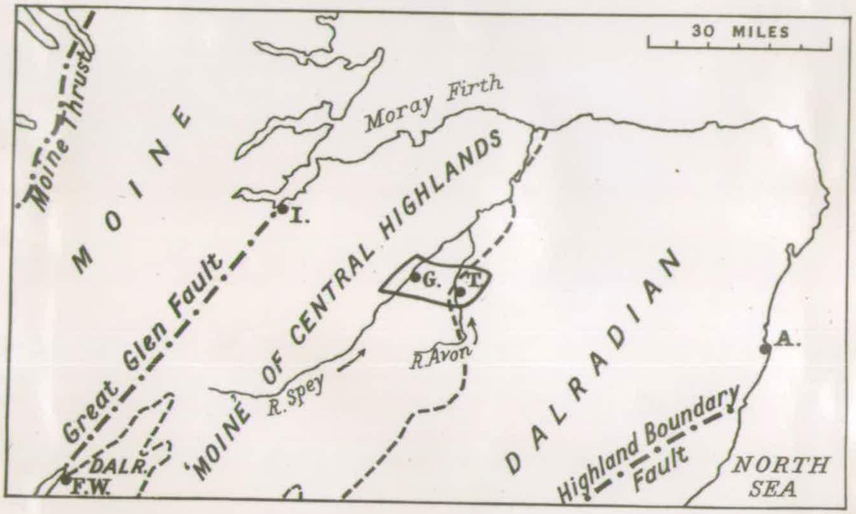
Professor Shackleton had raised the important question of the relationship between metamorphism and movements. The work described had been on macroscopic and larger scales, and therefore the detailed sequence of crystallization and movement had not yet been determined. The available evidence showed that regional metamorphism and migmatization were syntectonic, as defined by Demay (Microtectonique et tectonique profonde, *Mém. Carte géol. France*, 1942, p. 239). In some cases it appeared probable that granitization had been effected after the main folding, yet, elsewhere, the migmatites were cut by small slides syngenetic with the folding, micas were often plicated, and felspars were frequently ovoid. Foliation was nearly always parallel either to the bedding or to the axial surface. The author pointed out the difficulty of distinguishing between post- and syn-tectonic granitization. Where granitic rocks had a structure parallel to that of their environment, the structure might have been induced by movements synchronous with, or post-emplacement, but it might be a palimpsest. Both apo- and syn-tectonic granites occurred in Strathspey, and it was not always easy to distinguish between their respective effects. The author said that he hoped to study this whole question in more detail than had so far been possible. He was grateful to Professor Shackleton for drawing attention to its importance. Perhaps, in this connexion, the most significant fact now available was the correlation between tectonic depth and regional metamorphism and migmatization.

The author thanked Dr. Wilson for his kind remarks. He was particularly glad to have his support and encouragement in view of his own admiration for Dr. Wilson's tectonic work. That part of mid-Strathspey described by the author was homo-axial. It was emphasized, however, that the limits taken were those of the homo-axial segment; it was therefore not possible to extrapolate beyond its bounds. The author said that he intended to describe the relationship of the area to its tectonic environment in a paper now in the course of preparation. It was by no means sure that the Grantown area was necessarily at a higher tectonic level than was Strath Oykell. In spite of this, the constancy and amount of axial plunge to the north-west of the Great Glen did raise a very real problem.

Dr. E. M. Anderson had mapped the western part of the author's area, and was one of the few geologists familiar with the ground. The author had been privileged on numerous occasions to discuss the tectonics of Strathspey with Dr. Anderson, and he was most grateful for Dr. Anderson's continued interest in the work. Tectonic analysis must begin with geometric analysis, and only when the geometry had been fully elucidated was it legitimate to discuss the kinematics. Yet, in spite of this obvious fact, many writers had discussed the dynamics of non-existent structures. Some of the so-called "double systems of folding" in the Moine were examples. The author was therefore delighted that Dr. Anderson's criticism was of his interpretation of the kinematics, and not of the geometry. Dr. Anderson had asked whether the author's tectonic inclusions ("fish") were closed bodies or whether they were to be interpreted as the prongs of a fork, i.e. were they truly isolated, or did they unite at some level other than that of the present topographic surface. The author said that, unless axial culminations or depressions brought the rocks back to the present surface outside the area described, it would be impossible to answer that question. Dr. Anderson had suggested that the form of the bodies could be interpreted as due to a fraying out of the folds in the *a*-direction, instead of in *b* as had been concluded in the paper. In reply, the author insisted that there was no evidence whatever for any movement parallel to the fold-axis, whereas conclusive evidence of movement at right angles to that direction was available at numerous exposures. The author wished to stress the fact that bodies could be elongate without having suffered extension in the direction of elongation. Tectonic thickening along hinge-lines produced elongate bodies of this kind; normal boudinage also formed bodies elongated in *b*. Numerous examples of such structures had been observed throughout Strathspey, and, indeed, throughout the Highlands.

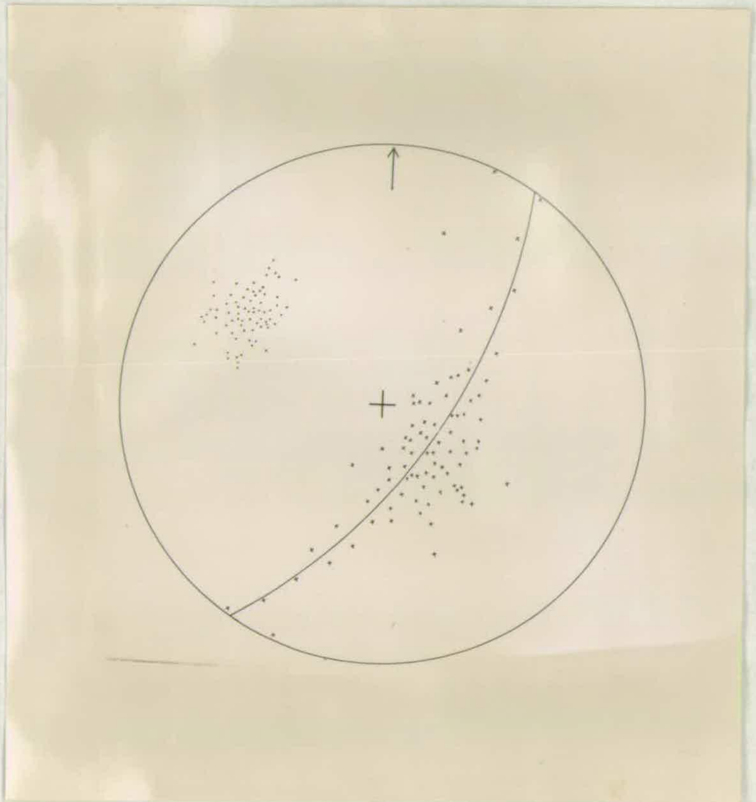
In presenting the paper the author had emphasized that the fold-axis was the direction of minimum change and not a direction of no change. He pointed out to Dr. Lees that he had introduced his imaginary, seven-mile deep bore-hole merely as a teaching device to assist Fellows, unfamiliar with the method, to follow the argument. If the large-scale structures maintained a continuity in the axial direction approximating to a third of that of the visible folds, then the construction of the profile was valid. The profile was to be considered as the integration of an infinite series of *coulisse*-profiles, each of which had an accuracy dependent only on that of the map. The method had no relation to Highland second sight! Only with geophysical methods was it possible to predict the occurrence in depth of structures which did not somewhere appear at the surface. Dr. Lees had asked if there was any evidence in the author's area of the role of the basement complex in the orogeny. In reply, the author stated that, in Strathspey, the Moine and Dalradian had suffered the same movement and had reacted to it in a similar way. If the Moine represented the basement complex it had been so reworked by the last movement that, so far, no evidence of older movements had been detected. The author thought it probable that the structures which he had described resulted from the deformation of a geosynclinal pile, and that the basement complex, if now distinguishable from the geosynclinal filling, lay at a still deeper level. The author was glad that Dr. Lees had emphasized the importance of the method and joined him in hoping that it would be applied in other areas. The author had successfully applied the method in the Jura, the High Calcareous Alps and the Pennine Alps (under the guidance of Professor Wegmann); he had utilized it in the study of the "Lewisian inliers", the "double system of folding" in the Moine, and also in the Southern Uplands. He wished to suggest that others might attempt its application elsewhere; the study of published maps, not excluding some of those published by this Society, sometimes showed that the folds had a trend nearly normal to that stated in the accompanying text.

The author had benefited by many discussions with Mr. Rutledge; for his help and present support the author was grateful. In conclusion, he thanked the Fellows for the kind and interested reception which they had given his paper.



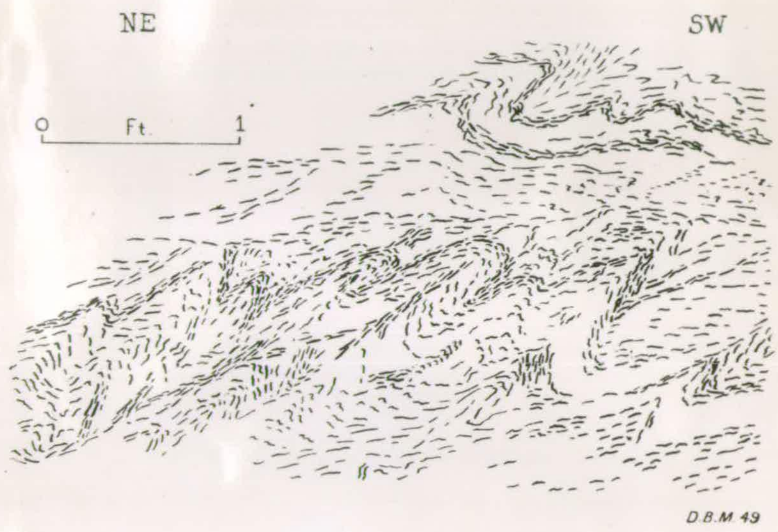
Locality map.

A Aberdeen; G Grantown; I Inverness;
T Tomintoul; FW Fort William.



Stereographic projection (upper hemisphere).
Grantown Series.

· lineations
x normals to s-surfaces



Pelitic migmatite. Dulnain Bridge.

(Grantown Series).

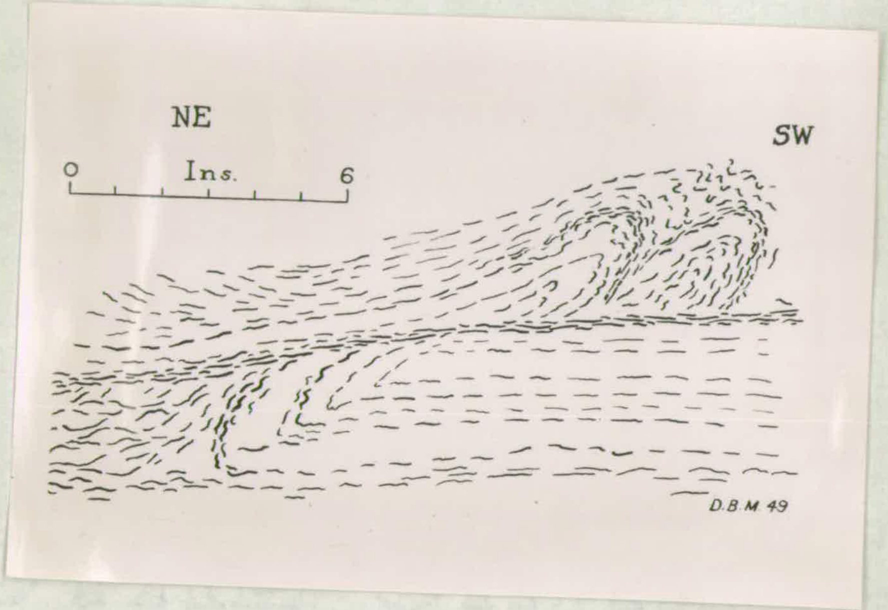


Fig. 4. Profile of pelitic gneiss at Dulnain Bridge (Grantown Series).

Sense of movement on the principal s-surface is towards the south-west.

Greatly affected by syn-kinematic granitisation.

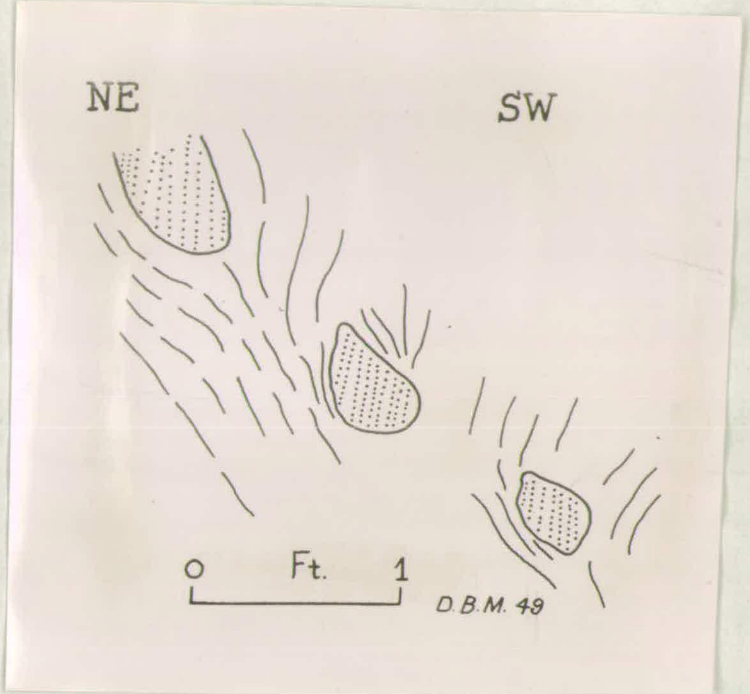
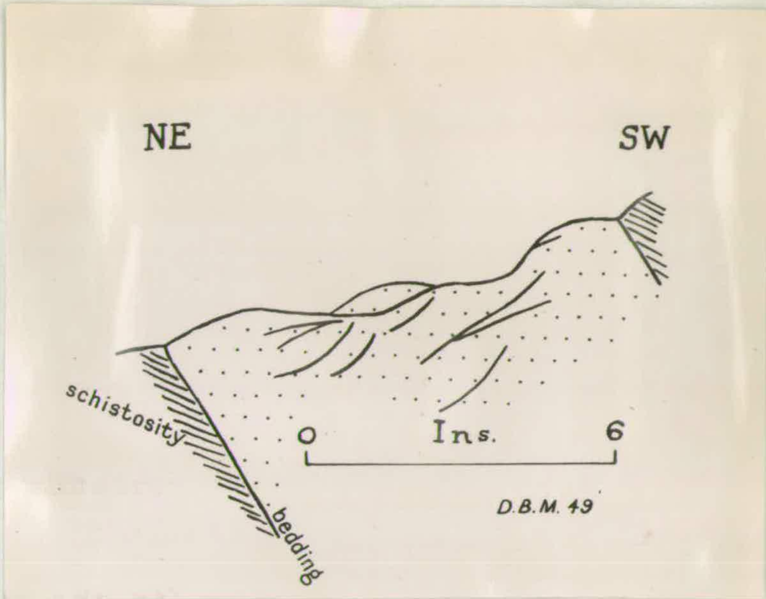
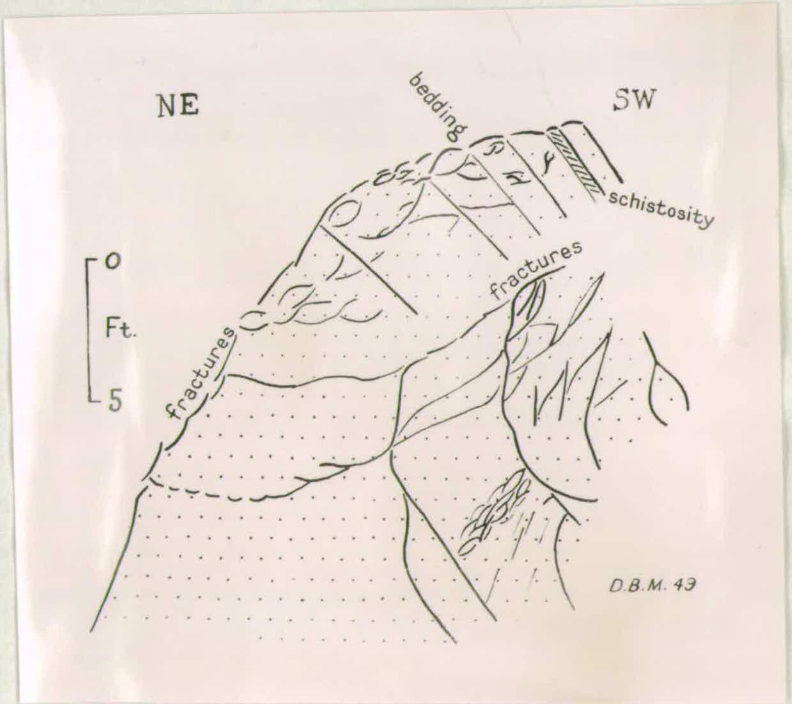


Fig. 5. Profile of garnetiferous inclusions ("fish") in biotite granulite in Broomhill Quarry.

The rock of the inclusions is more siliceous than that of the host.

The structures illustrated are visible because of preferred orientation of crystals.


NE
SW
schistosity
bedding
0
Ins.
6
D.B.M. 49


NE
SW
bedding
schistosity
fractures
fractures
0
Ft.
5
D.B.M. 49

Figs. 6 and 7.

Profiles of the s-surfaces producing rodding in Broomhill Quarry.

The relation of schistosity (in the more pelitic beds) to bedding indicates a slip on the bedding planes that carried the apparently higher beds downwards to the south-west relative to the underlying beds.

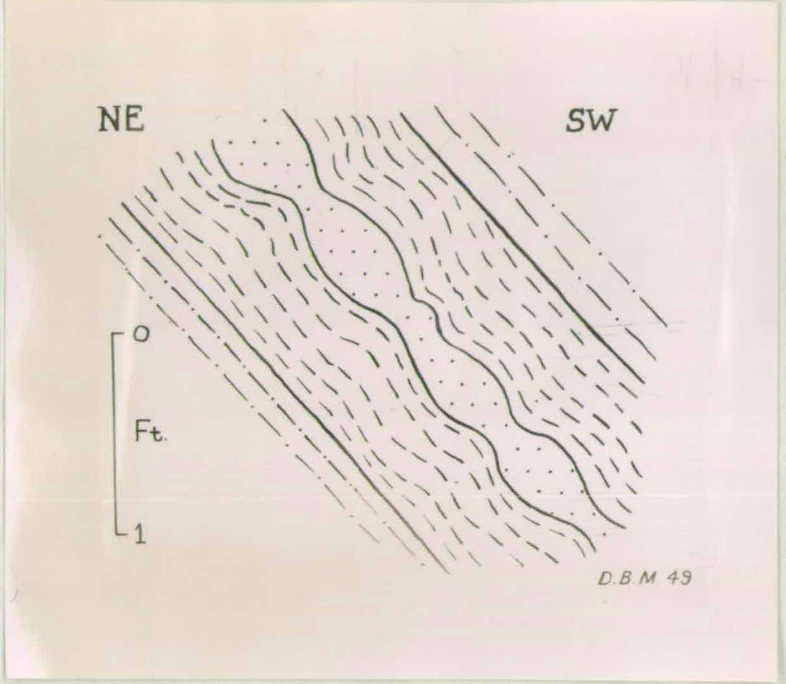
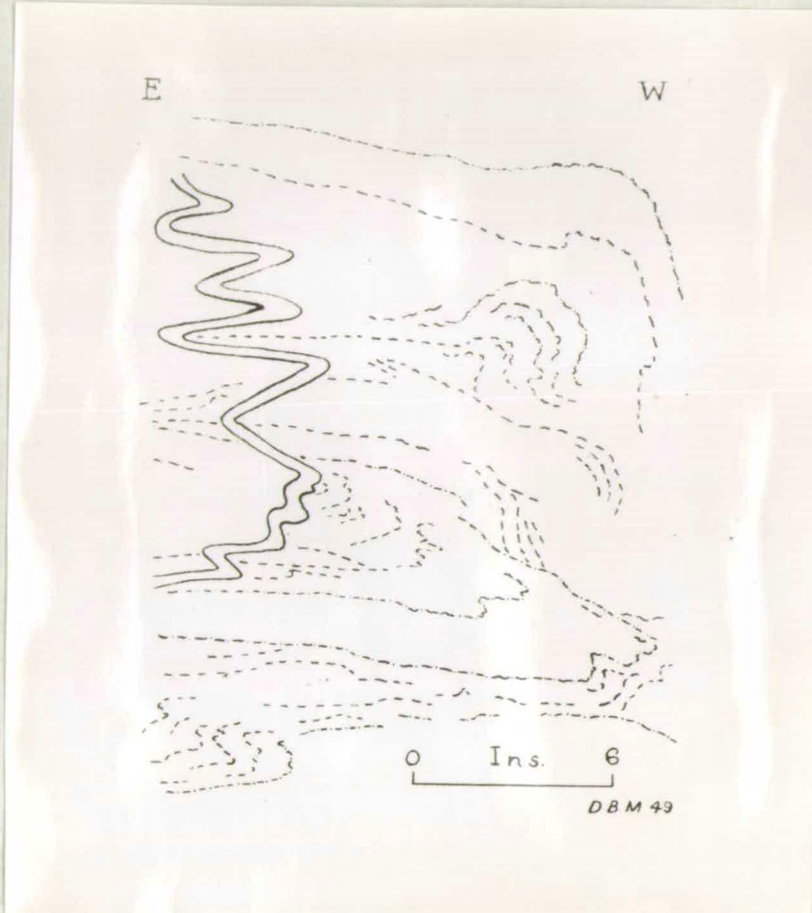


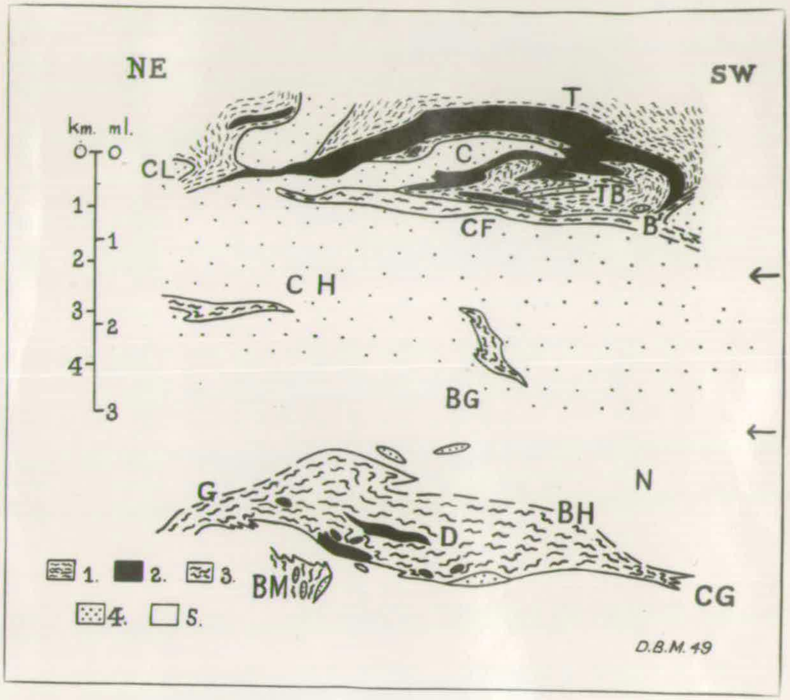
Fig. 8. Profile of incipient boudinage in siliceous granulite (dots) enclosed in semi-pelitic schist (Moine).

Castle Roy, Nethy Bridge.



Migmatite with ptygmatic vein.

Duthil (W. of Grantown Series).



Profile of structure between Grantown and Tomintoul. Plane strikes 30°E and dips 64° N.W. Above uppermost arrow the profile is displaced 1¾ miles to the S.W. A similar displacement has been made at the level of the lower arrow.

Ornament etc. as on map (Plate 6).

D. THE TECTONICS OF THE AVIEMORE DISTRICT, MID-STRATHSPEY.

I. INTRODUCTION

The area described here extends up the Spey valley for a distance of some fifteen miles, from Boat of Garten almost to Kingussie. Its northern limit is the Grantown-Tomintoul homo-axial region described above. To the west, it includes the area between the Spey and that section of the Dulnan valley from near Carrbridge to Cairn Dulnain (six miles north-west of Kincraig). East of the Spey, it extends along the northern margin of the Cairngorm Granite to the River Avon north of Inchrory.

The maximum difference in altitude is nearly 3,400 feet, but, if the granites be excluded, the difference is not more than 2,000 feet. Extensive parts of the region are heavily drift-covered, but there are many excellent exposures. Most of the principal contacts can be located with sufficient accuracy for interpretation on the scale of one inch to a mile. The best exposures are those on An Suidhe, at Kincraig; on Ord Ban and Craigellachie, near Aviemore; on Beinn Ghuilbin, south-west of Boat of Garten; on the Kincardine Hills and Mam Suim, north and east of Loch Morlich; in the overflow-channels on the Braes of Abernethy /

Abernethy; in the Water of Caiplich and Water of Ailnack, and in some of their tributaries; and in the River Avon and its tributary, the Muckle Fergie Burn.

That part of the area lying to the east of the River Spey was mapped by L.W. Hinxman; most of the ground to the west of the river was mapped by E.M. Anderson. Their results were published by the Geological Survey: Sheet 75 (Hinxman) appeared in 1895 and its explanatory memoir in 1896; Sheet 74 (Hinxman and Anderson) appeared in 1917, but was preceded by the explanatory memoir published in 1915. By far the greater portion of the area is covered by rocks of Moine type, but, in the extreme east, the fringe of the Banffshire Dalradian is included. Parts of four of the Newer Granites of the Highlands outcrop in this area; these are the Cairngorm, Monadhliath, Boat of Garten, and Dorback Granites. They are believed to be post-kinematic; they have no influence on the tectonics of the schists.

The rocks assigned to the Moine Series have been divided into three main lithological groups; namely pelitic, semi-pelitic, and siliceous. In addition to these, there are smaller outcrops of marble, calc-silicate rock, and amphibolite. In this area the semi-pelitic and siliceous rocks greatly predominate over the other types. The principal Dalradian types are /

are graphite-schist, marble, quartzite, mica-schist, and phyllite.

II. LINEATION

Linear structures are of common occurrence in the rocks of this region. The following types are present:- (i) crests of small folds and of boudins, (ii) corrugation and puckering of micas, (iii) preferred orientation of elongated crystals, (iv) trains of crystals, (v) intersection of cleavage and bedding, and (vi) intersection of cleavage and cleavage. At any one locality these are all mutually parallel.

Kinematic analysis is not necessary for determination of tectonic form. It is sufficient to establish that successive profiles resemble one another rather closely, even although they may be spaced at distances, measured in the axial-direction, of several times the amplitude of the folds. This is demonstrably the case on the macroscopic scale; that it is so also on the grand scale is suggested by the parallelism over wide areas of all lineations, and by the fact that, when plotted on a stereographic projection, the normals to bedding and to foliation lie on a great-circle. Thus the plunge of the grand scale structures can be determined from (i) the plunge of the macroscopic structures, (ii) the strikes and dips of bedding and of foliation /

foliation, and (iii) the strike and dip of major contacts where topographic relief is sufficient to allow the form of these to be determined (e.g. between the Spey and the Dulnan).

Lineation in the Mid-Strathspey metamorphics was described by L.W. Hinxman (1896, 1915), and by E.M. Anderson (1915). According to these authors ~~and~~ the lineation is parallel to a. In the descriptions given above of the Grantown-Tomintoul area, to the north of Aviemore, the present writer has attempted to show that the lineation there could not be in the direction of a; on the scale considered, it is perpendicular to the direction of transport, and is therefore b-lineation. The lineation in the Aviemore district has identical characters and kinematic orientation. The writer has shown above that the lineation in the Ord Ban quartzites, near Aviemore, is parallel to the b-kinematic-axis. The lineation found on Ord Ban is typical of that present throughout Mid-Strathspey. Thus the characteristic lineation-direction is b.

This conclusion is of more than local interest. In his masterly exposition of the a-lineation hypothesis, E.M. Anderson (1948, p. 100) recognised what he called "Tummel-type lineation". To define this type of lineation, Dr. Anderson quoted a description which had been given by him in 1915. That description referred to the Mid-Strathspey lineation, and thus one may claim that the region discussed in the present paper is the type-area for "Tummel" lineation.

Dr. /

Dr. Anderson considered (1948, p. 122) that "the only really valid evidence" in support of the hypothesis that lineation is usually parallel to _b_ "seems to consist in Schmidt's observations in the Leoben district and in the Tauern Mountains". He then indicated why he found that evidence unconvincing. Dr. Anderson finally rejected not only the _b_-lineation hypothesis, but even the suggestion that lineation is sometimes _a_ and sometimes _b_. His conclusion was that lineation is parallel to the "shearing direction" (_a_). The writer finds this extreme position surprising. The direction of movement of the great nappes of the Swiss Alps has long been known, and it is a matter of observation that the lineation is usually normal to that direction. As Dr. Gilbert Wilson pointed out in the discussion of Dr. Anderson's paper (p. 126), there is a very considerable body of evidence for the existence of _b_-lineations.

The present writer considers that the "Tummel-type" lineation, as developed in the type-locality of Mid-Strathspey, is a _b_-structure. This conclusion is based on the style of the structures from the macroscopic scale to the grand-scale. It is believed that the genesis of the folds and other tectonic forms present required movement at right-angles to the observed lineation-direction.

III. GENERAL STRUCTURE

In Mid-Strathspey and Strathavon the general trend of the outcrops is north-east - south-west, and the Spey is a longitudinal river in the sense that it is parallel to that trend. One is not, however, entitled to conclude that this direction is parallel, even approximately, to the tectonic trend. The axial-direction of recumbent structures may be normal to the trend of the outcrop-pattern. This, indeed, is the case throughout large areas of Mid-Strathspey and Strathavon where the characteristic tectonic trend is north-west - south-east.

In the Grantown-Tomintoul area the plunge is rather constant at nearly 30° towards the south-east. The Dalradian is structurally above the Moine. Passing at right-angles to the tectonic trend south-westwards into the present area, the amount of plunge lessens and, near Aviemore, the plunge is towards the north-west. Nevertheless, throughout Strathavon the Dalradian overlies the Moine.

The decrease in regional plunge to the south of Tomintoul accounts for the arcuate outcrop-pattern in that area. On approaching the Cairngorm granite from the north the direction of the outcrops swings round from north-east - south-west through north-south to north-west - south-east. This arc, which /

which can be seen on the Geological Survey map at twenty-five miles to the inch, was noted by Hinxman (1896, p. 7). According to Professor Gregory "the curvature of the strike affords a good test of direction [i.e. sense of tectonic transport] . In normal cases a crescentic or curved mountain range is due to pressure from the concave side". Referring to the arcuate outcrops north of the Cairngorm granite, Gregory wrote, "the concavity indicates movement from the E, and the main direction for the whole curve is from the ESE (1931, p. 166).

It is hardly necessary to point out that Gregory's reasoning is correct only if the axis is horizontal, or such a large area be taken that this condition holds on a regional scale. In the case in question the arcuate trend of the outcrops is in no sense a virgation, for it does not correspond with a change in tectonic trend. It is a straight-forward example of the influence on outcrop of change in axial-plunge without change in axial-direction.

Further towards the south-west the plunge becomes horizontal. This is the case in the Kincardine Hills, north of Loch Morlich, from Meall a'Bhuachaille to near Loch Pityoulish South of Aviemore the sense is reversed and the plunge is gently towards the north-west; it decreases from nearly 30° east of Loch Morlich, to about 10° near Aviemore and becomes horizontal when /

when traced across the Monadhliaths to the upper Dulnan.

On the 1948 Geological Survey map on the scale of ten miles to an inch, the suggestion is made that the Spey follows the line of a fault. The evidence for this hypothesis is probably (i) that the Spey is a pronounced topographic feature parallel to other supposed tear-faults, and (ii) that certain beds on the north-west side of the valley appear to be displaced some three miles towards the south-west relative to the beds on the opposite side. The writer is not convinced of the necessity to postulate faulting. It may, however, be relevant to remark that anomalous tectonic directions are found at certain localities close to the river. These localities are Callart Hill, at the south-west corner of Loch Pityoulish; various points on Craigellachie, above Aviemore; and Tor Alvie, east of Loch Alvie. If a tear-fault is present it is certainly younger than the folding. It is possible that drag on this supposed fault might have been responsible for the observed deflections in axial-direction, but the writer considers this to be unlikely.

The form of large-scale structures can be determined only where mappable units have been differentiated. In the present area this has been effected (i) in the neighbourhood of Kincraig, and (ii) towards the eastern boundary of the area, where /

where the Moine and Dalradian rocks are in contact. These will be described in turn.

(i) The Kincraig Series

A belt of pelitic schists and gneisses follows the Spey from Loch Pityoulish to Loch Insh, and these rocks are particularly well exposed on the slopes of Ord Ban above Loch an Eilean, and on An Suidhe above Kincraig. At both these localities coarse-grained marbles, with some bands of calc-silicate rock, amphibolite, and quartzite, are associated with the pelitic rocks. At Loch Insh the outcrop of this belt changes direction abruptly and runs north-westwards across the Monadhliaths to the upper Dulnan. For convenience of reference this pelitic belt is here termed the Kincraig Series; it is analogous to the Grantown Series (Anderson, 1915, p. 27). Like the latter it is considered as a geographical subdivision of the Moine, or of the Dalradian, and in no sense does it compete with these terms in importance.

The curved outcrop of the Kincraig Series was noted by Hinxman and Anderson (1915). "On looking at the map it will be seen that a zone of pelitic and semi-pelitic rocks . . . . can be followed from the Abernethy Forest, east of the Spey, or even - if certain rocks in the Dulnanbridge area [the Grantown Series] be included in this belt - from the extreme north-east corner /

corner of the map [Sheet 74] , to Loch Insh, and thence north-westwards across the Dulnan valley to the north side of Strathdearn. It is also apparent that the general strike of this belt, and of the smaller outcrops of limestone and quartzite conforms roughly in direction to the outline of the major intrusive masses of Strathspey: it will be further noticed that that successive bands of pelitic and semi-pelitic or undifferentiated Moine schist are also bent round to the north-west in a direction approximately parallel to the western boundary of the Monadhliath granite. This correspondence in direction suggests either (1) the introduction of the granite as a huge sill along a pre-existing major fold of the altered sedimentary rocks, or (2) a deflection of the strike of the schists caused by the intrusion of this great mass of plutonic rock" (pp. 12-13).

It cannot be pointed out too often that, unless the fold-axis is horizontal, the strike will, in general, not be parallel to the axial-direction. This geometrical fact is frequently ignored. Over the outcrop of the Kincraig Series the axial-direction is constant, except for one or two exposures referred to above, in a north-west - south-east direction. The plunge is towards the north-west and decreases in amount when traced in that direction. These facts can be read from the data on Sheet 74, and have been confirmed by numerous measurements /

measurements made in the area by the writer. The outcrop of the Kincraig Series is curved for reasons analogous to those responsible for the curvature of the outcrops south of Tomintoul (p. 181). Where rather flat-lying, or recumbent structures are gently plunging, the trend of the outcrops is nearly normal to the axial-direction. This is the case in the Spey valley between Aviemore and Kincraig, and in Strathavon north of Tomintoul. On the other hand if the axis becomes horizontal, each minor fold becomes exaggerated and its trace on flat ground is elongated parallel to the axial-direction. The outcrops between Loch Insh and the Dulnan, and again south of Tomintoul, approximate to this condition.

It is stated in the Memoir (1915, p. 16) that "the general strike of the schists . . . indicates that the pelitic rocks fold round the southern extremity of the Monadhliath granite mass, pass north-eastwards down the Spey valley and appear to pitch out somewhere to the north of Inverdruie". In fact the pelitic rocks do not "fold round" the granite. The curvature of the "general strike of the schists" is due to change in axial-plunge and not to change in axial-direction. It is probable that the outcrop of the Kincraig Series does close to the north of Aviemore, as suggested in the Memoir. The extent of the superficial deposits along the Spey makes it impossible /

impossible to determine the nature and form of the closure. It is however obvious that this north-easterly termination of the Series cannot be explained as a "pitching out" of the pelitic rocks, for the plunge is towards the north-west.

The Kincraig Series is thus a gigantic flat lens enclosed in the Moine granulites. In lithology, form, and structural position it corresponds to the Grantown Series. It should be noted, however, that the change in the sense of plunge implies that the upper side of the Grantown Series lies to the east, whereas that of the Kincraig Series is to the west. It is difficult to avoid the conclusion that these two tectonic units were once united. This would imply that they are gigantic boudins and that their contacts are tectonic and not stratigraphic. Anderson has suggested (1915, p. 30) that the Grantown Series may be part of the Dalradian. If this is correct it would imply that not only the Grantown Series, but the Kincraig Series also is an immense tectonic inclusion of Dalradian in the Moine. This implication would in turn raise the question as to whether other comparable assemblages, such as Kyllachy House limestones and schists, were also tectonic inclusions (cf. Anderson, 1915, p. 30).

(ii) /

(ii) The Moine-Dalradian Relations

A number of quartzite bands cross the eastern part of the area. According to Hinxman (1896, p. 8), "the system of isoclinal folding that has determined the arrangement of the metamorphic rocks in this area has caused what is possibly but a single zone of quartzite to be repeated in a series of parallel bands of varying breadth stretching across the Map; or in isolated lenticular or boat-shaped masses". The writer believes that the relations are more complex. In the following description the tectonic position of each quartzite is considered in turn.

The most easterly of these quartzites is seen in the River Avon, south of Tomintoul. Hinxman traced this band towards the south-south-west across the Muckle Fergie burn, Liath Bheinn, and Creag Mhean, to the Feith Bhait, at the source of the Don, one and a half miles north-east of Inchrory. Its outcrop is enclosed by the graphite-schist - marble assemblage of the Banffshire Dalradian, except in the north where it passes under the Old Red Sandstone outlier of Tomintoul. This quartzite is largely outwith the area studied in detail. In the Muckle Fergie burn both quartzite and graphite-schist plunge gently towards the south. It seems rather probable that the graphite-schist covers the quartzite and separates it from the higher /

higher Geal Charn quartzite, which outcrops two miles south-east of Inchrory. There is, however, insufficient data available to test this suggestion.

The four-mile long gorge of the Ailnack provides a spectacular continuous section nearly perpendicular to the tectonic trend. Three conspicuous quartzite bands are exposed. The first can be traced from near Bridge of Brown, across Tom nan Damh Mora, Carn an Fhir Odhair, Cath Dubh, and Carn Ruadhbhruaich, to the Avon some two miles north of Inchrory. The second terminates at a short distance to the south-east of its outcrop in the Ailnack; towards the north-west it appears to unite with the third Ailnack quartzite. The latter can be followed from the Braes of Abernethy, across Carn Sheilg, the Geal Charns, the Garabhoums, and Drum Loin, to the Avon a mile south-west of Inchrory. For convenience of reference these quartzites are termed the Ailnack Quartzites Nos. 1 to 3 respectively.

To the south-west of the Ailnack No. 3 Quartzite there is yet another quartzite outcrop. This is the Carn Bheur quartzite. Its form cannot be determined with precision because of the extensive deposits of peat on the high tableland north of the Water of Caiplich.

The Muckle Fergie and Ailnack No. 1 quartzites were included by Hinxman as part of what would now be called the Banffshire /

Banffshire Dalradian. The Ailnack quartzites Nos. 2 and 3, and the Carn Bheur quartzite, on the other hand, were grouped with the Cromdale Hills Series (Moine). The writer has already demonstrated the prevalence of tectonic contacts in Mid-Strathspey, and has pointed out that some of the so-called Dalradian quartzites are actually tectonic inclusions of Moine. A glance at Hinxman's map (Sheet 75) is sufficient to show that also in the area considered here, many of the contacts are tectonic.

The Carn Bheur quartzite is not well exposed and accordingly our knowledge of its tectonics is limited. There is no evidence to suggest that there is either an axial culmination or depression at this locality; the available data suggest that the plunge is still gentle towards the south-east as is the case in the Water of Caiplich and in the headwaters of the Allt na-h'Airidhe. This would imply that the Carn Bheur quartzite was enclosed in the more pelitic rocks that are found surrounding it.

It is clear that the Ailnack No. 3 quartzite is the continuation of the Cromdale Hills Series, even although the Dorback granite and the extensive fluvio-glacial deposits near Dorback Lodge effect a separation of the outcrops. In the Tomintoul area the Cromdale Hills Series is separated from the graphite-schist of the Dalradian by the Cnoc Feargan flagstones. This /

This group of mica-schists and phyllites reappears to the south of the Dorback granite and forms the eastern margin of the Ailnack No. 3 quartzite. However, between the Allt Deareaige and the Ailnack, a subsidiary mass of quartzite (No. 2) has broken out of the side of the main No. 3 quartzite, from which it is now almost separated, and is in direct contact with the graphite-schist. This is striking evidence of the degree of <u>décollement</u>.

The Ailnack No. 1 quartzite is a tectonic inclusion. Although in the central part of its outcrop the plunge is locally towards the north-west, it is definitely towards the south-east at the critical northern and southern extremities, i.e. near Bridge of Brown, and in the Avon. This gigantic inclusion is of special interest because it is enclosed partly in the Moine (Cnoc Feargan flagstones) and partly in the Dalradian. It is therefore a question merely of definition whether it should be referred to one Series rather than to the other.

The existence of very large tectonic inclusions makes it impossible to use ordinary stratigraphic principles to determine either structure or sequence. The Muckle Fergie burn quartzite, for example, may well be a great raft of quartzite "floating" in the graphite-schist, and with no direct stratigraphic relation to the Dalradian rocks with which it is now in contact /

contact. It is indeed probable that the majority, if not all, of the mappable contacts are tectonic rather than purely stratigraphic. The absence of mylonite and of other evidence of crushing, and the observed fact that these contacts are generated (in the geometrical sense) by the same axes as are the folds, prove that the differential movement ("sliding") on the tectonic surfaces was syngenetic with the folding.

Conclusions:

One of the most interesting features of the style of the Mid-Strathspey structures is that both siliceous and pelitic lenticular masses, or tectonic inclusions, are found. The tendency for a siliceous layer enclosed in a pelitic environment to develop boudinage is well known. When thoroughly developed, boudinage leads to the formation of lenticular tectonic inclusions; these are more competent than their surroundings. The Grantown and Kincraig Series, on theother hand, are probably less competent (more pelitic) than their surroundings. It has been suggested (see Skerl, 1948, p. 576) that lenticular masses of incompetent material can be formed by tectonic flowage towards fold-hinges. Tectonic thickening may sometimes affect a limb rather than a hinge; it is therefore impossible at the present time /

time to state whether these two Series represent the hinge areas of gigantic and highly deformed folds or not.

LIST OF WORKS REFERRED TO

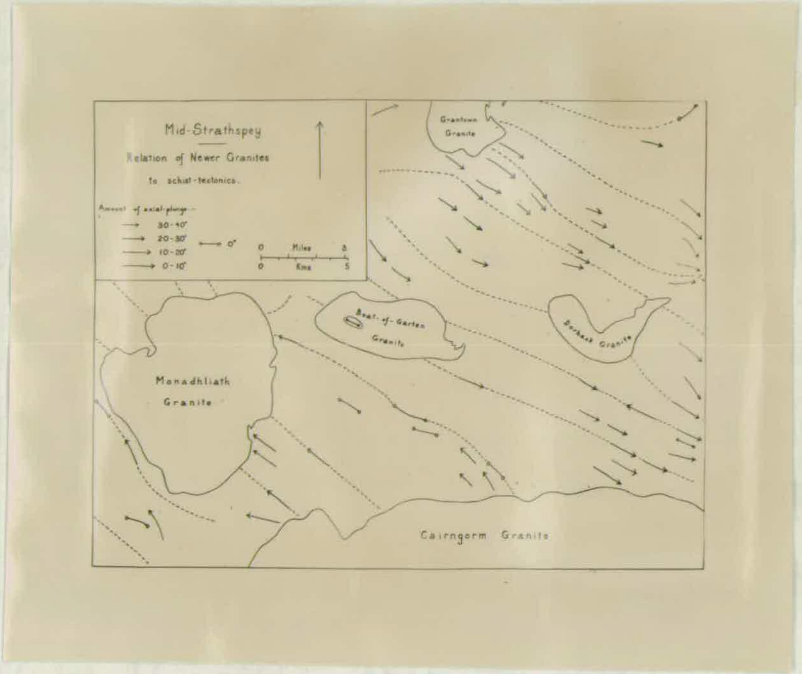
ANDERSON, E.M. 1948. On lineation and petrofabric structure and the shearing movement by which they have been produced. Quart. Jour. Geol. Soc., 104, pp. 99-132.

GREGORY, J.W. 1931. Dalradian Geology. London.

HINXMAN, L.W. 1896. Explanation of Sheet 75. Mem. Geol. Surv. Scotland

HINXMAN, L.W. and E.M. ANDERSON. 1915. Explanation of Sheet 74. Mem. Geol. Surv. Scotland.

SKERL, A.C. 1948. Geology of the Cariboo Gold Quartz Mine, Wells, B.C. Econ. Geol., 43, pp. 571-597.



N.W. – S.E. trends in Mid-Strathspey in relation to Newer Granites.

VII. GRANITE TECTONICS: an outline of the Cloos method of granite investigation.

Since the earliest days of geological research, attempts have been made to map and interpret the structures of bedded rocks Igneous and granitic rocks, on the other hand, are even today usually represented on geological maps as massive bodies without internal structure. Professor Hans Cloos, of Bonn, has pioneered the study of granite tectonics; he has shown that many granites have mappable internal structure, and demonstrated that structure-maps of granitic plutons provide important evidence with regard to the mode of emplacement of these masses. The work of the Bonn school has become widely known not only through Professor Cloos' publications, but by the dispersal of his students throughout the world, and particularly in the United States of America.

The methods employed by Cloos, and some of the outstanding results achieved by his school, have been made available to English-speaking geologists in a monograph by R. Balk (1937). Few granites are structureless; most have either a planar or a linear arrangement of the constituent crystals. By careful macroscopic study of good exposures, it is possible to determine the nature and orientation of these structures. It is often assumed that a parallel arrangement of crystals seen on an exposure-surface /

exposure-surface is the outcrop of a planar structure within the rock; the Cloos school has repeatedly emphasised that such an arrangement may equally well be due to a linear structure. Only careful three-dimensional study of exposures can decide between these possibilities.

Most investigations of this sort have been of plutons where differential movement has taken place between granite and country rock. Many workers have thus come to assume that the structures observed in granitic masses were necessarily due to flowage of liquid magma, and so the terminology has become genetic instead of descriptive (see particularly Balk's monograph). This result is entirely at variance with one of the basic principles of tectonics, viz. elucidation of descriptive geometry must be separated from and must precede discussion of kinematics, dynamics and genesis. One may observe planar or linear arrangements of crystals within a rock, but more evidence is required before such arrangements should be described as "flow planes" or "flow lines".

An important advance was made in 1949 when Dr. Gerhard Oertel, at the writer's suggestion, prepared a structure-map of the northern part of the Loch Doon pluton. It was already known that both planar and linear arrangements of crystals can exist together in a single rock, and, moreover, that in such a case the /

the lineation is not necessarily in the plane: but the geometry of these compound structures had never been analysed. Apparently no one had appreciated that ~~such with~~ such structures show more than one direction of preferred orientation of crystals on a random exposure-surface. Dr. Oertel demonstrated that it is possible to map the disposition of a pair of nearly vertical planes within the plutonic rock; these planes are defined by preferred orientation of tabular plagioclase crystals.

Dr. Oertel's demonstration that, in favourable circumstances, it is possible to determine more than one direction of preferred orientation on a rock-surface is of great significance for the study of complex structures. A systematic discussion of this matter is given in the following section.

REFERENCES

BALK, Robert. 1937. Structural Behavior of Igneous Rocks; with special reference to interpretations by H. Cloos and collaborators. Mem. 5, Geol. Soc. Amer., pp. 177.

OERTEL, Gerhard. 1950. Discussion on Paper by D.B. McIntyre. Abstr. Proc. Geol. Soc. London, No. 1457, pp. 31-33.

VIII. A MACROSCOPIC METHOD OF FABRIC ANALYSIS

Jointly with R.H. CLARK

(To be published in the American Journal of Science)

ABSTRACT

The study of a rock is not complete unless the nature and orientation of its fabric have been determined. The whole fabric of a rock cannot be determined without the use of the universal stage, for the crystal lattices may have a preferred orientation which cannot be detected macroscopically. For this reason many petrologists, lacking the necessary apparatus, make no attempt to analyse the fabrics of the rocks which they are investigating. The object of this paper is to describe a rapid and accurate method of macroscopic fabric analysis that is applicable to a large variety of rocks, and that requires no complex equipment; indeed, it is often possible to use the method directly in the field. If the lattice fabric can be detected only by optical methods, the universal stage must, of course, be used. The danger of reaching erroneous conclusions by using insufficient data is pointed out. In view of the simplicity of the method and its widespread applicability, it is suggested that it should be used to complete routine petrological examination of a rock.

A. NOMENCLATURE

Discussion of the terminology will be found in Knopf & Ingerson (1938), Fairbairn (1949), and Clark & McIntyre (1951). For the purposes of this paper, the following definitions are adopted:-

The /

The <u>fabric</u> of an object is described by all the spatial data (fabric elements) which it contains. A rock is said to have a <u>simple fabric</u> when it contains a single fabric element (e.g. lineation or plane). A rock is said to have a <u>compound fabric</u> when it contains more than one fabric element (e.g. lineation + plane; 3 planes; etc.).

A <u>face</u> is an exposure-plane, either natural or artificial.

A <u>trace</u> is the intersection of a fabric element with a given plane.

<u>Pitch</u> is the angle, measured in some specified plane, between a lineation, or a trace, and the horizontal.

<u>Plunge</u> is the vertical angle between a lineation, or a trace and the horizontal.

<u>Trend</u> is the strike of the vertical plane containing a lineation or a trace.

<u>In this paper the writers are concerned only with the geometric analysis of the fabric</u>; <u>the genesis of the fabrics discussed is not dealt with</u>. For example, the origin of even a "simple" fabric is commonly far from simple.

B. /

B. INTRODUCTION

In the course of a structural investigation of the macro-porphyritic basalts of Arthur's Seat, Edinburgh, one of the writers (R.H.C.) encountered considerable difficulty in determining whether the fabric was linear or planar. The method used was that developed by Hans Cloos (see R. Balk, 1937). The direction of preferred orientation of the macro-phenocrysts is determined in the field on two or more faces of an outcrop, and the nature and orientation of the structure responsible for these traces is estimated by eye. Provided that only a planar structure is present, this method is satisfactory, being both simple and reasonably accurate. However, in localities where lineation may be present, visual determination of the structure is not practicable unless the exposures are unusually perfect.

Balk (1937, pp. 139-155) suggested, although in different terms, that strength of trace might be used as an aid to fabric analysis. Unfortunately, in many outcrops degree and nature of weathering play an important role in determining the apparent strength of a trace. Moreover, in the field, the number of suitable faces is rarely sufficient for the fabric to be determined by eye with complete confidence.

If traces can be measured with reasonable accuracy on a /

a minimum of three suitable, non-parallel faces, although a larger number is to be preferred, the nature and space orientation of the structure responsible can be determined with the aid of a stereographic projection. Should sufficient suitable field exposures be lacking, an oriented hand specimen can be collected, and the required number of faces cut or ground upon it. The fabric can then be determined by analysis of the traces observed on these faces.

C. THE USE OF THE STEREOGRAPHIC PROJECTION[1]

Fabric may be planar, linear, or cylindroidal, but the last is rarely developed on so small a scale that the curvature of the traces is noticeable in a single hand specimen or small outcrop, except in the case of metamorphic rocks. For this reason, only linear and planar fabrics are considered here. An interesting example of a cylindroidal fabric, developed on a macroscopic scale in an igneous rock, has been described by Tomkeieff (1946).

1. /

---

[1]Like all structural geologists who use the stereographic projection, the writers owe a debt to Professor Bruno Sander, the pioneer of modern fabric studies. Readers unfamiliar with the use of the projection should refer to the useful article on the subject by W.H. Bucher (1944).

1. <u>Simple Fabrics</u>

If the structure is planar, the traces on random faces are the intersections of the planes with these faces. In this case all traces have one common feature: viz: they lie parallel to the structure planes. Any two traces define the space orientation of the planar arrangement; the remainder must all lie in this plane. Thus in a stereographic projection, the poles of the traces must lie upon the great circle representing the planar structure.

If the structure is linear, the traces are the projections of the lineation upon the faces studied; i.e., any trace is the intersection of the exposure face with the plane which contains the lineation and which is normal to the exposure face. If the orientations of the faces and traces are known, the great circles representing these normal planes are easily constructed on the projection. The point at which these great circles intersect is the pole of the lineation (Lowe, 1946).

To determine the nature and orientation of the fabric elements in an outcrop or hand specimen, it is necessary to know the strike and dip of each face, and the pitch of the trace upon it. These data are plotted on the projection. If the poles of the traces lie upon, or are close to a great circle, then the fabric /

fabric is probably planar (fig. 2). The great circle may be constructed and its strike and dip read directly from the projection.

Should the traces not lie on a great circle, lineation may be suspected, and the normal planes referred to above must be constructed. For each exposure surface, and for each trace, the required normal plane is represented by the great circle containing the pole of the trace and the pole of the face on which that trace was observed. If these great circles, representing the normal planes, intersect at or near a point, then the fabric is linear and the trend and plunge of the lineation can be determined (figs. 3 and 4).

Example:

An oriented specimen of macro-porphyritic basalt (fig. 3) had six faces cut and ground upon it, and traces were marked upon each face. The following orientations of faces and traces were recorded:

Face	Strike	Dip	Pitch of Trace
1	-	0°	106° E of N (trend)
2	168°	85°E	45°N
3	45°	90°	44°SW
4	157°	80°W	46°N
5	53°	85°SE	50°SW
6	134°	18°SW	36°NW

Plotting /

Plotting procedure: A sheet of tracing paper is laid over a Wulff stereographic net; centre and north points are marked by a cross and an arrow respectively.

Face 1. As this face is horizontal the normal to it is vertical, and its pole lies at the centre of the net. The pole of the trace on this face is at the circumference, 106° east of north.

Face 2. The tracing paper is rotated until the north arrow on it is 168° in an anticlockwise direction from the north point of the net. The north-south meridian on the net then gives the strike of the face, and the pole of the face-normal lies on the east-west diameter, 5° from its eastern end. The projection of the face itself is the great circle 90° distant measured along the east-west diameter. The trace lies on this great circle, 45° from its north-western extremity. The remaining face-normals and traces are plotted in a similar way.

Analysis of the fabric: No great circle can be drawn through the poles of the traces; hence the fabric is not planar. Normal planes must now be constructed. The paper is rotated until face-normal 1 and trace 1 lie on the same great circle on the underlying net. This great circle, which in this case is a straight-line, is the required normal-plane. This procedure is repeated for each pair of faces and traces. The six normal planes /

planes thus constructed intersect nearly at a point. Hence the fabric is linear, and the point of intersection represents the pole of the lineation. Its trend is given by the diameter passing through the point. If the paper is rotated until the pole of the lineation lies on the east-west diameter of the net, the amount of plunge is given by the angular distance from the circumference measured along this diameter.

Result: Lineation, trend 106°; plunge 30° down to west.

The traces produced by a linear fabric may chance to lie near a great circle. This is particularly likely to happen if several exposure surfaces are nearly parallel to the lineation. For this reason normal planes should always be constructed, as a "test" for lineation, even when the existence of a planar structure seems obvious. If any ambiguity should remain, it is necessary to cut control faces with selected orientations, e.g. one in the suspected plane and another normal to the possible lineation.

The stereographic projection should be regarded as a "structural tool" rather than as an infallible geometric construction. On completing the construction, the specimen must be re-examined to ensure the absence of traces on faces parallel to a planar or normal to a linear arrangement. Traces nearly normal /

normal to a lineation should show random orientation of platy minerals, and cross-sections of prismatic crystals. Surfaces almost parallel to a purely planar structure should contain a large proportion of flat surfaces of platy crystals, with a random orientation of their long axes, and/or the long axes of prismatic crystals with random orientation.

The projection furnishes information as to which faces can be expected to be unreliable. If lineation has been correctly determined, then, unless some of the crystals are unusually transparent, poles of faces on which traces have been measured will not lie near the pole of the lineation; the latter will lie close only to those poles representing faces on which no trace could be found (fig. 4, faces 2 and 5). Conversely, traces willbe strongly developed on faces whose poles are 90° from the pole of the lineation. With a planar fabric, on the other hand, the nearer the pole of the face lies to the great circle of the fabric plane, the stronger the trace upon that face will be.

It may be remarked here that faces cut upon a hand specimen are analogous to perfect natural exposures. The relative strength of the traces on them depends solely on the nature of the fabric and its orientation with respect to the observation surfaces. The effect of directed weathering has been eliminated.

2. /

2. Compound Fabrics

In some specimens of certain rocks, particularly metamorphic rocks, granites, and micro-porphyritic basalts, more than one trace may be clearly recognised on some or all of the faces. In such cases the fabric is compound. Two traces may be produced by two lineations, two planes, or a plane with a lineation either on or off it, and still more complex combinations occur; but fabric analysis is still comparatively simple if a sufficient number of measurements are accurately made and carefully plotted. Two traces on a single face cannot both be produced by the same fabric element, and this most important point must be kept in mind while the determination is being made.

Example 1. Fig. 7.

A specimen has six faces, of which five display two traces and the sixth, one. The poles of the eleven traces fall into two groups. Six, each from different faces, lie upon one great circle, and six upon another great circle. Intersections of normal planes are widely scattered. The fabric therefore consists of two planes. The face yielding only one trace, face 3, contains the line of intersection of the two planes.

Example /

Example 2. Fig. 6.

A specimen has six faces, each with two distinct traces upon it. When the twelve traces are plotted it is found that the poles of six of the traces, no two of which are from the same face, lie near a great circle. The normal planes containing these six traces intersect at widely scattered points, but the normal planes which contain the other six traces (1, 2, 3, 4, 5', 6') intersect near a point. Hence the fabric consists of a plane and a lineation. One of the traces observed on each face was that of the plane; the other, that of the lineation. In this case, the lineation is normal to the plane.

For a case where lineation lies in the plane, see fig. 5.

Example 3. Fig. 8.

A specimen has seven faces. Four of these contain two traces; the remaining three contain one single trace. It is found that no great circle can be drawn through the poles of any seven traces from different faces. The eleven normal planes appear at first to intersect at random on the projection, but, on careful examination, it is found that seven of them intersect near one point, and six near another point. Each of these groups comprises normal planes which contain traces from different /

different faces. Therefore the fabric consists of two lineations.

D. PRACTICAL DETAILS

1. Field Exposures

When it is desirable to work directly from field outcrops, strikes and dips of surfaces must be measured with reasonable accuracy. If faces are smooth, this is simple, but, when they are uneven, an instrument such as that shown in fig. 1 is useful. The pitch of a trace is best measured with a protractor and a small spirit level.

2. Collection of Oriented Specimens

A suitable specimen should be broken from the outcrop and fitted back into place. North is indicated by an arrow marked upon the upper surface. Two horizontal lines, drawn with the aid of a small spirit level upon two steep surfaces at suitable angles to each other, complete the orientation. The marks should be made permanent as soon as possible by cutting them into the specimen with a diamond wheel.

3. Facing of Specimens

Much time is saved if, where possible, faces are cut instead of ground. A horizontal face is not necessary; five or six random, non-parallel surfaces are all that are required. Unless the rock is fine-grained the faces need not be polished. Strike and dip, with respect to the face nearest to the horizontal plane, is measured using the instrument shown in fig. 1, with its spike removed.

4. Etching of Faces

The ease and accuracy with which traces may be determined depends upon the degree of visibility of the oriented minerals. Dark minerals are very easily seen in leucocratic rocks; but in melanocratic rocks, such as basalt, phenocrysts of feldspar and ferromagnesian minerals are barely discernible against the dark groundmass. If such specimens are immersed for some minutes in a moderately dilute solution of hydrofluoric acid, the large crystals become clearly visible. The small crystals of the groundmass are attacked relatively rapidly by the acid, and a grey colour results. Ferromagnesian phenocrysts remain black. The large feldspars become coated with transparent silicic acid; the black rock beneath gives them a dark appearance. Thus, if the rock is washed and kept wet, all phenocrysts appear dark against a light grey background. Traces may /

may be marked with considerable accuracy. If the specimen is allowed to dry, the silicic acid gel on the feldspars forms a white powder (SiO_2), and only the ferromagnesian minerals remain clearly visible. Hence drying should not be permitted until fabric determination is complete, unless, of course, no feldspar phenocrysts are present, e.g. in Scottish Carboniferous basalts of Craiglockhart type.

5. Trace Determination

In many cases, preferred orientation of crystals on a particular face is obvious at a glance, and the trace or traces may be drawn at once with considerable accuracy. When some of the crystals are transparent, the others are often seen in three dimensions. Sometimes the direction is not so clear, and considerable care must be exercised. The face should be observed from all directions; if doubt remains, no trace should be recorded. Fine-grained rocks, such as micro-porphyritic basalts, should be lightly etched and then examined under strong light with a hand-lens or binocular microscope of low power. If the rock is very fine-grained, oriented sections may be necessary.

6. Relating the fabric to the horizontal

When the orientation of the fabric has been determined with respect to a non-horizontal face, the true strike and dip of /

of this face must be found so that the orientation of the fabric can be related to the horizontal plane. This is most simply accomplished with an instrument similar to that designed by Knopf and Ingerson (1938, Plate 20, fig. 2). This may be constructed with two pieces of three-ply and the universal joint of a camera tripod. The specimen is clamped on the upper board with elastic bands, and the board moved until the horizontal marks on the specimen are restored to the horizontal. Strike and dip of the board are measured, and the appropriate correction applied to the projection.

E. CONCLUSIONS

It is possible to obtain with considerable precision the nature and space orientation of the fabric of any rock which contains a definite and continuous structure. If the fabric is indistinct, so also willbe the traces. As the only possible source of significant error need be the determination of the traces, it is obvious that this should be carried out with great care.

F. ACKNOWLEDGMENTS

Interest in macroscopic methods of fabric analysis was greatly stimulated in Edinburgh by the visit, during 1948-49 of Dr. Gerhard Oertel of the University of Bonn. It was in the course of structural studies undertaken as a result of this interest, that the method described here was evolved. The writers wish to record their indebtedness to Dr. Oertel for introducing them to this aspect of tectonics. They also wish to thank Mr J. Dennis and Mr D.J. Hooton for several valuable suggestions which have been incorporated in the paper.

G. LIST OF WORKS TO WHICH REFERENCE IS MADE

BALK, R. 1937. Structural Behavior of Igneous Rocks. Geol. Soc. Amer. Memoir 5, pp. 177.

BUCHER, W.H. 1944. The Stereographic Projection, a Handy Tool for the Practical Geologist. Jour. Geol., lii, pp. 191-212.

CLARK, R.H. and D.B. McINTYRE. 1951. The Use of the Terms Pitch and Plunge. To be published in the Amer Jour. Science.

FAIRBAIRN, H.W. 1949. Structural Petrology of Deformed Rocks. Addison-Wesley. pp. 344.

KNOPF, E.B. and E. INGERSON. 1938. Structural Petrology. Geol. Soc. Amer. Memoir 6, pp. 270.

LOWE /

LOWE, K.E. 1946. A Graphic Solution for Certain Problems of Linear Structure. Amer. Min., xxxi, pp. 425-434.

TOMKEIEFF, S,I. 1946. Magmatic Rolls. Nature, clviii, pp. 420-1.

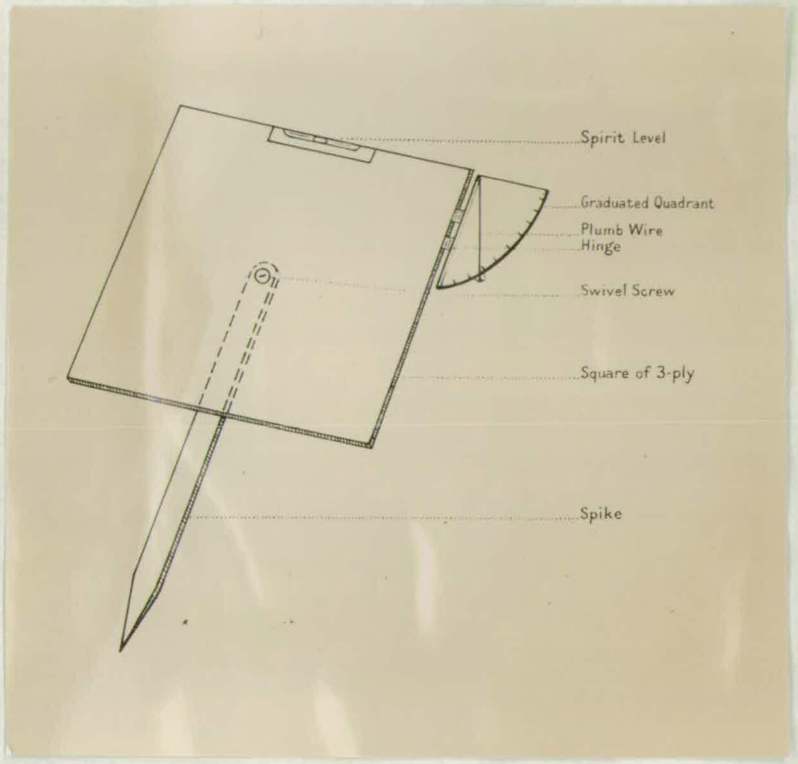


Fig. 1.

Apparatus to assist field-determination of fabric.

N.B. Figs. 2-9 represent lower hemisphere projections.

$\odot_1$ Pole of face; $\otimes_1$ Trace on that face.

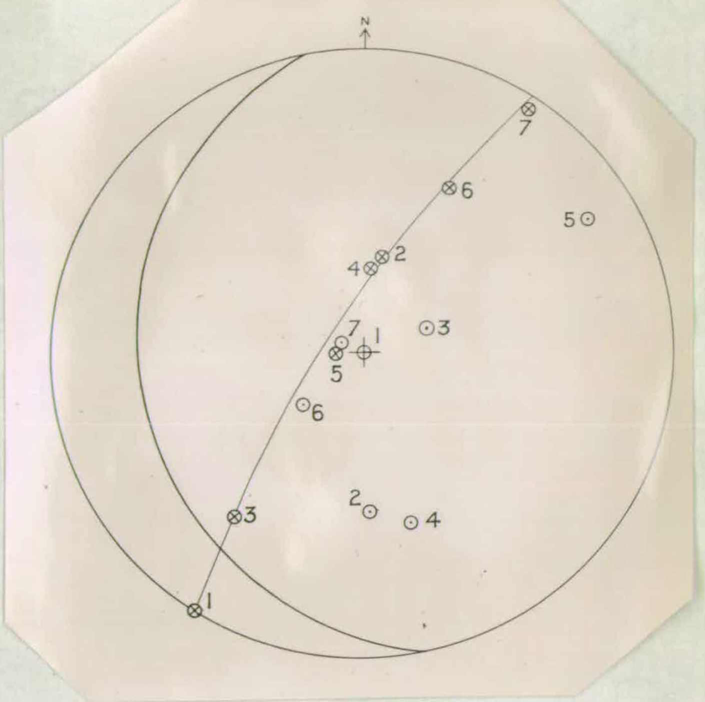


Fig. 2. Single plane. Macroporphyritic basalt of Dunsapie-type, Lion's Haunch, Arthur's Seat.

For convenience, the traces were plotted with reference to face No.1. This face strikes N 62° E and dips 68° to the south-east. The corrected orientation of the planar structure, relative to the horizontal, is shown by the heavy great-circle.

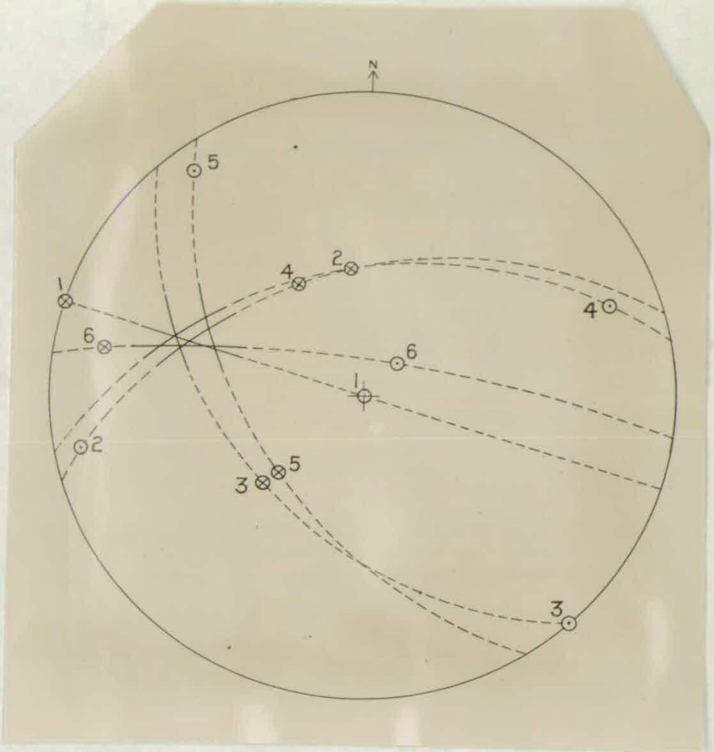


Fig. 3. Lineation. Macroporphyritic basalt of Dunsapie-type, Lion's Haunch, Arthur's Seat.

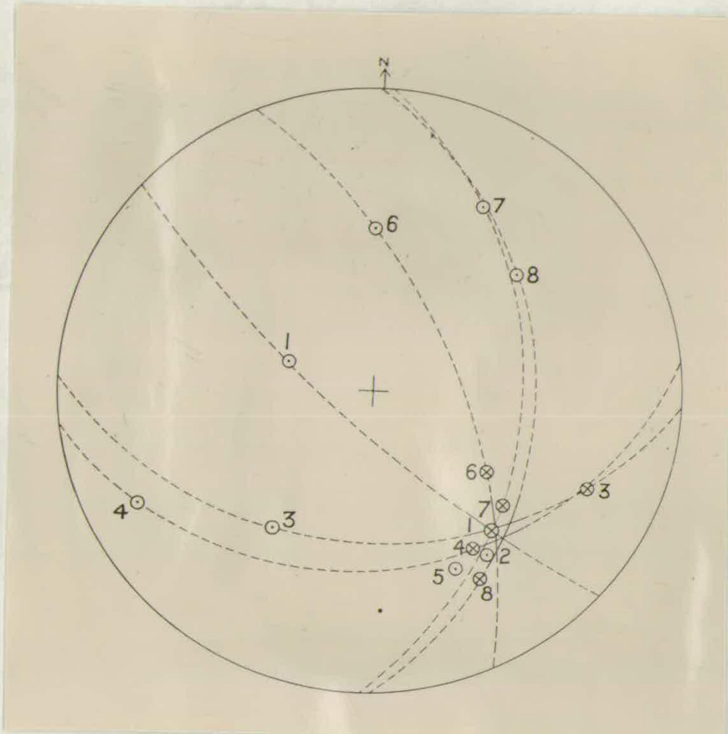


Fig. 4. Lineation. Amphibolite ("Lewisian"), An Sguman, Fannich. The absence of traces on faces 2 and 5 is to be expected, for these are almost normal to the lineation.

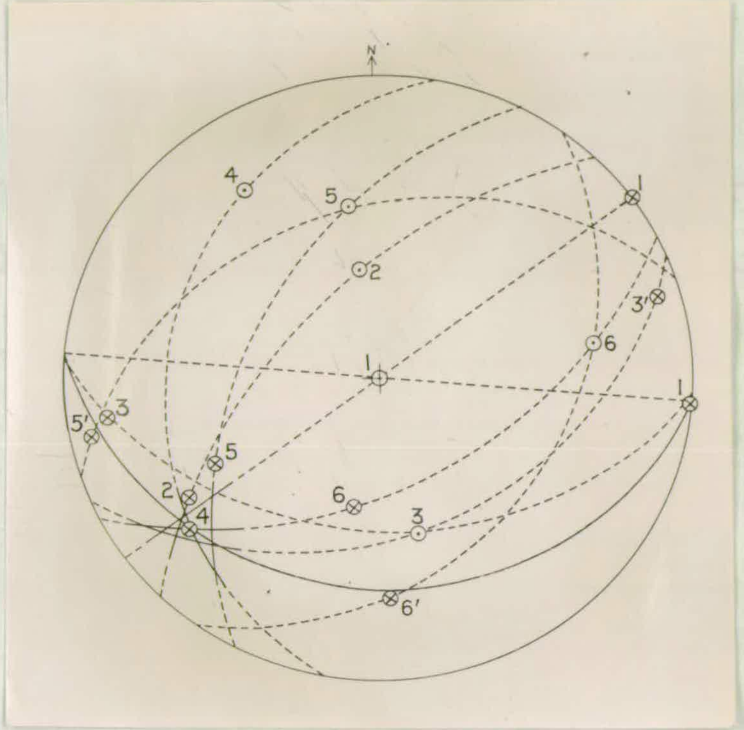


Fig. 5. Planar structure with lineation on the plane. Microporphyritic basalt of Jedburgh-type, Whinny Hill, Arthur's Seat.

Normal planes have been constructed through all traces; those through traces produced solely by the planar structure intersect at random. Faces 4 and 2 contain the lineation; hence the traces of plane and lineation coincide.

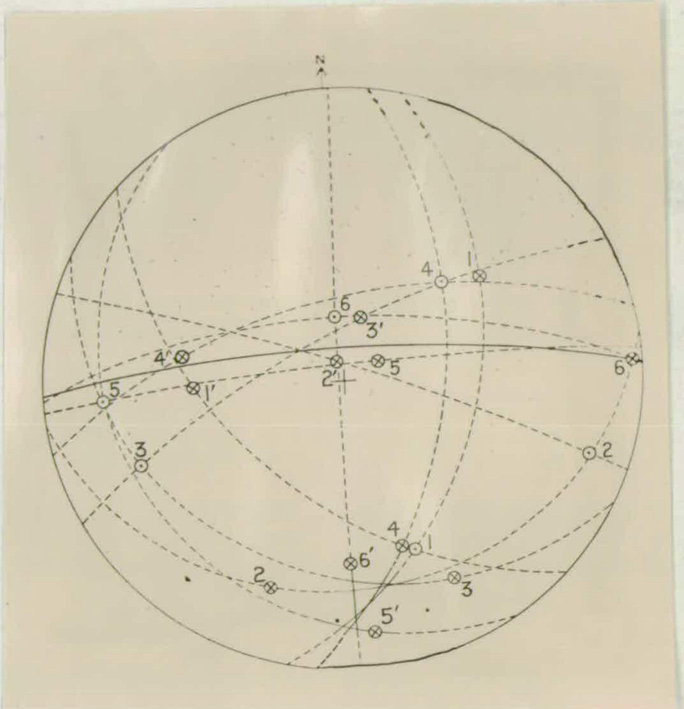


Fig. 6. Planar structure with lineation normal to plane. Hypersthenic rock, Loch Riecawr, Loch Doon.

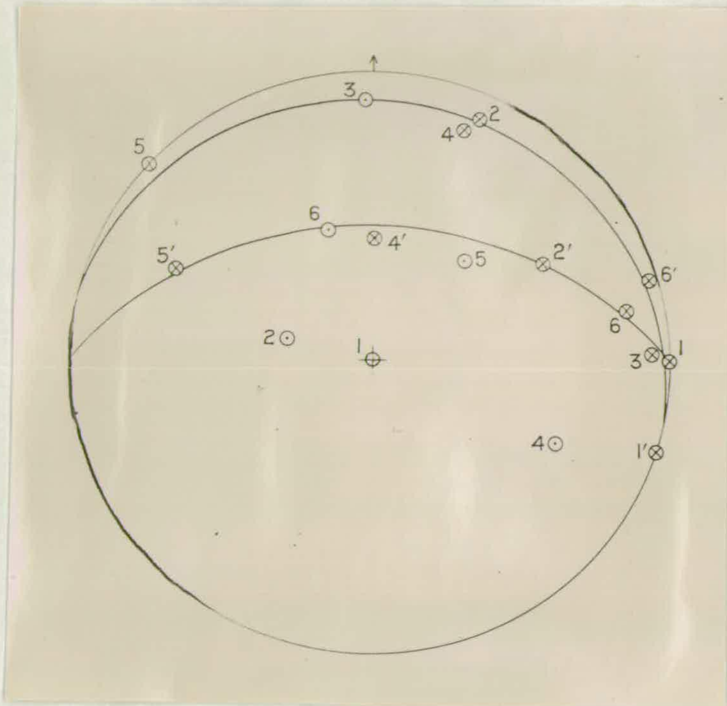


Fig. 7. Two Planes. Schist (Moine), Sgurr Mor, Fannich. Specimen not oriented.

The single trace on face 3 is the line of intersection of the two planes. The trace of the flatter plane is visible on face 1 because this plane is so strongly developed.

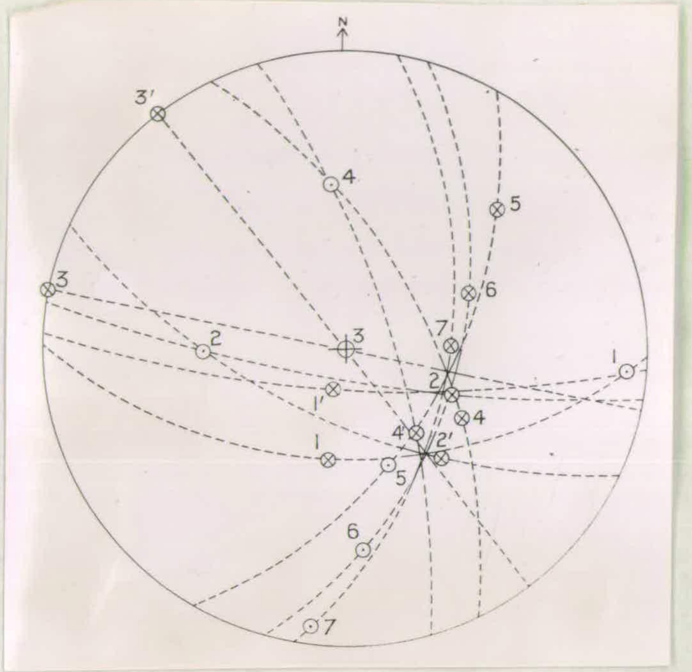


Fig. 8. Two lineations. Porphyritic granodiorite, Glen Fyne.

Traces were determined by observing preferred orientations of ferromagnesian crystals. Faces 6 and 7 each display only one trace, for these faces contain the normal to the plane of the two lineations. Face 5 is nearly normal to one of the lineations; the single trace on this face is that of the other lineation.

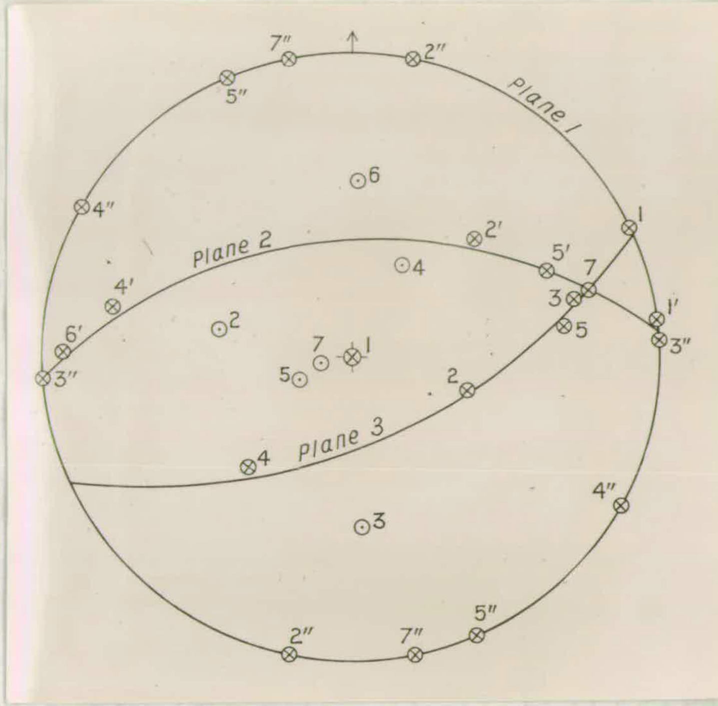


Fig. 9. Three planes. Graphite-schist (Dalradian), Glen Livet. Specimen not oriented.

The fabric was determined from the traces on faces 1 to 6. Subsequently the space orientation of a face which would contain the line of intersection of the two inclined planes (2 and 3) was predicted from the projection. This face (No. 7) has been ground; one of the traces on it lies on the intersection of planes 2 and 3. It may be noted that planes 2 and 3 are very nearly symmetrically inclined with respect to plane 1.

IX. THE STRUCTURE OF THE GARABAL HILL PLUTON

A. INTRODUCTION

The Garabal Hill - Glen Fyne pluton outcrops to the west of the head of Loch Lomond. It is one of the best known of the Caledonian "Newer Granites"; its petrology has been exhaustively studied by Dakyns & Teall (1892), Wyllie & Scott (1913), and Nockolds (1941). The early attention directed to the complex by the publication of Dakyns & Teall's classical paper, ensured that reference was made to it in many petrological text-books from Harker's "Natural History" onwards.

Nockolds mapped the distribution of the diverse plutonic rocks, and investigated their petrology in detail. He concluded that "crystallization-differentiation has been responsible for the rocks of the complex and that this, coupled, for certain types, with contamination by earlier igneous or sedimentary matter, is fully competent to explain every rock type so far observed. There is no evidence of differentiation in situ and the process must have operated in depth." (p. 507). Nockolds postulated that there had been at least ten successive intrusions of progressively more acid magma.

Many petrologists accept the Garabal Hill pluton as a typical example of a complex emplaced by successive intrusions arising /

arising from a magma differentiating in depth. Indeed Nockolds has attempted to use this interpretation of the pluton as a key to Caledonian petrogenesis (1946). However the writer has recently demonstrated that the large potash-feldspar crystals in the Glen Fyne granodiorite, which forms the major part of the present outcrop of the pluton, are porphyroblasts and not phenocrysts as had been supposed by previous workers. This raises serious doubt of a purely magmatic origin of the pluton.

<u>Extract from Abstr. Proc. Geol. Soc. No. 1468, 22nd December 1950.</u>

Dr. D. B. McIntyre, F.G.S., exhibited and commented on a number of specimens illustrating the porphyroblastic character of the large potash-felspar crystals in the Garabal Hill–Glen Fyne pluton. The pluton, situated to the west of the head of Loch Lomond, had been described to the Society by Dr. S. R. Nockolds (1941). Its western and principal part consists of "porphyritic" granodiorite containing numerous dioritic inclusions. The latter frequently enclose porphyroblasts of potash felspar. "There seems to be no escape from the conclusion", wrote Dr Nockolds (p. 479), "that these porphyroblasts have grown in the solid xenolith with the aid of material introduced by the granodiorite magma." The large potash-felspar crystals in the granodiorite, on the other hand, were interpreted as phenocrysts and not as porphyroblasts: e.g. "In view of the fact that several investigators have found microcline phenocrysts in similar rocks to be of very late, or even replacement, origin it is perhaps as well to emphasize that here they started to develop at a comparatively early stage in the cooling history of the magma" (pp. 477–8).

The similarity between the " phenocrysts " in the granodiorite and the porphyroblasts in the inclusions, is striking: (1) both occur as euhedral individuals of comparable size and form; porphyroblasts nearly three inches long have been observed in the inclusions in the tunnel above Butterbridge; (2) in both rocks potash felspar occurs also interstitially, and, indeed, the large crystals are often optically continuous with the neighbouring potash felspar of the groundmass; (3) " phenocrysts " and porphyroblasts alike contain numerous inclusions of all the other minerals (plagioclase, quartz, biotite, hornblende, sphene, magnetite, apatite); and (4) rapakivi structure is at least as common in the porphyroblasts as it is in the " phenocrysts ".

From these facts it is concluded that the large potash-felspar crystals in the granodiorite have the same origin as those in the inclusions. Indeed, examples have been observed in which the large crystals lie athwart the boundary of inclusion and granodiorite. The classic " argument of the big felspars ", to which attention has been drawn by Professor Read (1944) and Professor Holmes (1945), would appear to be relevant to the granitic rocks of the pluton. Additional proof is furnished by the fact that, although the smaller crystals of the " porphyritic " granodiorite usually have a complex fabric, the large potash-felspar crystals are not aligned.

The speaker acknowledged the assistance he had been given by Mr T. P. Mayo, the engineer in charge of the tunnel driven through the " porphyritic " granodiorite as part of the Loch Sloy hydro-electric scheme.

References :—

HOLMES, A. 1945. Natural history of granite. *Nature*, clv, p. 412.
NOCKOLDS, S. R. 1941. The Garabal Hill–Glen Fyne igneous complex. *Q.J.G.S.* xcvi (for 1940), pp. 451–511.
READ, H. H. 1944. Meditations on granite: Part two. *Proc. Geol. Assoc.* lv, pp. 45–93.

Dr. S. R. NOCKOLDS sent the following comment on the exhibit :—

" In 1948, Mitchell and I determined the trace element content of the large phenocrysts of potash felspar and of the bulk potash felspar in the granodiorite and proved that the large crystals commenced their crystallization earlier than the potash felspar of the matrix (*Trans. Roy. Soc. Edin.* lxi, table 21, p. 571). The question of their porphyroblastic character does not, therefore, arise, but the exhibit should be of value as a warning of the dangers involved in interpreting textural relations and similarities."

In a written reply Dr. MCINTYRE said : " Dr. Nockolds has compared the amounts of certain trace elements in the ' phenocrysts ' on the one hand and in the bulk potash felspar of the granodiorite on the other. This comparison bears only indirectly on the exhibit, in which attention is drawn to the similarity of the ' phenocrysts ' in the granodiorite to the porphyroblasts in the inclusions. Dr. Nockolds has deduced theoretically that early potash felspar should contain more Ba and Sr and less Rb than late potash felspar. Dr. Mitchell's determinations are as follows :—

	Bulk K-felspar	' Phenocrysts '
Sr	2000	2000
Ba	5000	8000
Rb	500	400

Dr. Mitchell pointed out (1948, p. 537) that the error in these figures, which are in parts per million, may be ± 50 per cent. The available data are therefore insufficient for the application of Dr. Nockolds's criterion of relative age."

B. PRESENT WORK

When he visited the pluton in the early summer of 1950, in the company of Mr R.H. Clark, Dr. B.C. King and Dr. H. Rutledge, the writer was impressed by the well-developed fabric of the plutonic rocks exposed on the high ground between the River Arnan and Strath Dubh-Uisge. Accordingly he returned to the ground shortly afterwards and prepared a structure-map of the pluton following the methods of the Cloos school (Plate 8). In the field it proved impossible to map the internal structures of either the ultrabasic rocks or the porphyroblastic granodiorite. Some months after this mapping had been completed, Mr Clark and the writer evolved the macroscopic method of fabric analysis outlined in the preceding section. In order to control the writer's field-mapping by this more refined technique, a number of oriented specimens were collected in Glen Fyne and in the River Arnan. It was confirmed that the granodiorite exposed in the River Arnan had in fact a planar structure as shown on Plate 8 ; the porphyroblastic granodiorite of Glen Fyne proved to have a compound fabric consisting of two lineations (fig.X.8). By collecting a large number of oriented specimens it may ultimately prove possible to determine the internal structure of the Glen Fyne granodiorite.

In /

In an attempt to discover the nature of the tectonic environment of the pluton, the writer attempted to analyse the published data one-inch maps published by the Geological Survey. Unfortunately the data available were insufficient for this purpose; this was particularly true of the area to the north-east of the pluton. The area involved covers more than 500 square miles, and as much of this is isolated and difficult of access, it is clear that a complete study of the region will be a prolonged task. However, it is believed that the evidence already gathered is sufficient to enable certain provisional conclusions to be reached; the new observations are therefore set out on Plate 9 .

C. CONCLUSIONS

As the internal and external structure-patterns are at variance, it is evident that the pluton is, at least in part, intrusive into the surrounding metamorphic rocks. On the other hand the amount to which the external structures are deflected on approaching the pluton suggests that the necessary space was not gained entirely by pushing aside and upwards of the country rocks.

Although there was undoubtedly differential movement between the plutonic and country rocks, the internal structural pattern /

pattern shows very clearly that the rocks of the pluton moved as a whole. The hypothesis of successive intrusions appears to be definitely disproved.

It may be observed that, to the north-west of the pluton, the axial trend-lines are convex towards the north-west, whereas, to the south-east, they are directed NE-SW. The writer believes that this is likely to be an original character of the metamorphic complex. It is even probable that it was the existence of this structure that controlled the location of the pluton.

D. LIST OF WORKS TO WHICH REFERENCE IS MADE

DAKYNS, J.R. & TEALL, J.J.H. 1892. On the Plutonic Rocks of Garabal Hill and Meall Breac. Quart. Jour. Geol. Soc. 48, pp. 104-121.

NOCKOLDS, S.R. 1941. The Garabal Hill - Glen Fyne Igneous Complex. Quart. Jour. Geol. Soc., 96, for 1940, pp. 451-511.

________ 1946. The Order of Crystallization of the Minerals in some Caledonian Plutonic and Hypabyssal Rocks. Geol. Mag., 83, pp. 206-216.

WYLLIE, B.K.N. & SCOTT, A. 1913. The Plutonic Rocks of Garabal Hill. Geol. Mag., dec. 5, 10, pp. 499-508, 536-545.

X. A GENERALISED STRUCTURE-MAP OF THE SCOTTISH HIGHLANDS

The general trend of outcrops in the Scottish Highlands is roughly NE-SW, i.e. approximately parallel to the strike of the Moine thrust-plane. Many geologists have argued from this that folding and thrusting were syngenetic. The fallacy of this argument will be obvious from the discussions in the preceding sections, where examples are given, from both sides of the Great Glen, of regions where the general strikes are very oblique to the axial-trends.

For several years the writer has been collecting data for the preparation of a structure-map of the Scottish Highlands. The area is very large and much of it is either very inaccessible or badly exposed; thus the present conclusions are to be considered provisional. Nevertheless certain broad aspects of Highland tectonics seem to emerge even at this stage of the work and for this reason the map, Plate 10 , has been included in this thesis.

The directions given on the map are of two kinds, viz. (1) vertical strikes recorded on the one-inch maps of the Geological Survey, and (2) axial-trends determined by the present writer. In some cases numerous field-measurements have been averaged /

averaged to give a single symbol on the map; but in many areas only scanty information is available.

An approximately NE-SW trend is confined to three main areas: (1) from Kintyre north-eastwards beyond Fort William probably to the Spey valley; (a) east-nerth-eastwards from Loch Lomond along the southern edge of the Highlands almost to Aberdeen; and (3) the south coast of the Moray Firth. The central part of the Grampians, from near Dalmally to the coast north of Aberdeen, is a region of great complexity; it appears to consist of a number of great arcs, convex towards the south-west.

With the exception of the great migmatite complex of south-east Sutherland, where there may have been extensive mobilisation, the structure of the Highlands between the Great Glen and the Moine Thrust is relatively simple. The general pattern agrees with that given by Cole Phillips (Q.J.G.S., 1937, 93, fig. 5). The general trend is NW-SE, nearly normal to the strike of the Moine Thrust.

This work has an important bearing on the hypothesis of tear-faulting along the line of the Great Glen, but the writer feels that still further work is required before the validity of the hypothesis can be decided.

XI. CONCLUSIONS

The detailed conclusions have already been given at the end of each section; there are, however, one or two general principles which may be repeated here in way of a summary.

The writer has attempted to outline a way of looking at structures rather than a new method. Examination of the rocks should be first of all from the point of view of descriptive geometry, and only afterwards should kinematics be discussed. Stratigraphy should, of course, be used where possible as an instrument in tectonic analysis, but ideas based on a false or even doubtful stratigraphic successions should not be allowed to prejudice a geometrical analysis of the structures present. In highly deformed regions, such as the Scottish Highlands, the degree of discontinuity often makes it impossible to apply the usual stratigraphic methods of investigation.

The common occurrence of structures approximating to the ideal cylindroidal form implies that an integral relationship between map and section is to be expected. The axial method of tectonic analysis has indeed a wide applicability both in the range of scale and range of style covered. It is no longer sufficient merely to be able to distinguish anticlines from synclines; a high degree of precision is required if the tectonic /

tectonic style is to be adequately described, and this necessitates construction of true profiles of the structures. Even where the rocks depart from the ideal cylindroidal form, the very degree of departure may be used as a measure of the mobility of the rocks at the time of their deformation.

The importance of the Cloos method of investigation of granitic and igneous bodies is emphasised. Some of the weaknesses of the method are pointed out, and a new method is described which overcomes these. This new method is equally applicable to the study of complex schists and gneisses. The writer has attempted to illustrate how these different methods may be co-ordinated in the study of a single pluton and of its surrounding country rocks.

APPENDIX

Scottish examples of cylindroidal folds.

Ord Ban.

Ord Ban.

(nose of fold shown above.)

(non-cylindroidal)

Ord Ban.

Craig Garten.

Craig Garten.

Crubenmore.

Urlarmore.

(Profile).

(oblique). Urlarmore.

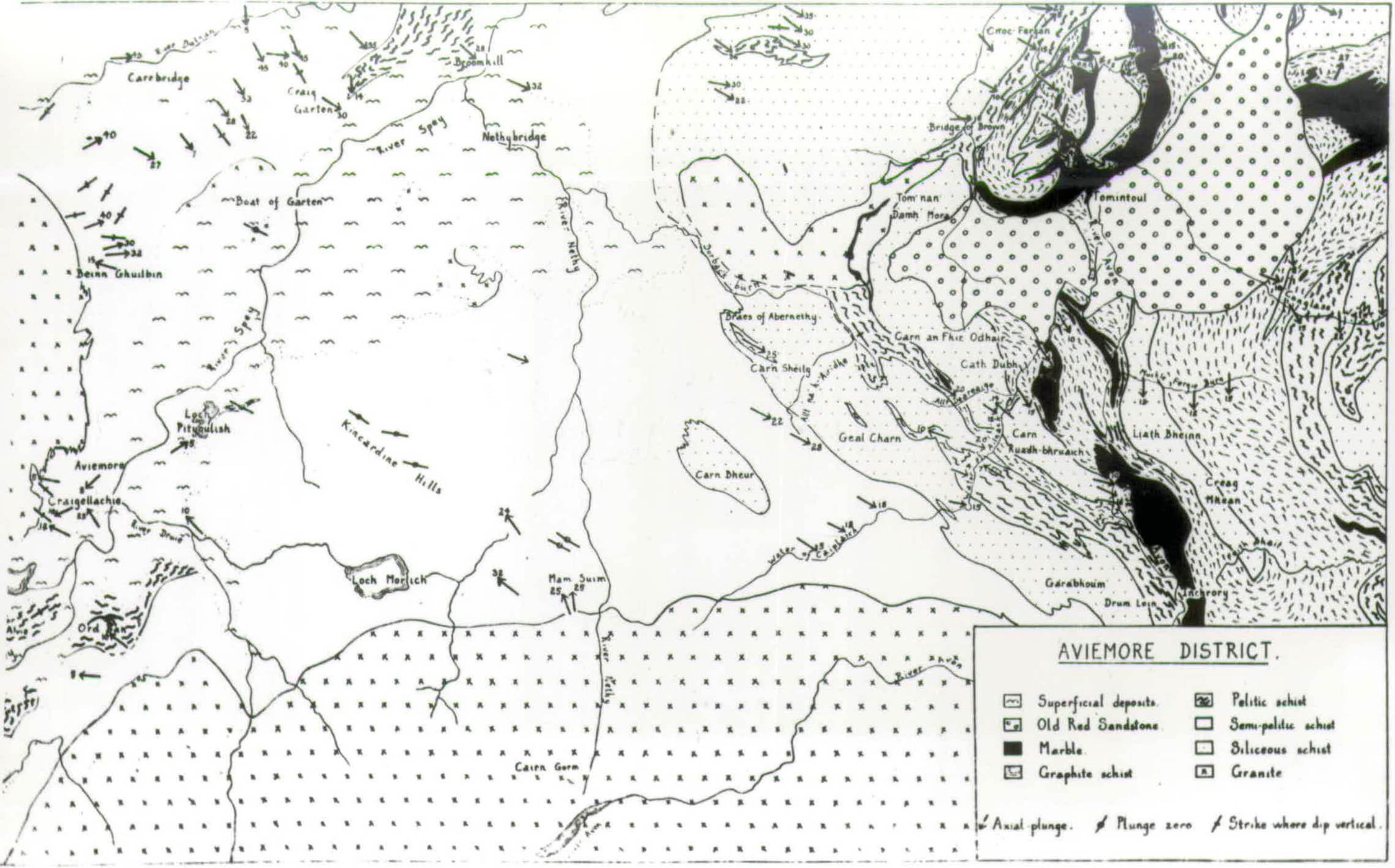

AVIEMORE DISTRICT.
Superficial deposits.
Old Red Sandstone.
Marble.
Graphite schist.
Pelitic schist
Semi-pelitic schist
Siliceous schist
Granite
Axial plunge.
Plunge zero
Strike where dip vertical.
Carrbridge
River Dulnan
Craig Garten
Broomhill
River Spey
Nethybridge
Boat of Garten
Beinn Ghuilbin
River Nethy
Loch Pityoulish
Aviemore
Craigellachie
River Druie
Kincardine Hills
Loch Morlich
Mam Suim
River Avon
Cairn Gorm
Croc Fergan
Bridge of Brown
Tom nan Damh Mora
Tomintoul
Braes of Abernethy
Carn Sheilg
Carn an Fhir Odhair
Cath Dubh
Geal Charn
Carn Dheur
Carn Ruadh-bhruaich
Liath Bheinn
Creag Mhean
Water of Caiplaich
Garabhoum
Drum Loin
Inchrory

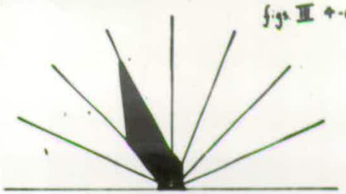
Plate 4.
figs III 4-6.

Relation of fold-axis to regional strike.

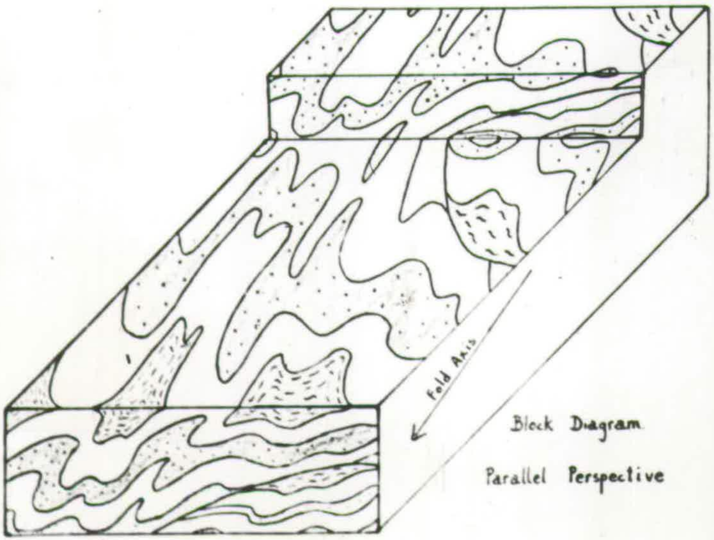
Axial-trend and regional strike do not coincide.

Axial-trend coincides with strike of vertical strata.

Axial-plunge coincides with the minimum dip.



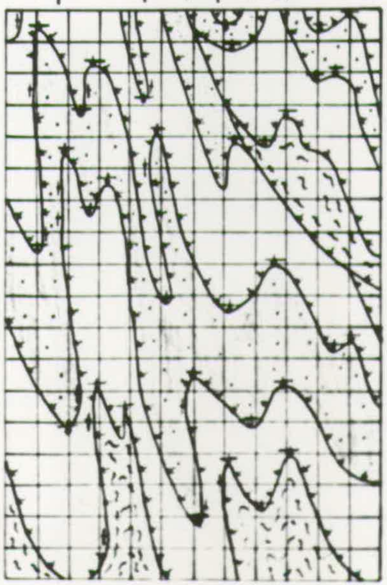
Statistical analysis of strike-directions.



Block Diagram.

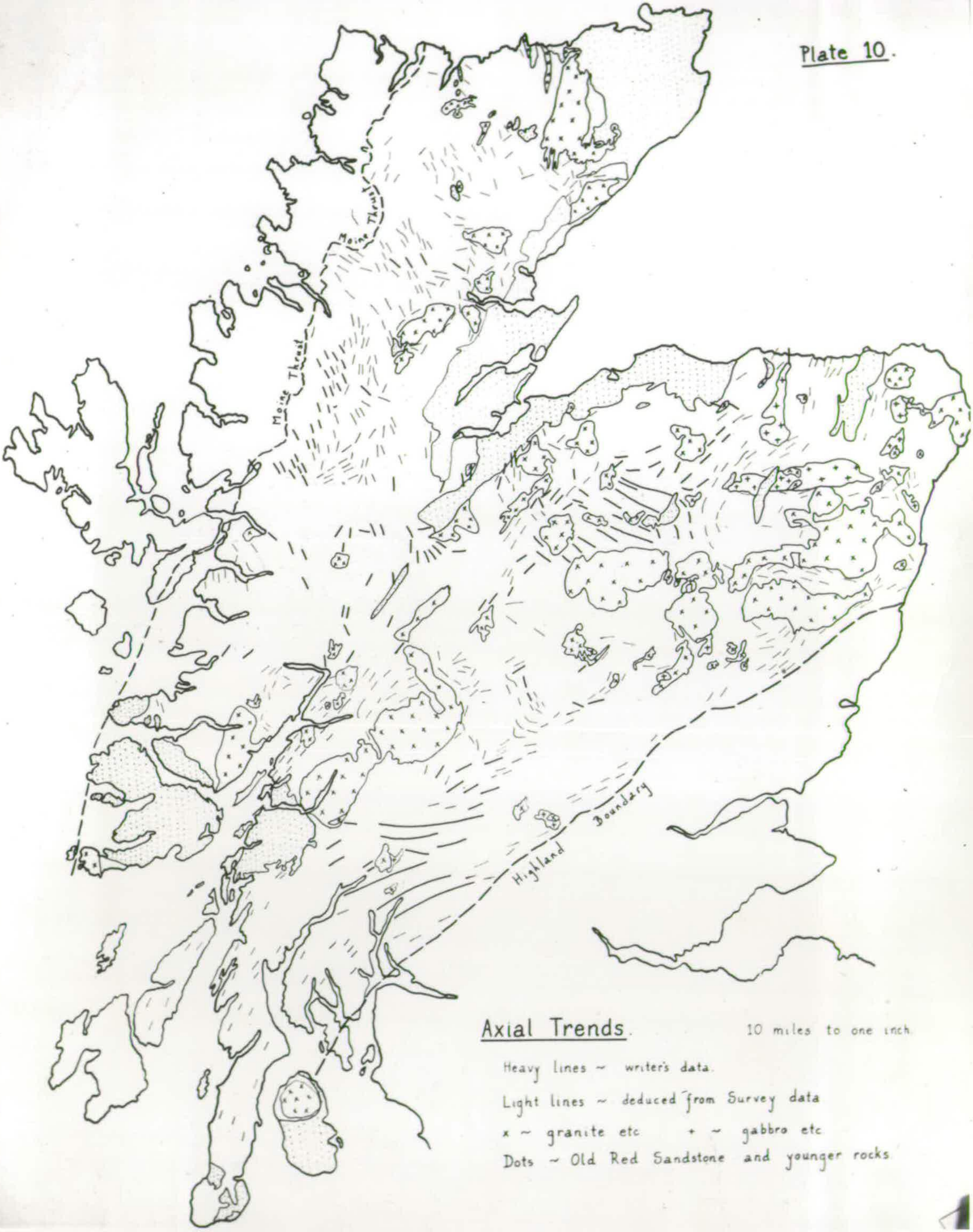
Parallel Perspective

Map. × dip; † dip vertical, ‡ minimum dip



DBM Neuchâtel Oct 47

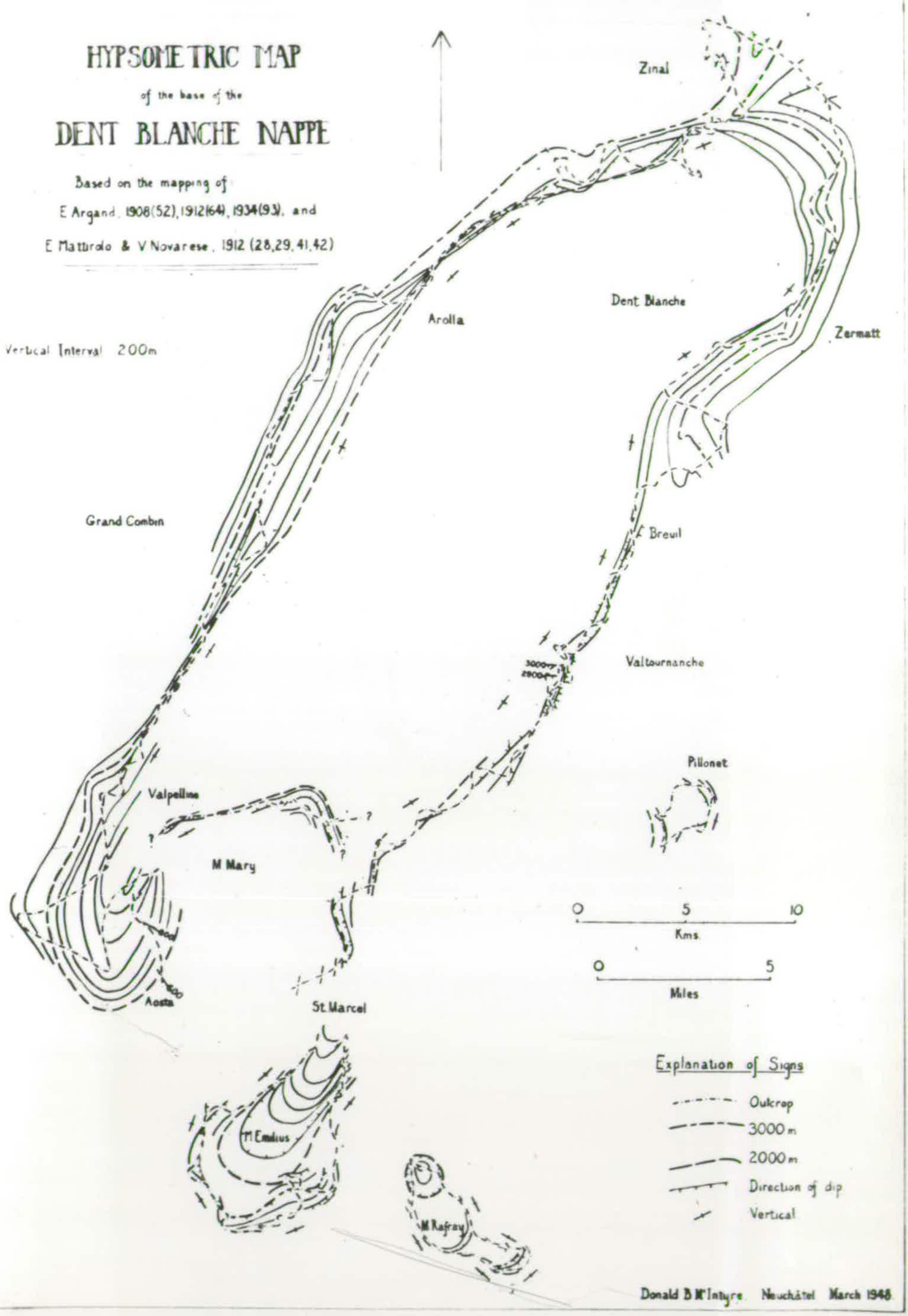
Plate 10.

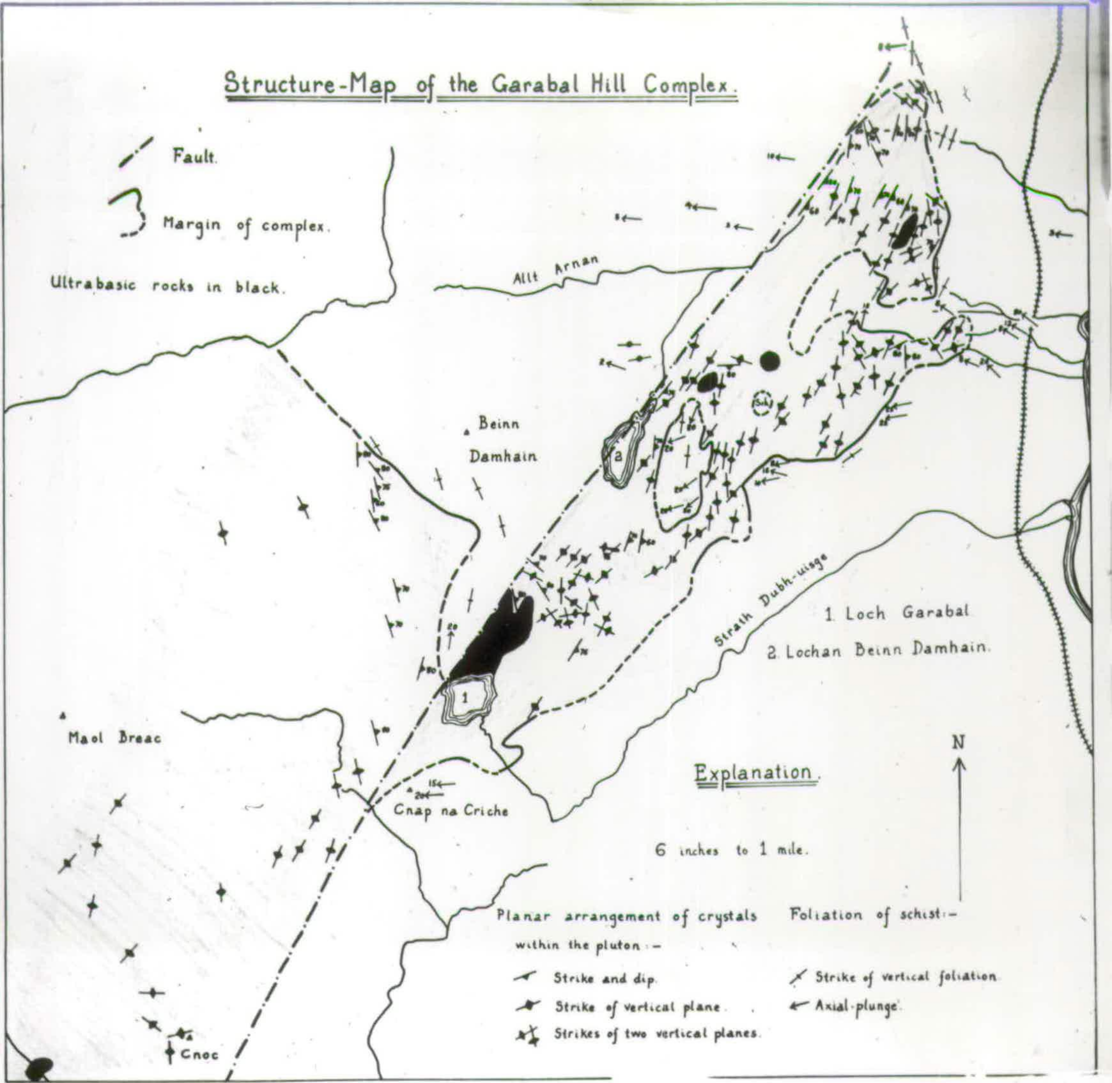


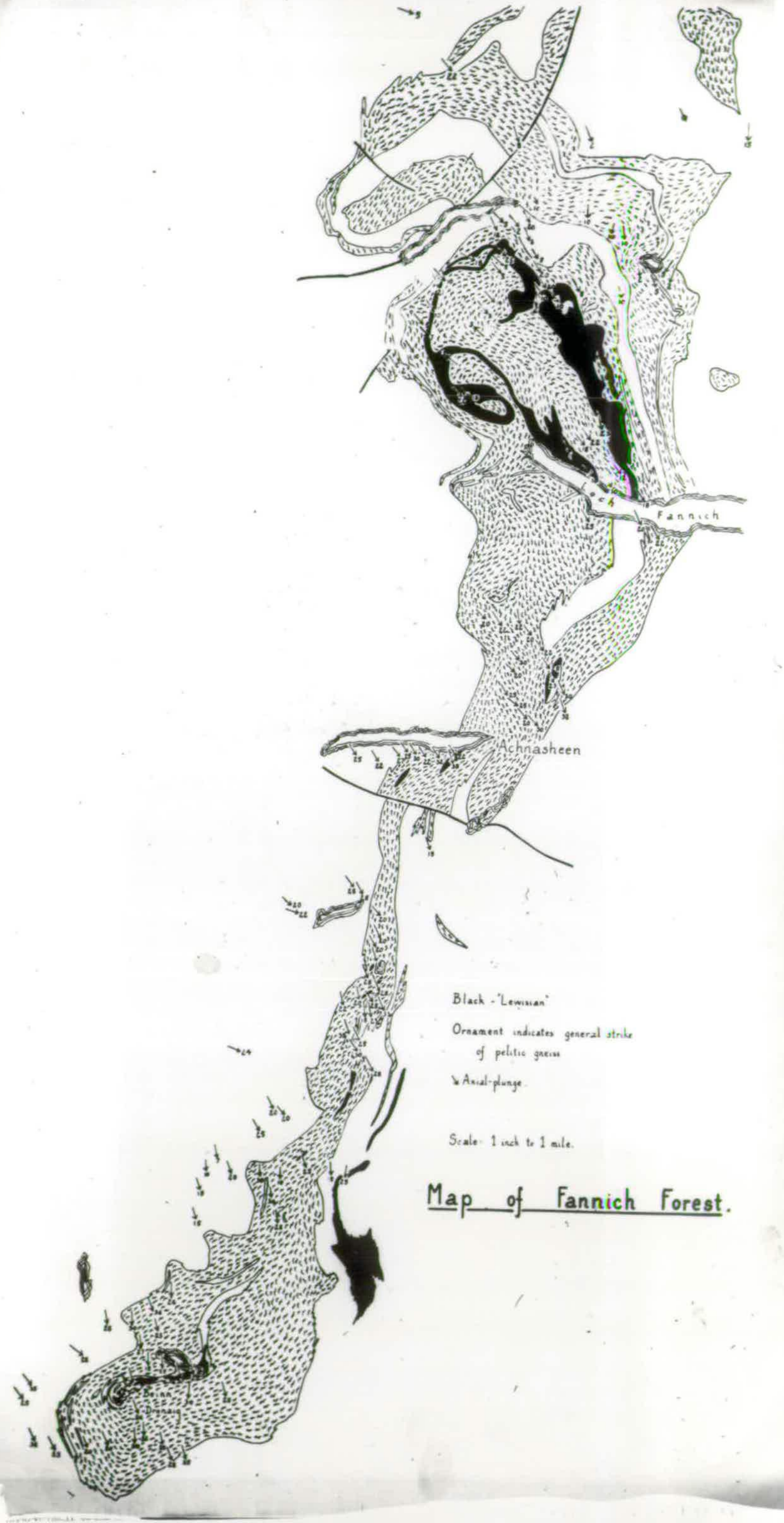
Axial Trends.

Hypsometric Map of the Hauenstein Region
showing the main thrust
&
the base of the Hauptrogenstein.
After the map & profiles of F. Mühlberg, 1914 & 1916.
Scale 1:25,000. Vertical Interval 50 m.
D.B. McIntyre.
Neuchâtel. Feb. 1948.
Rünenberg
Oltingen
Hölsten
Diegten
Zeglingen
Niederdorf
Inverted
Bennwil
Oberdorf
Läufelfingen
Eptingen
Waldenburg
Hauenstein
Klippe
Langenbruck
Mümliswil
Holderbank
Olten
R. Aare
Mont Terri Anticline
Passwang Anticline

Plate 1


HYPSOMETRIC MAP
of the base of the
DENT BLANCHE NAPPE
Based on the mapping of
E Argand, 1908(52), 1912(64), 1934(93), and
E Matturolo & V Novarese, 1912 (28,29,41,42)
Vertical Interval 200m
Zinal
Arolla
Dent Blanche
Zermatt
Grand Combin
Breuil
Valtournanche
Pillonet
Valpelline
M Mary
Aosta
St Marcel
M Emilius
M Rafray
0 5 10
Kms
0 5
Miles
Explanation of Signs
Outcrop
3000 m
2000 m
Direction of dip
Vertical
Donald B M'Intyre Neuchâtel March 1948

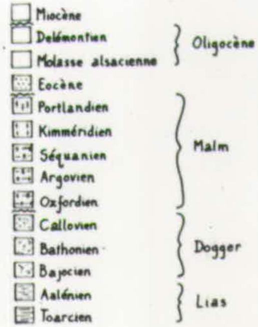

Structure-Map of the Garabal Hill Complex.
Fault.
Margin of complex.
Ultrabasic rocks in black.
Allt Arnan
Beinn Damhain
Maol Breac
Cnap na Criche
Cnoc
Strath Dubh-uisge
1. Loch Garabal
2. Lochan Beinn Damhain.
N
Explanation.
6 inches to 1 mile.
Planar arrangement of crystals within the pluton:-
Strike and dip.
Strike of vertical plane.
Strikes of two vertical planes.
Foliation of schist:-
Strike of vertical foliation.
Axial-plunge.



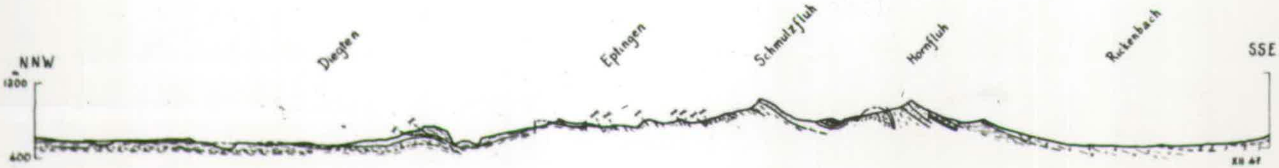
Map of Fannich Forest.

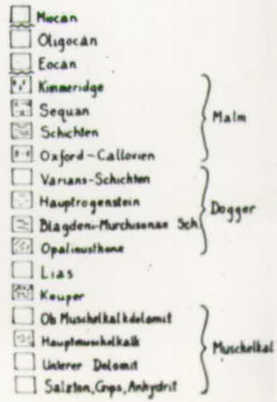
Three Jurassic Sections.

Section after the Carte des Environs de St. Imier (1893) by L. Rollier. 1:25 000



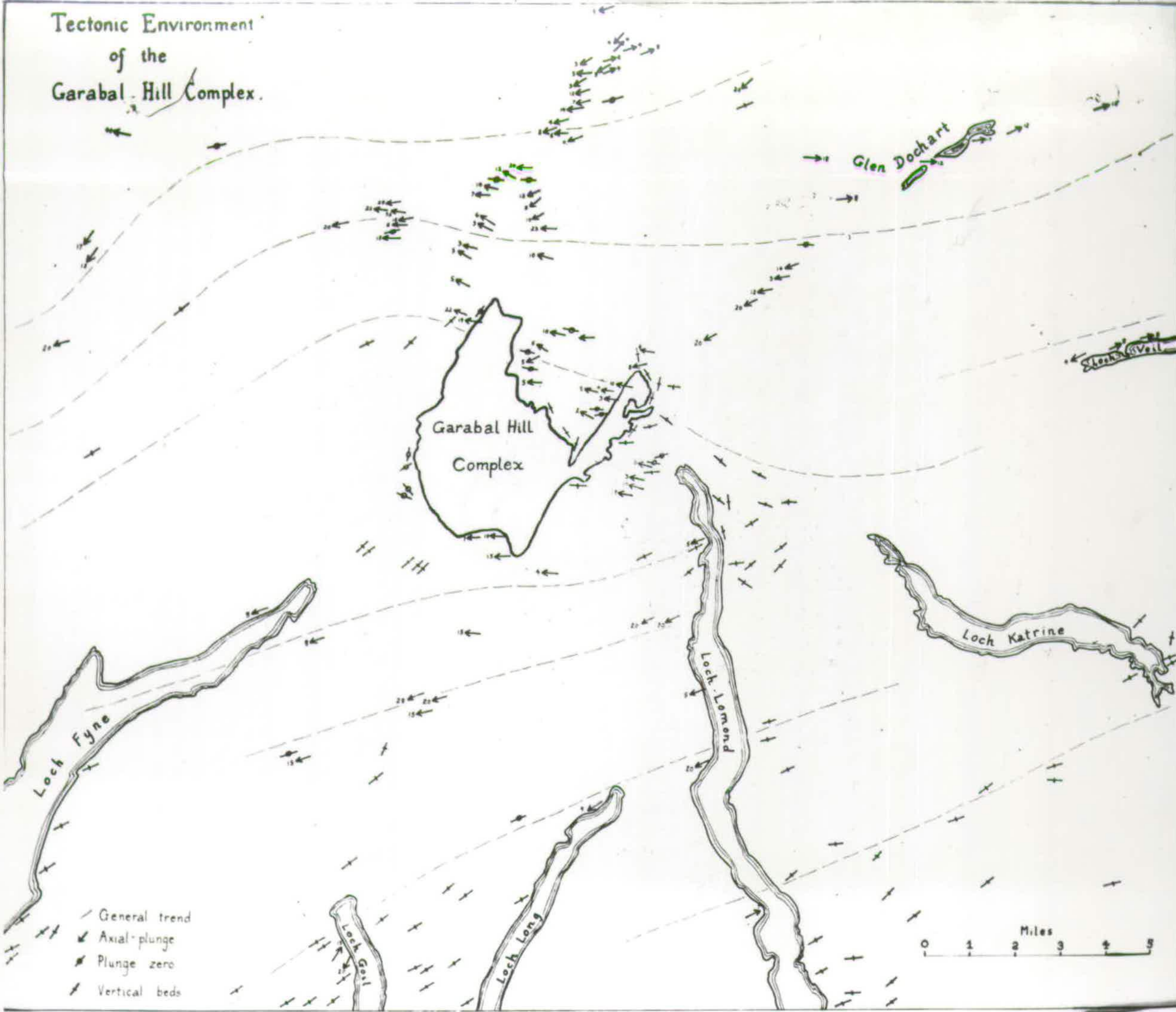
Section after the Carte des Environs de Moutier (1900) by L. Rollier. 1:25000

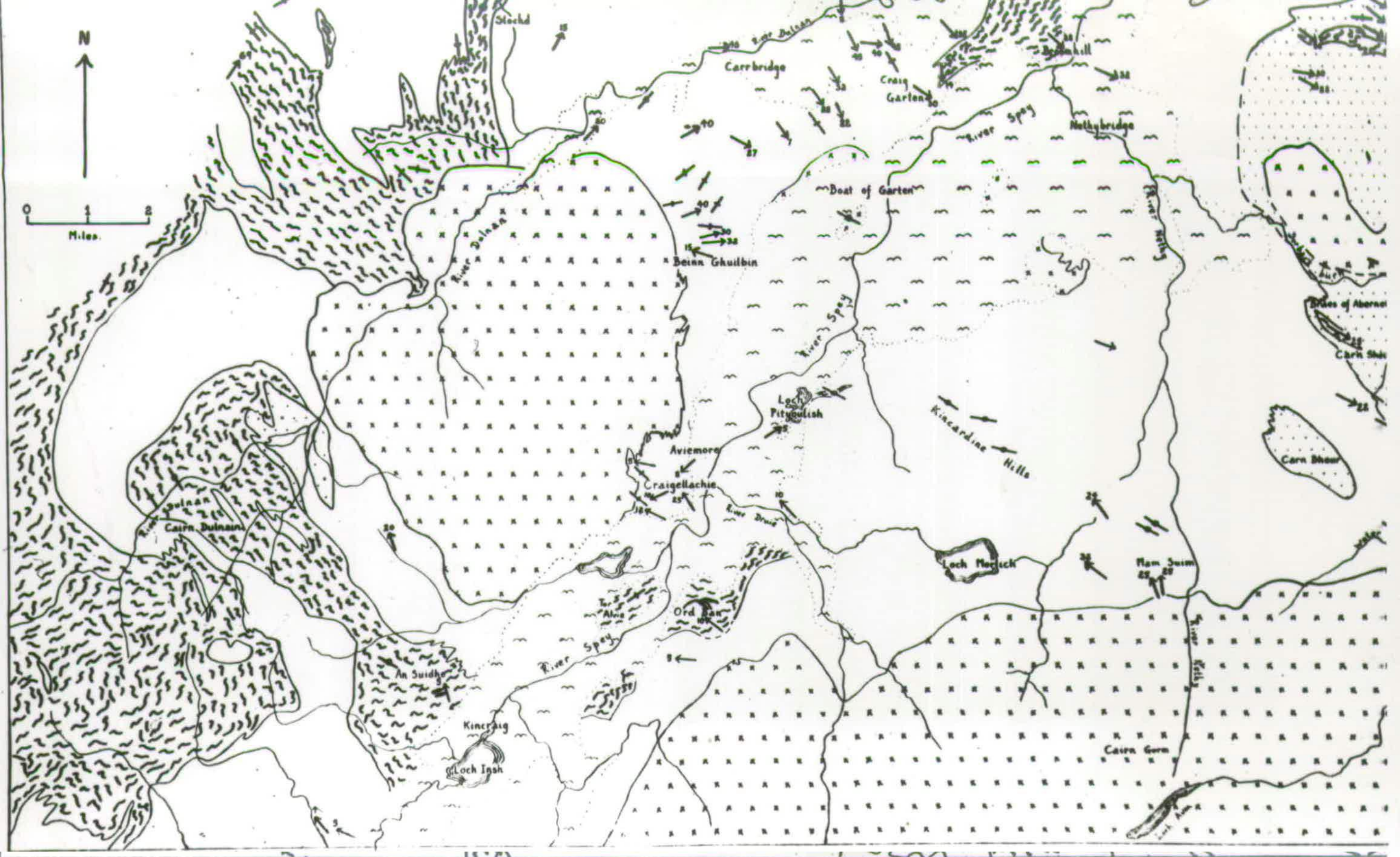




Section after the Karte des Hauensteingebietes (1914) by F. Mühlberg. 1:25000.

Donald B. McIntyre Neuchâtel 8.I.48


Tectonic Environment
of the
Garabal Hill Complex.
Glen Dochart
Loch Voil
Garabal Hill
Complex
Loch Katrine
Loch Lomond
Loch Fyne
Loch Long
Loch Goil
General trend
Axial-plunge
Plunge zero
Vertical beds
Miles
0 1 2 3 4 5


N
0
1
2
Miles.
Slochd
Carrbridge
Craig Garten
Nethybridge
River Spey
Boat of Garten
River Dulnan
Beinn Ghuilbin
River Nethy
Loch Pityoulish
Aviemore
Craigellachie
Kincardine Hills
River Druie
Loch Morlich
Carn Bheur
Cairn Dulnain
Ord Ban
An Suidhe
Kincraig
Loch Insh
Cairn Gorm