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# METHODS USED IN THE STUDY OF DEEP LEVEL TECTONICS

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## ABSTRACT

The analytic procedure used in the disentanglement of superimposed structures in catazonal rocks is reviewed, and the advantages and limitations of the "paper and scissors" method are discussed. Examples from West Greenland, where the "paper and scissors" method made it possible to trace regional structures formed during consecutive orogenies, are cited.

The structural methods used in the study of the tectonics of deeper crustal levels depend to a large extent on the experience gained from work in Phanerozoic mountain chains and on the more shallow-level structures in these, but as demonstrated repeatedly by Wegmann (e.g. 1966) who himself (Wegmann, 1929) introduced alpine-tectonic methods to the study of Precambrian terrains, the disentanglement of deep level tectonics also requires the application of some special methods. Foremost among these are (1) the methods developed in order to study multiple deformation and folding, and (2) those methods that make use of traces of former basic dykes. In this contribution I shall deal mainly with the methods of the first category.

Rocks of the deep zone (catazone) can often be shown to have received their structural imprints during more than one orogeny. Where erosion has been so deep that the rocks exposed belong predominantly to what once constituted the basement of the successive orogenies, classic stratigraphic methods offer little if any help. In such cases, detailed regional mapping of marker horizons combined with structural analysis may help us to separate out complex outcrop patterns and to work out the relative chronology of the major geologic events which left their traces in the rocks of the region. An outstanding example of such a study, and to the best of my knowledge the first of its kind, was given by Paul Michot in his three-dimensional presentation of the Storefjell nappe and its superimposed structures in the Precambrian of southwestern Norway (Michot, 1956*a* and *b*). It is true that the classic pioneers working in Scotland at the end of last century showed the lead. Reynolds and Holmes' (1954) study—particularly their experiments with plasticine models—also aroused great interest among

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students of deep level tectonics. I was at that time (1954) engaged in a study of the extremely complex structures of the Tovqussaq area, West Greenland, and I cannot emphasize too much how stimulated I was to read Professor Michot's paper. When an estimated professor did not hesitate to depict so large and so complex structures from so high-grade rocks, I decided that I also should attempt to do something similar.

When I presented the results from Tovqussaq in my thesis (Berthelsen, 1960*b*), I explained the procedure used in the structural analysis in a way that—I hoped—would appear logical and intelligible to the reader. However, to be honest, it was far from the way in which I arrived to the results myself! This was done in a far less deductive, but more empiric and inductive way by means of the "paper and scissors" method.

The geological map of the Tovqussaq area was compiled and sent for reproduction well before I properly understood the structural evolution of the area. The structural readings had been processed, and fold axes constructed from $\pi$-diagrams (Wulff net), so that the major structural units could be outlined, see figure 1. This step in the analysis is discussed in Berthelsen *et al.* (1962). Where possible, the structural contour method was utilized so that full use could be made of the relief in the area (Berthelsen, 1960*a*). See figure 2. A large lunar structure had been outlined on the map (see fig. 1), so I knew that the constructed fold axes could represent "inverted" lines, and for a while I planned to build an axial model of the area in flexible copper wire, but soon I realized

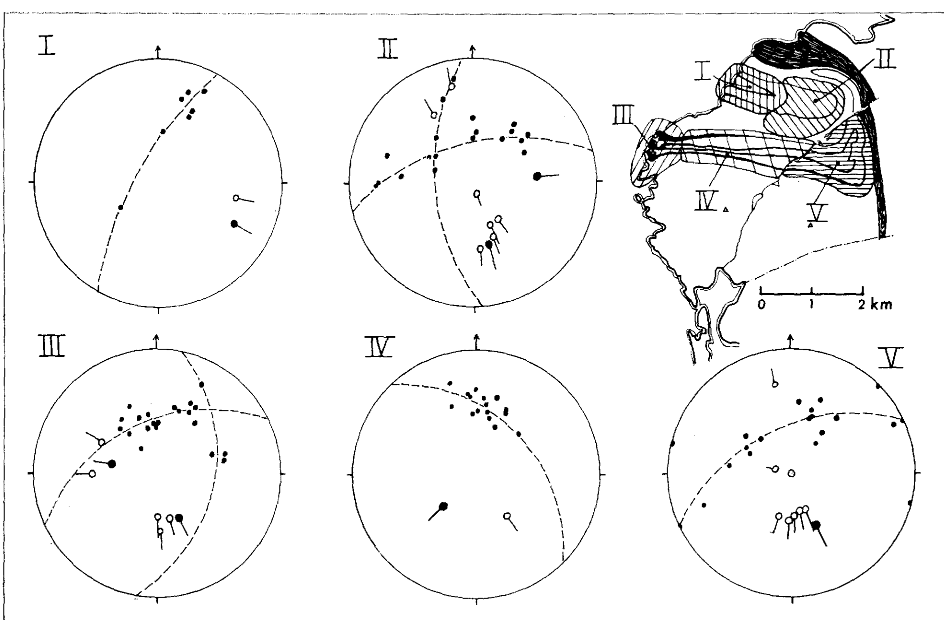


FIG. 1. — *$\pi$-diagrams from subareas in two major, refolded antiforms, Northwestern Tovqussaq area (from Berthelsen, 1960b).*

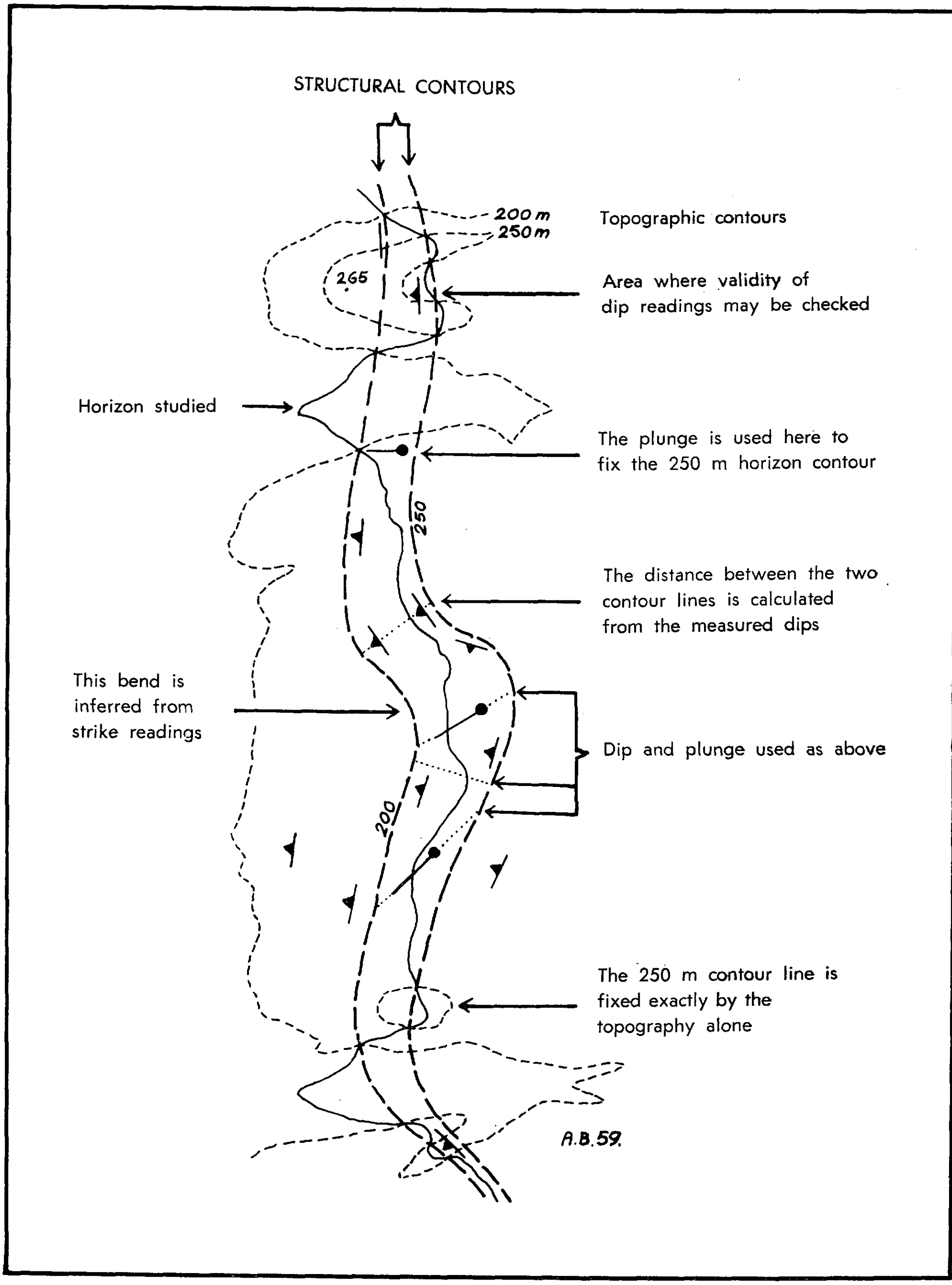


FIG. 2. — *Example showing how all available information should be used in construction of the structural contours (from Berthelsen, 1960*a*).*

that this would not tell more than the map. Striving for an understanding of the geometric relations between neighbouring structural units, i.e. the youngest antiforms and synforms, I felt as if I stood in front of a combination safe lock which I had to open up—even if I did not know the code.

To fold plasticine sheets in so complicated structures would hardly be possible, so in despair I started to play with sheets of paper—using a sheet of paper for each well-mapped marker horizon (pyribolite layers between gneiss units). The paper sheets were folded and refolded with different axial directions, and the model was "eroded" with the aid of a pair of scissors. These attempts went on for more than a year. In the meantime, I did some proper work at the microscope, but the paper cuts kept piling up. A burglar unlocking a safe in this way would have been captured, but on I went until one day the combination fitted the lock! Applying triple folding, I could reproduce the outcrop pattern, and what was still more satisfying, the stratigraphic implications turned out to agree with the actual compositional peculiarities observed in the units involved.

Since then I have used this empiric, semi-experimental method several times and taught it in student courses on structural geology. Its name, the "paper and scissors" method, stems from the students.

An obvious advantage of the paper and scissors method is that it helps to develop the operators three-dimensional imagination by means of quite simple and inexpensive tools. Once one have produced a satisfactory model, one can hold it at distance and view it from all sides so that the best angle for illustrative presentation can be chosen.

In order to proceed from a satisfactory model to a publishable tectonogram, much detailed work has however still to be done. But once one understands a complicated structure, the construction and projection work becomes merely a technical problem of analytical geometry. In this work all structural readings and parametres are involved, and a model can only be called satisfactory, if it satisfies all these—and does so on all scales.

One important assumption is made when the paper and scissor method is applied: the structures to be reproduced are assumed to be more or less cylindrical, more in case of the first-formed structures, less so when the younger structures are considered. Under favourable conditions with a strong topographic relief, the correctness of this assumption can be checked.

In the semi-experimental procedure where sheets of paper (or cloth or plastic) are deformed, forceful bending, and lateral compression and shortening are involved. But most models thus produced could also have originated by some sort of shear folding or laminar flow folding. It is important that the models are only considered as (often rough) approximations to the purely geometrical relations.

Any field geologist who has started to plot his readings in $\pi$-diagrams (Wulff or Schmidt net) may become so used with this three dimensional operation that after some practice he can almost tell the attitude of the fold axis by just glancing at the strike and dip readings on the map. In a similar manner, use of the "paper and scissors" method helps to train one's capacity for three dimensional thinking.

Once the large scale geometric relations of an area have been established, the kinematic evolution becomes intelligible. Quite often, detailed studies of key areas with well exposed mesoscopic to medium-sized structures form a step towards the establishment of the kinematics on a regional scale. Caution should naturally be exerted so that the "law of homology" (Demay, 1942) is not misused, particularly when the possibility exists that mesoscopic structures of different ages can be misread as being of similar age.

Wynne-Edwards (1963*b*) questioned the validity of my interpretation of the Tovqussaq structures. Relying on Carey's principle of flow folding (or rheid folding) as well as his own experience from the Westport area, Ontario, Wynne-Edwards suggested that the Greenlandic structures had been formed by unsteady (i.e. non-laminar) flow folding causing local swirls and eddies in the flow pattern, rather than they should have evolved through superimposed folding during consecutive phases of folding as visualized by me (Berthelsen, 1960*b*).

In a way, Wynne-Edwards' (1963*a* and *b*) suggestion meant a return to the ideas on the origin of Schlingenbau that were held in the twenties and thirties. Apparently he did not pay any regard to the fact that at Tovqussaq there occur comparable superimposed structures on almost all scales (cm, m and km). Unsteadiness could hardly be expected to obey the "law of homology."

It might however be appropriate that I myself correct a mistake I made in 1960. At that time I concluded that the entire orogenic evolution probably belonged to a single orogenic period. However, recent work in neighbouring regions where basic dyke and geochronological methods have been used (McGregor, 1973; Moorbath *et al.*, 1972), indicates that the oldest Tovqussaq structures of "orogenic type" evolved at least 3 750 m.yr. ago, while the youngest date from only about 2 500 m.yr. back. This time span is so long, that each deformational phase could well represent the traces of a separate orogeny!

The "paper and scissors" method was also used in a reinvestigation of the structures of the Ivigtut area (Berthelsen and Henriksen, in press). In this area

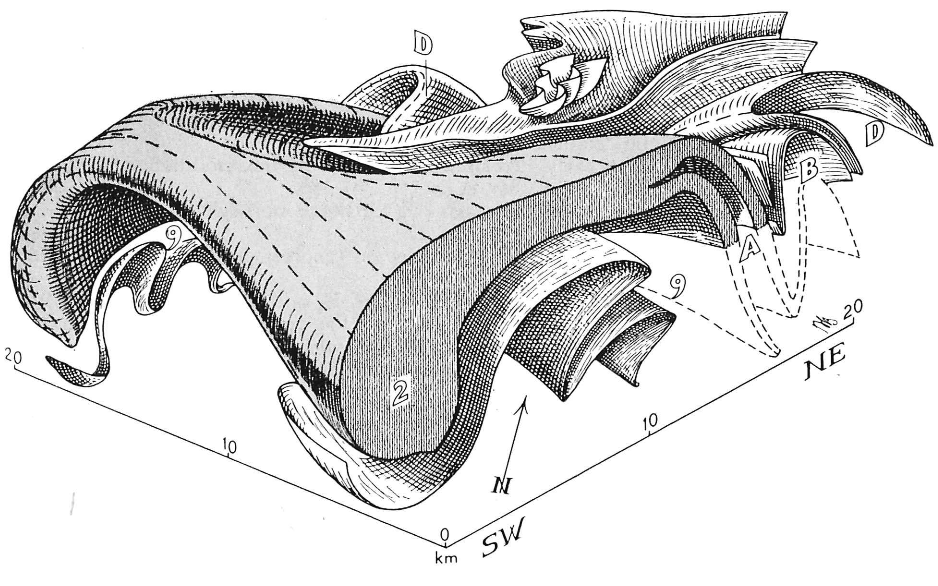


FIG. 3. — *Tectonogram of the Northwestern part of the Ivigtut region. It may be seen how the formation of the Maturian synform influenced the older Serrilian nappe structure.*

three major episodes of deformation can be discerned, and the occurrences of two supracrustal sequences of different age helped me to establish that the three episodes all possess the rank of an orogeny. The first and the second—for convenience called the Senilian and the Maturian—are separated by an almost obliterated unconformity, the Maturian and the Ketilidian (second and third orogenies) are distinguished by means of both basic dykes and an unconformable sedimentary contact at the base of the Ketilidian supracrustals.

These Greenlandic examples show that the "paper and scissors" method, when applied to marker horizons of regional extent, is a useful additional method when tracing and distinguishing between deformational belts of orogenic nature (see fig. 3).

But of course, the geochronologists could rightly claim to have the last words (I put words in the plural because they also correct themselves sometimes).

I cannot conclude this confession-like contribution without disclosing that actually I cannot claim priority for having invented the "paper and scissors" method in the study of multiply folded deep level rocks. I have recently learned that this honour goes to Professor Paul Michot, who used the method in his 1956 study—the one that inspired me so much. I am grateful to you, Monsieur Michot, for giving me your permission to disclose this paternity.

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