NOTES ON THE MECHANISM OF FOLDING

BY

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§ 1. In this study only those folds as observed in the upper sedimentary layers of the Earth's crust will be treated. Even with this restriction the subject is still so complicated, that we must narrow the scope to be able to treat it from a theoretical point of view. Hence we will confine ourselves to simple folds as synclines and anticlines, leaving alone those intricate structures generally known as Alpine folding. On the other hand faults connected with folding are such a common feature that any theory that does not take them into account will be valueless.

Folding is the result of tangential forces acting at unknown depth. Only in very few instances we have some idea at what depth the force is active. In the Jura mountains for instance we know that the sedimentary layer must have been pushed over its granite basement rock, as it has glided over the granite on a very incompetent layer of Anhydrite. But such knowledge of the total depth of a system of folds is an exception.

In general it is understood that the upper limit of a fold is the surface of the Earth, its lower limit being a more or less horizontal hypothetical shearing plane, along which the folded strata have been detached from their basement rock. The determination of the depth of this shearing plane offers an highly interesting problem, which however lies outside the scope of this paper.

We are at present chiefly interested in the problem how, somewhere in the central part of a cross section, the deformation of the material has taken place, in such a way that a fold resulted.

In textbooks folds are divided into two classes, viz.:

(1) competent or parallel or concentric folds, where beddingplanes remain parallel and the thickness of the strata remains unchanged,

(2) incompetent or similar folds, where the shape of the fold in subsequent beddingplanes is the same, but where the thickness of the strata undergoes considerable change by thickening or attenuation.

As the thickening of the strata in the crests of anti- and synclines and the attenuation in the flanks necessitates considerable deformation [1]),

[1]) This phenomenon is often referred to as „flow'', but as fig. 1 B shows „flow'' in general is nothing but a rather extreme form of deformation, without extensive displacement of material. Real „flow'' takes place in diapiric structures, saltdomes etc.

it is obvious that only material in extremely plastic condition will follow this mode of folding. Any normal sequence of strata is priory competent, and competent folding in simple folds will be the rule.

The detailed tectonical studies of oilfields have revealed the fact that this kind of folding is the principal law, when only a few hundred meters of stratigraphical tickness of strata are considered. However the section construction along those lines tends irrevocably to a flattening of the structure downwards, which is in direct contradiction to the majority of observed folds. Accordingly we must keep in mind that competent folding has its well defined limits.

In experimental tectonic work the same mode of folding is expressed by all those artificial folds, though many other features, inherent to folding in nature, are absent. When a fold becomes compressed to a high degree pure competency becomes an impossibility, and faulting or (and) attenuation will take place.

§ 2. It will be instructive to inquire deeper into the nature of competent and incompetent folding. In figure 1 the two modes of folding are represented.

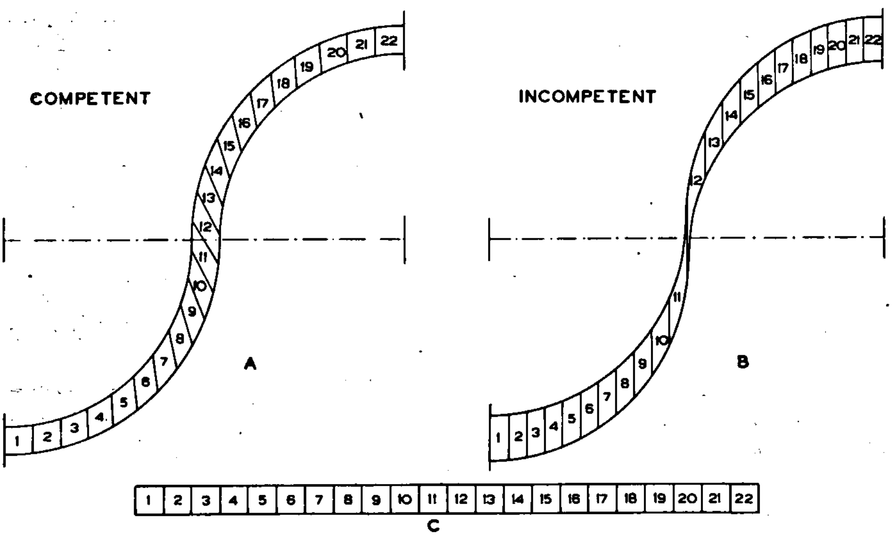

Fig: 1 Shortening to 63,6% of its original length by folding

In both cases, A and B, the volume of the original (C) has been maintained. The unit cubes drawn in C have been deformed by the folding and their shape in A and B is a measure of the necessary deformation (Also the volume of each deformed cube has remained the same.)

There is no doubt that the deformation in case A is considerably less than in case B.

This leads to the tentative conclusion that competent folding is the result of the maximum shortening of horizontal distance between two points, while maintaining the minimum internal deformation of the strata.

(We must bear in mind however that our graphic solution of the competent folding is not a mathematical proof and it may be true that a slight deviation of the geometrical construction will be still better in concordance with the stated definition of competent folding. However I feel confident that our geometrical construction method is at least a good approximation.)

The conclusion we arrived at is a perfectly logical one and represents a principle of prime importance. Hence there is no reason to expect that strata of different material will act differently. All strata, argillaceous or arenaceous, limestones or coals will follow this same law. The subdivision of textbooks into competent and incompetent folding refers to another *stage* of the folding process, when pure competency is no longer possible. Then competent strata will fracture and break, whereas incompetent strata will be squeezed out. In this stage of fracturing, the incompetent stage one might say, the internal cohesion of the material is broken up in both cases but in different ways.

Thus we can distinguish three successive phases in a folding process, following one another during increasing pressure.

(1) The unvarying phase; when the folding force has not yet attained the limit at which deformation of the strata is possible. A general compression of the material may take place.

(2) The competent phase; competent folding without thickening or attenuation.

(3) The incompetent phase, characterised by fracturing and faults, attenuation and thickening.

Although every kind of material will undergo these three phases successively, the limits between two phases might not be situated at the same degree of compression. One kind of material will yield to the deformative force earlier than some other. Complications will arise in very heterogeneous sedimentary series. A quick alternation of strata of different character will probably act as an homogeneous mass, whereas a series consisting of thick horizons of different character must be regarded as a heterogenous series.

Also within one fold the deformative force will not be equal throughout the fold. In the core of the anticline the force must have been greater because greater deformations have taken place. Hence the limit between competent and incompetent folding will be reaached first in the core of a fold and will spread from this centre outwards and upwards.

§ 3. Before competent folding can be fully understood more must be known about the mode of deformation during the folding process.

Very often folding of strata has been compared to folding of a block of paper.

When we bend a block of paper the cohesion of points on one horizontal plane is great, whereas the cohesion of the sheets is nihil. The adjustments are wholly taken up by slip between the sheets. The maximum slip can be measured by the difference in length between the arcs *a* and *b* (Fig. 2) which equals:

$$\begin{aligned} \text{slip} &= \alpha R - \alpha (R - t) \\ &= \alpha t \end{aligned} \qquad (1)$$

α being a measure of the intencity of folding.
t = thickness of strata.

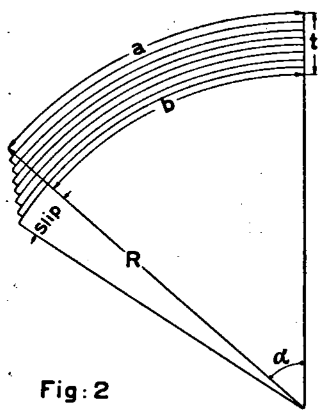

Fig: 2

Thus the slip is independent of the size of the fold (a) but is a function of t and the intencity of folding (α).

The maximum slip is encountered at the steepest part of the fold, and diminishes towards left and right. If we consider an unbroken limestoneband 1 cm. thick, surrounded by shale, folded through 90°, then the slip between its upper and lower boundery would be

$$\tfrac{1}{2}\,\pi \text{ cm or } 1{,}57 \text{ cm.}$$

By inner adjustment of the grains within that 1 cm thick limestone a displacement of 1,57 cm is necessary [1]) between a point in the roof relative to a point in the floor. Also if we consider two adjacent grains in a sandstone the relative movement would be 1,57 × the grainsize.

When we bend, instead of a block of paper, a long strip of cardboard to an arc of 90°, this will be effected without difficulty. But the bending of a piece of 1 cm. length to this same arc will require much more strength and will probably result in the rupture of the smooth arc. In this cardboard adjustment by slip is impossible, but the fold is effected by means of compression of the inner arc and by tension of the outer arc. That the amount of compression is a function of size and radius of the fold is demonstrated by the greater resistance of a smaller piece of the same material. The total amount of necessary adjustment can be measured in terms of slip and formula (1) can be used. But the material being compressed a distribution of the

[1]) Busk (Earth flexures) distributes erroneously this maximum displacement over the whole fold, and concludes that slip is unnoticeable in its effects. If this were true the size of the fold would determine the slip, which is contrary to the formula. Furthermore it is obvious that the increasing slip can not be redistributed back along the arc.

shortening of the inner arc over its whole length takes place. Hence the rate of compression equals

$$\alpha \frac{R - t}{a} \text{ or } \frac{a - \alpha t}{a} \; ^{1)} \qquad (2)$$

When a thin layer, thin comparative to the length of the arc, is considered the compression is small, but with a thick layer a considerable compression per unit length must occur. The maximum compression of a sandstone has been determined experimentally to about 5 % of its original volume.

The foregoing examples have lead to considerations of movements exclusively parallel to the curve. Adjustments in sediments might however as well take place perpendicularly or obliquely to the curve of the fold. The material that constitutes sediments are grains of various size, which hardly can show a marked preference to one or the other direction as long as we consider homogeneous strata.

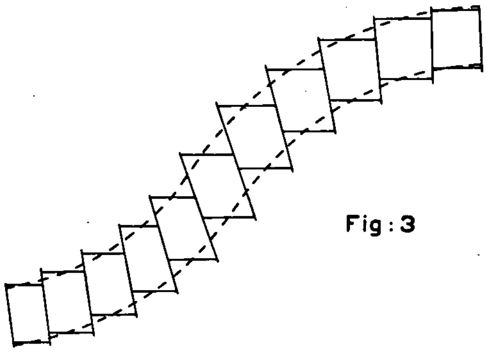

Fig: 3

In Fig. 3 we have drawn a fold, where the displacement of the particles has taken place along shearing planes perpendicular to the bedding, only the number of those planes must be imagined to be infinitely great.

§ 4. To be able to judge which of the many possible ways of adjustment of the grains to the folded status seems to be the most logical one, we have drawn Fig. 4, representing an anticlinal fold.

A theoretical fold of a constant length a, and the thickness t, has been drawn in three successive stages (B, C and D) of its folding. By means of the construction method of Busk, making use of concentric circles, pure competency has been maintained.

On the upper and lower boundery line of the fold the course described by a series of points during progressive folding has been traced.

We observe that the central part of the fold has risen vertically, while the flanks have undergone a more complicated movement. Here all the points have also started on their vertical course but quite suddenly one after the other they change their course to an horizontal one. The turning point is sharp. Thus a fold can be divided in a central part moving in a vertical direction, and two flanks which move horizontally towards each other.

1) We take it as if only compression takes place in the inner arc and no tension in the outer arc. Otherwise the compression of the inner arc would be $= \alpha \frac{R - \frac{1}{2} t}{a}$ and the lengthening of the outer arc $= \alpha \frac{R + \frac{1}{2} t}{a}$.

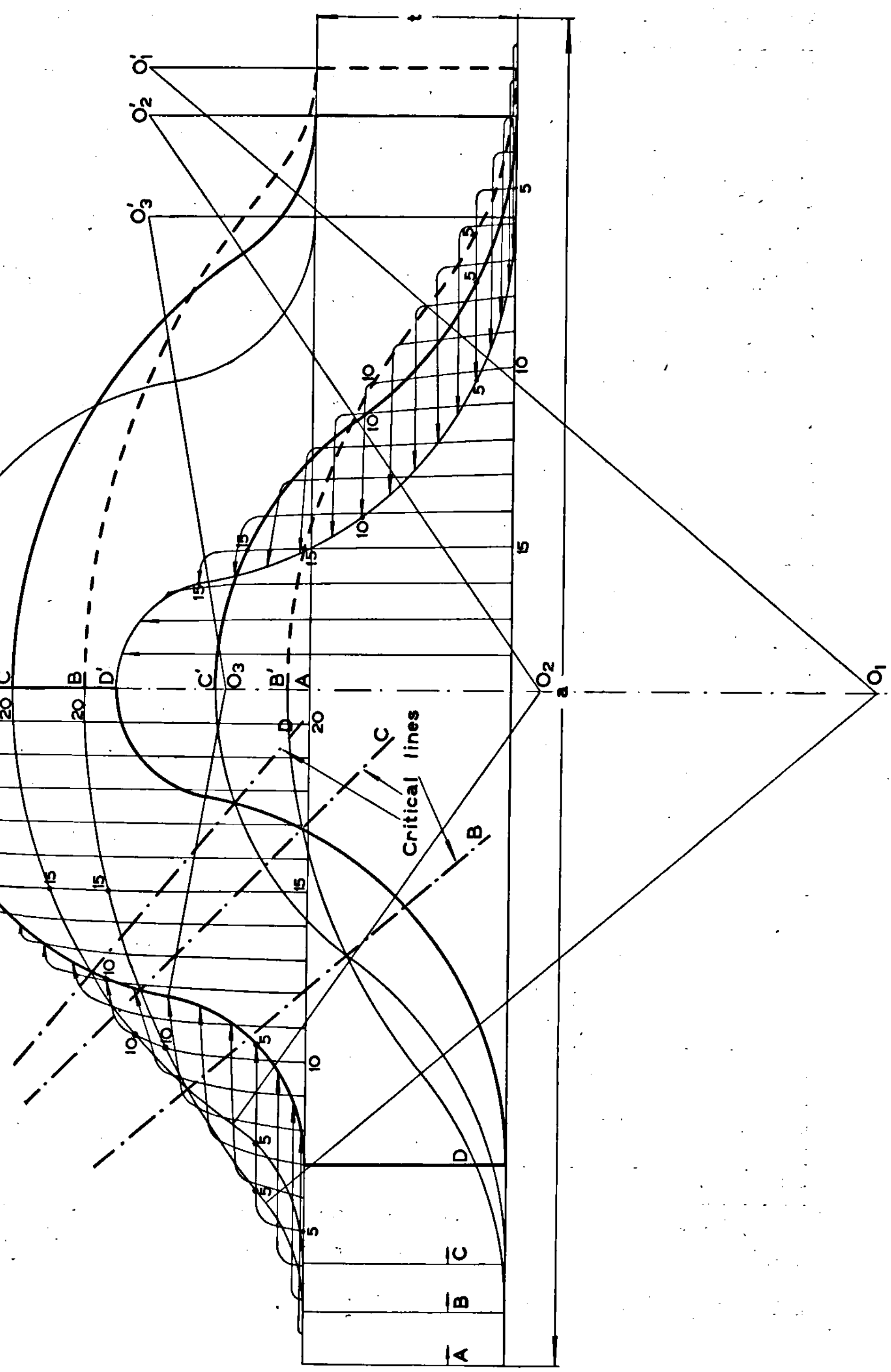

Fig: 4

In the central part only little deformation takes place, necessitated by a slight difference of velocity of two adjacent points, which increases, however, towards the flanks. In the horizontally moving part no further deformation seems to be necessary, the velocity being the same for all points which move in this direction. The maximum deformation takes place however where two adjacent points have perpendicular directions. Hence the history of a fold can be described as follows: first all points move vertically upwards, the velocity being greatest in the centre and decreasing towards the flanks. Then starts, from the flank, the curious perpendicular movement, starting far into the flank and moving towards the centre. The point where this change in direction occurs we will call the critical point. In the critical point the strain on the material is greatest, especially so in the steepest part of the fold. Accordingly here the first fracturing or incompetent folding will occur. When we connect by a line these critical points at increasing depths at one moment in the folding process, we get in our drawing a straight line, hading towards the core of the fold with a dip of some 45°.

Or when the formation can not stand the strain any longer and tends to break or fracture, a shearing plane along this line will be formed. If the formation is brittle or very much opposed to folding the development of this shearing plane will occur in an early stage of the folding process, or near to the flank, while a very competent sedimentary series will reach this incompetent stage later, and the shearing plane will be found near the centre of the fold. Thus the position of the shearing plane relative to the centre of the fold will be an indication of the character of the material.

After the break the flank will continue its horizontal movement and the centre its vertical movement, the shearing plane being the boundary between the two movements.

Thus far our theoretical considerations, based on the law of competent folding has lead us to a very satisfactory result, as shearing planes of the nature described above are a very common feature in nature.

§ 5. In § 3 we have surveyed some possible ways of deformation, and came to the conclusion that movements of points on a fold relative to one another may be oblique or perpendicular to be beddingplanes. In § 4 we have traced the course of those points in space, and concluded from these movements the differential movement at any point of the arc. These differential movements are the source of the deformation of the material.

The tangential force thus can be divided into two actions, viz. (1) the deformative force (2) the displacement. The deformative force can be measured by the change of shape of the unit cube as represented by Fig. 1. The displacement has to act against Gravity and friction along the basal shearing plane, and in a later stage of folding along other shearing planes within the fold. There can be little doubt that the former action of the stress will absorb considerably more energy than the latter action.

In a homogeneous mass the grains will move according to the deformative force, there course will be determined solely by the direction and intensity of this force.

We could represent this movement as taking place along minute shearing planes. Thus we would find in the centre of the fold vertical or almost vertical shearing planes, whereas inclined shearing planes, are formed at the critical points where the grains move in perpendicular directions.

The inclination of those latter planes is dependent of the relative velocities of the grains. When the flank of a fold has passed the vertical stage and the critical point, no more shearing planes are formed, the material moves more or less undisturbed in a horizontal direction.

According to this conception neither slip nor compression are applicable to folds. Also the simple representation of fig. 3 is erroneous. During the folding process the shearing planes change their position and inclination, according to the necessities of the shape of the fold. However there will be a tendency for shearing planes to maintain their original inclination, specially so those that occur at the critical points. Eventually these shearing planes can develop as major overthrust planes.