Geophysica. — *The principle of concentric folding and the dependence of tectonical structure on original sedimentary structure.* By L. U. DE SITTER. (Communicated by Prof. F. A. VENING MEINESZ).

(Communicated at the meeting of April 29, 1939.)

I. 1. The detailed study of simple folds in oil fields and elsewhere led to the conviction that natural laws govern the mechanics of folding, laws, which to a high degree are independent of the nature of the folded rocks and their stratification (DE SITTER 1937).

This general principle I call the concentric folding principle. It is the result of two fundamental laws: 1. the law of retention of volume, 2. the formation of spontaneous shearing planes parallel to the surface.

I. 2. The law of retention of volume signifies that the folding pressure

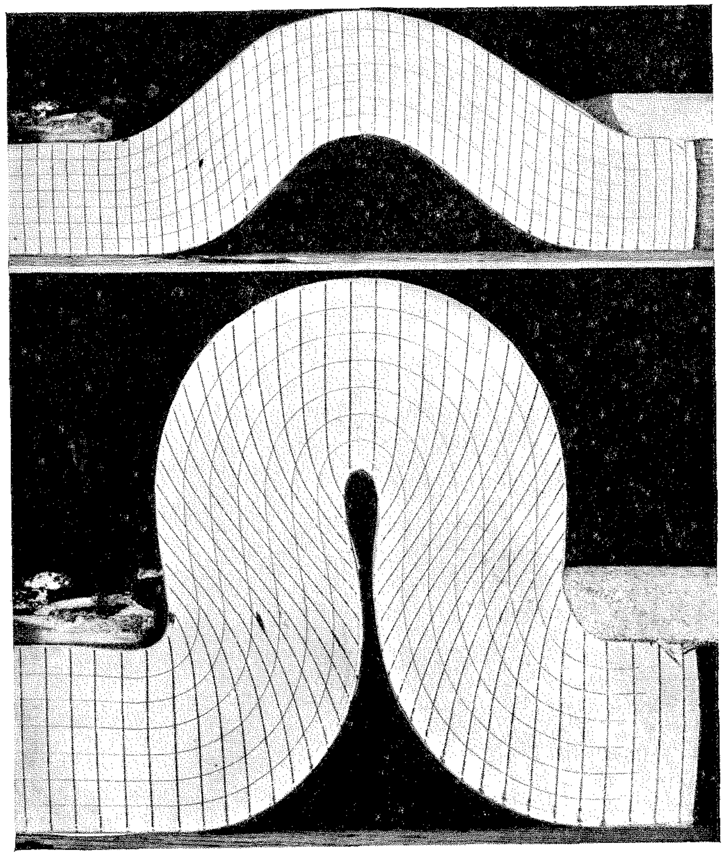


Fig. 1. Concentric folding of a block of paper.

does not compress the material of the folded rock to a denser material, or at any rate, that the compression is a finite phenomenon with very little influence on the folding mechanism.

I. 3. The spontaneous parallel shearing planes explain why an unstratified, thick formation, or a badly stratified complex, shows the same folding mechanism and ultimate shape of fold, as a well stratified complex of sediments. Wherever stratification planes, as planes of minimum cohesion, exist, it can be easily understood that most of the internal shearing during the deformation process will follow these planes of minimum cohesion and that the mechanism of folding will closely resemble the folding of a block of paper. (Fig. 1) (KUENEN and DE SITTER, 1938).

When no stratification planes exist, as in thick limestones, sands, or even clays and shales we still find the same final shape of fold. In order to investigate this apparent general validity of the "paper folding principle", KUENEN executed in close collaboration with myself a series of experiments (KUENEN and DE SITTER, 1938), which finally resulted in a few experiments where unstratified clay was folded as if it were stratified, spontaneous shearing planes having the function of stratification planes (fig. 2).

These shearing planes were formed already in a very early stage of folding and are certainly not due to shearing stresses, as they are parallel to the stress direction. They must be due to tensional stresses perpendicular to the general deformative stress. It is a kind of foliation of the homogeneous mass, taken advantage of by the deformation mechanism in using these foliation planes as shearing planes, in the same way as stratification planes are used as shearing planes. Thus it can be understood why a thick unstratified member of a sedimentary series does not disturb the general folding mechanism.

I. 4. The most general conception of the mechanism of folding of sedimentary rocks is therefore, that the internal differential movements of particles are always parallel to the bedding e.g. neither thickness nor length of a layer changes during the folding process. The contrary conception of a fold is either a fold slowly dying out downwards or a so-called true to shape or similar folding. A fold dying out downwards would infer decreasing dips, increase of thickness on top of the fold as sketched in fig. 3. Such shapes have never, or very seldom been observed in folds where the subsurface structure is really known either by mining operations or by deep erosion.

In the left part of fig. 15, Plate 1, representing the Graitery fold of the Jura Mts for instance, the fact that the tunnel encountered in the centre of the fold the Hauptrogenstein and the underlying Blagdeni-Murchesoni schists proves that there is no trace of slowly flattening of the anticline comparable to the structure of fig. 3.

In fig. 4, a layer, folded concentrically, is put next to the same layer folded true the shape. The latter folding mechanism is similar to faulting, the single straight fault plane being replaced by a multitude of small planes, all parallel and straight. When we find such folds we may be certain that

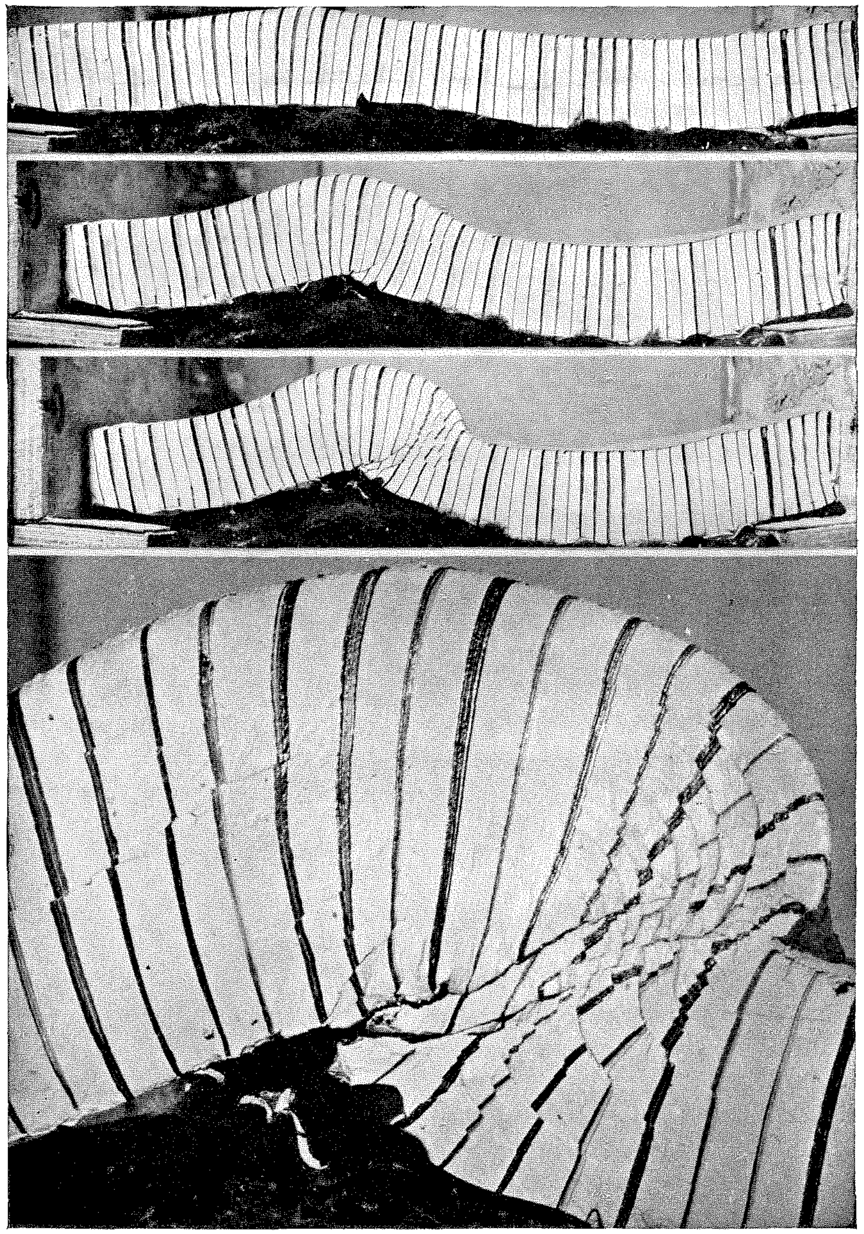


Fig. 2. Concentric folding of a homogeneous unstratified cake of clay.

they actually do replace faults as in flexures or attenuated steep limbs of an anticline.

In general it is a fact that in all folds the flank dips converge towards the centre. This fact and the resulting tectonic complications of the centre,

indicate that concentric folding is the leading principle. Every fold described and reproduced in this article illustrates these facts.

Without entering further into the theoretical merits of the concentric folding principle we will apply the law to well known structures, from the analysis of which it was originally derived. If it gives us a better understanding of the pecularities and explains general features of folds, it has at least a value as a working hypothesis.

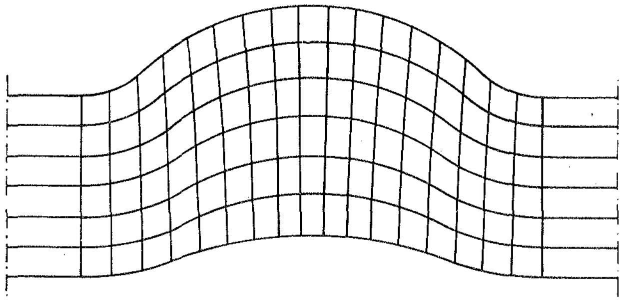


Fig. 3. Compression fold, dying out downwards.

II. 1. A necessary consequence of concentric folding is the fact that the downward extension of a fold is limited, because the disturbance, as noticed at the surface, is concentrated radially downwards and towards the centre of the fold. Therefore we can regard a system of folds as a folded block pushed over a substratum. What really happens to the substratum is a problem on itself, which we will not elaborate in this discussion,

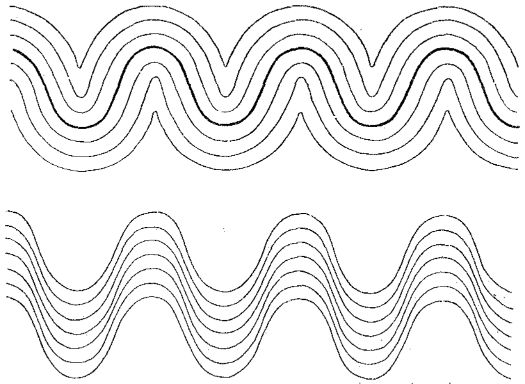


Fig. 4. *A.* parallel folding. *B.* folded true to shape.

but we may state our belief that the substratum will be folded mostly downwards and always in folds having a much larger wave length due to its much larger thickness. Also, it may be folded elsewhere as in the case of the Jura folds, where the shortening of the upper sedimentary strata is probably compensated by a shortening of the substratum in the central Alps.

A fold in its most simple form as represented in fig. 5, shows three important boundary planes: 1. The line $AA'FA''$: the upper boundary of concentric folding, 2. the line $BB'OB''$: the lower boundary of concentric folding, 3. the line $CC'EC''$: the basal shearing plane. The upper boundary need not necessarily be the surface of the earth's crust, nor need the basal shearing plane be the boundary between granitic substratum and sedimentary rock. For the sake of simplicity we will provisionally assume however that the above mentioned theoretical boundaries coïncide with these natural planes.

II. 2. In fig. 5, the shortening of the sedimentary block of thickness t, has been effected by the displacement of the vertical line ABC to the position $A'B'C'$, regarding only the left half of the figure.

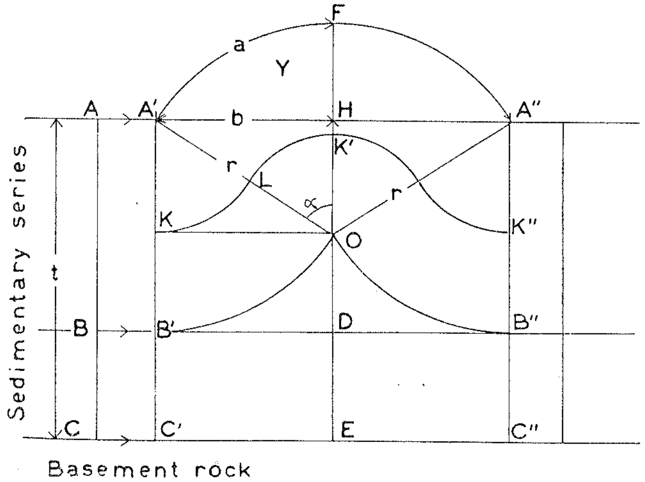


Fig. 5. Simplest shape of a concentric fold.

The pure concentric folding is necessarily confined to the upper part of the sedimentary series of the thickness AB, in the lower half some other way of adjustment to the desired shape has taken place. In the upper half, all the internal movement has been effected along planes parallel to the surface as for instance the line KLK'. Therefore the line KLK' has retained its original length and the same statement is true for all other lines as for instance $A'F$ and $B'O$. As $A'F$ and $B'O$ are sections of circles with the radius r and angle α, with the centres O and A', both $A'F$ and $B'O$ are equal to αr. The line KLK' has the length:

$$\alpha LO + \alpha A'L = \alpha(LO + A'L) = \alpha r.$$

Therefore every line in a section, representing an originally horizontal plane can retain its original length throughout the folding process, even when the shape of the fold is not a simple circular arc because every curve can be described by a number of successive circular arcs. In the latter case, however, only that part of the fold can be folded purely concentrically

inside which no centres of curves are situated. In fig. 1, the ideal concentric fold with perfect stratification, the fold is actually a circular arc with one centre O and two auxilliary centres at the surface, A' and A''. Any other shape will necessitate more centres and therefore a restriction of the concentric part of the fold, reducing the thickness $A'B'$.

II. 3. Thus, the assumption that the simplest and fundamental shape of a fold is a set of three circular arcs, seems to have a foundation. As can be easily seen in fig. 6, the length of the fold, a, and its radius, r, must be dependent of the thickness t of the sedimentary series.

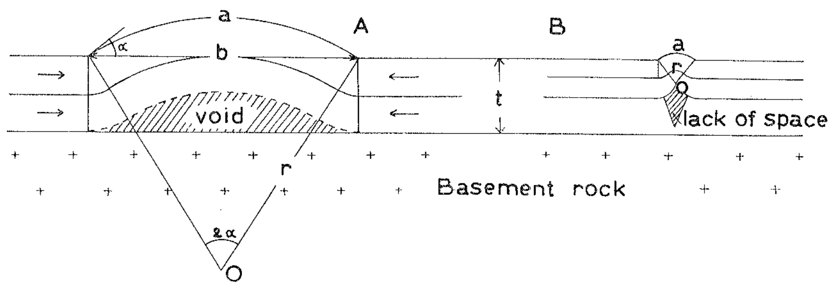


Fig. 6. *A*, too large radius. *B*, too small radius.

When the radius r is too large as in fig $6A$ there must be a void between the basement rock and the sediment and when too small (fig. $6B$) the lower part of sedimentary serie will not find enough place to fill up when compressed to the same degree as the overlying strata.

Thus, if there is a primary reason why the sediment should be folded, and the basement behave in some other way, then the size of a fold will be determined by the thickness t.

The relation between r, and t can be easily calculated, in the case of a circular arc.

In fig. 5, the upper part, having a thickness $A'B'$, of a sedimentary series is folded concentrically, the lower part necessarily in some other way, the whole gliding on its substratum.

As the original volume has been retained the superficies of triangle $B'DO$ must equal the rectangle $BB'C'C$.

$$B\,B'\,C'\,C = r\,(t - r)\,(\alpha - \sin\alpha)$$

$$B'\,D\,O = B'\,D\,O\,K - B'\,O\,K$$

$$= r^2\,(\sin\alpha - \tfrac{1}{2}\sin 2\alpha) - \tfrac{1}{2}\,r^2\,(\alpha - \tfrac{1}{2}\sin 2\alpha)$$

thus $(t - r)\,(\alpha - \sin\alpha) = r\,(\sin\alpha - \tfrac{1}{4}\sin 2\alpha - \tfrac{1}{2}\,\alpha)$

$$t\,(\alpha - \sin\alpha) = r\,(\tfrac{1}{2}\,\alpha - \tfrac{1}{4}\sin 2\,\alpha)$$

and

$$r = 2\,t\,\frac{\alpha - \sin\alpha}{\alpha - \frac{1}{2}\sin 2\,\alpha} \quad \ldots\ldots\ldots \quad (1)$$

further the length $a = \alpha r$ . . . . (2)

the width $b = r \sin \alpha$ . . . . (3)

the shortening $a - b = r(\alpha - \sin \alpha)$ . . . . (4)

and the uplift $y = tr(\alpha - \sin \alpha)$ . . . . (5)

Introducing different values of α in (1) we find that for values of $\alpha < 45°$ r will be $\frac{1}{2}$ t, larger values of α will be followed by an increase of r until $r = \frac{3}{4} t$ when $\alpha = 90°$.

Thus, in the case of the simplest shape of a fold the radius of a fold and its width is directly dependent on the thickness of the sedimentary series. As we have seen in II. 2, there is some reason to believe that the simplest shape really is the fundamental shape, but even other shapes will possess in some more complicated way a direct connection between their size and thickness.

II. 4. The relation between the size of a fold and the thickness of the sedimentary series participating in the fold is beautifully demonstrated by a comparison between folds in the Jura Mountains. In fig. 7 the Reculet fold of the Western Jura is put next to the Lägern fold of the Eastern Jura, drawn on the same scale (HEIM, 1922).

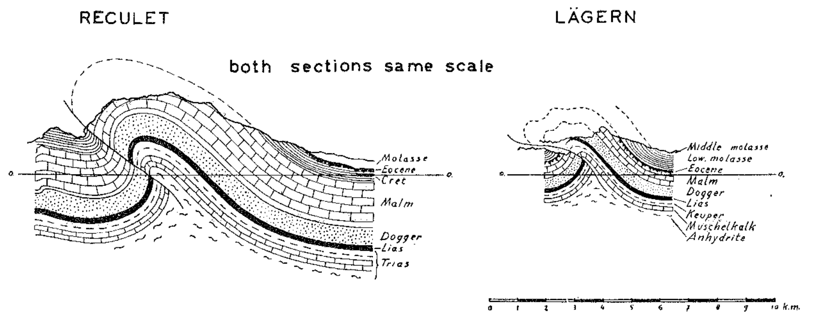


Fig. 7. Comparison between the Reculet and Lägern folds of the Jura Mts.

The sediments participating in the two folds are identical, and their shape is very similar, only the total thickness of the eastern fold is about half that of the western fold. Also the width of the Lägern fold is roughly half the size of the Reculet fold.

This relation is not incidental but could be demonstrated as well by other folds and even by comparing general sections of the eastern and western Jura.

Unfortunately we cannot measure the radius r of neither the Lägern nor the Reculet fold with any accuracy, nor do we know their size before the thrustplanes were formed. Consequently we are not capable of checking the equations 1 to 5.

III. 1. Until now we have assumed a sedimentary series of equal thickness. Often however a normal series thins out towards the margin of the basin (fig. 8). In such case in the left half of the fold, the radius r_1, will be dependent on the average thickness t_1, and will be larger than r_2, dependent on t_2, as $t_1 > t_2$.

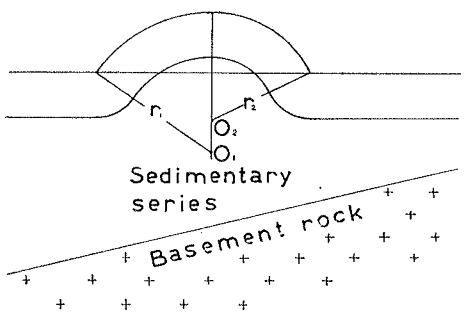


Fig. 8. Asymetric fold due to thinning out of sedimentary series.

The maximum dip in the left limb will be greater than that in the right limb, the fold will be asymmetric.

III. 2. The increase of the load of the uplift for every unit of shortening is unvariable, e.g. although the increasing load will try to prevent the further development in the way of the simple arc, there is no discontinuity in the loading effect. Still, the ever increasing load on a restricted surface will tend to disturb the simple arc by spreading the load over a greater surface. Instead of an ever rising fold with the advantages of minimum deformation, due to minimum dip, there will be a tendency to broaden the fold avoiding the extra load, but necessitating steeper dips in a broader zone than necessary in the first case (fig. 9). Thus we see that a deviation of the simple arc by steepening the dips in one or both flanks is the result of the loading effect, and that even a small thinning out of a part of the formation will be able to call forth a marked asymmetry.

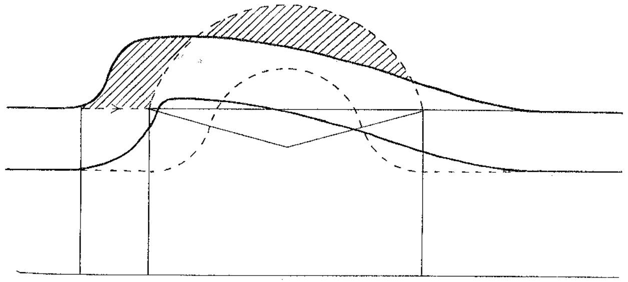


Fig. 9. Asymetric fold due to equal loading effect.

III. 3. In order to check these theoretical conclusions we examined several well known folds of which we will cite a few here.

The first shall be the Hauensteintunnel section (BUXTORF, 1916).

The tunnel happened to cut the overthrusted structure in such a way, that it disclosed the unconformable surface of the Tertiary on the Jurassic. This fortunate fact enables us to reconstruct the original position with some accuracy fig. 10a). Apparently the thinning of the strata towards the North determined the position of the fold, and its asymmetry, the north flank being the steep flank (fig. 10*b*). Progressive folding is shown in fig. 10*c*, the final situation in fig. 10*d*.

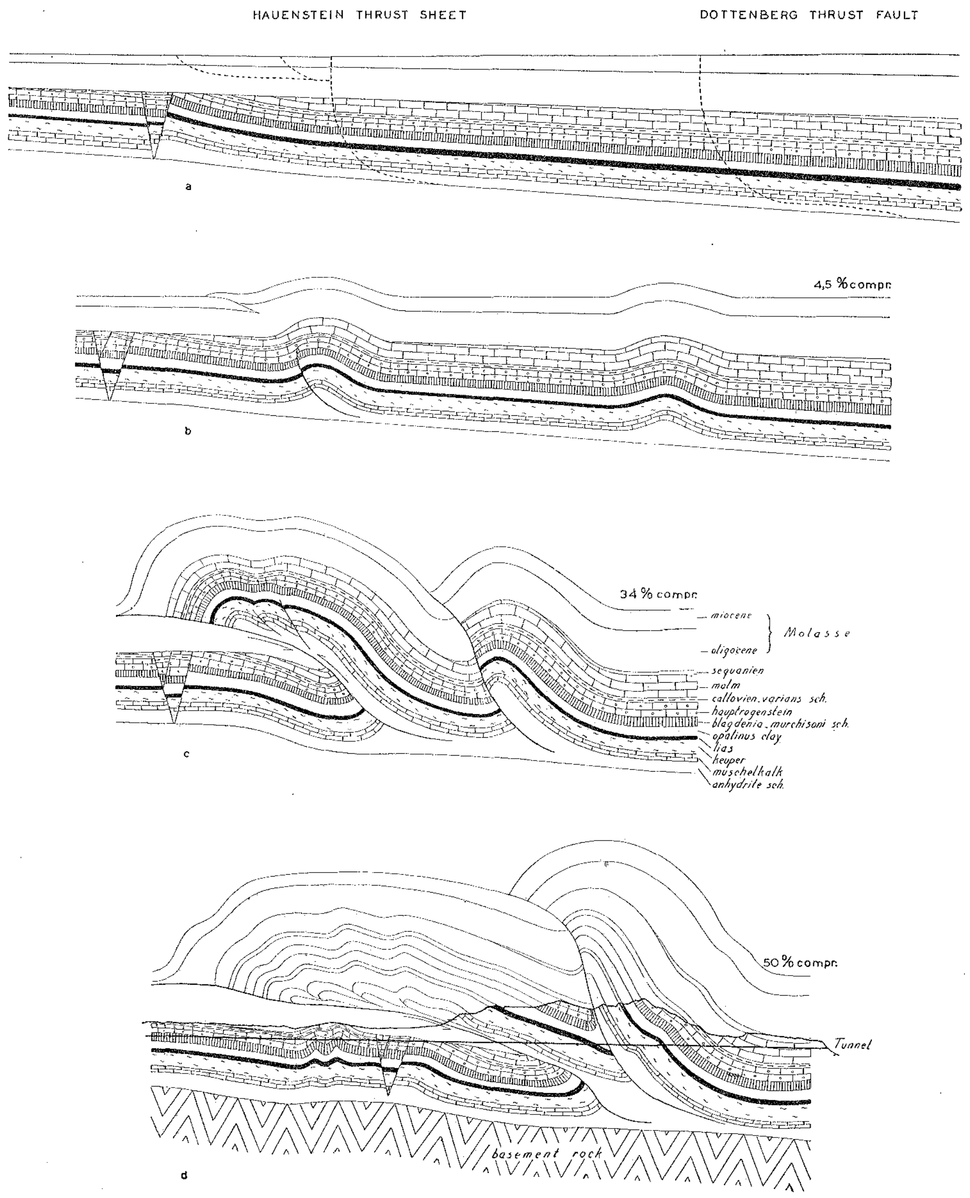


Fig. 10. Hauensteintunnel structure, its development and final stage (after BUXTORF).

The development of the fold is founded on the assumption that an asymmetric fold has been, in this example also, the forerunner of an overthrust, and illustrates our thesis of the cause of asymmetry.

In the Réculet and Lägern folds a similar thinning may perhaps be

assumed but cannot be proven, as neither possesses any subsurface structure disclosed by artificial means.

The anticline of Sarrebrück (PRUVOST 1934) (Fig. 11, plate 1) gives us the same result. We find here a steep S.E. flank, partly overthrusted. due to the thinning out of the lower part of Stephanien against the overlying Holz conglomerate. The steep flank has been explored to a great extent by the mining authorities and the conclusion that the decrease in thickness and disappearance of the Laudrefang member is due to an inter-Stephanien erosion and not to later tectonical causes, seems to be conclusive.

These few examples will suffice us to understand that the primary structure of the sedimentary basin may be in a large way the determining factor of its future structural formation.

III. 4. With a view to the possibility of such close connection between the primary stratigraphic sequence of a sedimentary basin and its future tectonical structure, the Helvetian thrustsheets offered a fruitful research problem.

Analogous to the three major Alpine thrustsheet units viz.: the East-Alpine sheets characterized by thick triassic sediments, the Penninic by their Bündnerschiefer, and the Helvetian by their jurassic and cretaceous limestones, we find here the upper, middle and lower Helvetian sheets, each with their own sedimentary character. The comparison cannot be carried beyond this superficial analogy. Whereas the major units each comprise a complete stratigraphical series, from basement rock up to the Tertiary, the Helvetian sheets are mostly incomplete. Our study restricts itself to the region South and West of the Walen See (Linthtal, Glarner Alps).

The upper Helvetian sheets (Säntis, Räderten, Drusberg) comprise only the Cretaceous, from the Valenginien marls upwards, and the Tertiary. The lower Helvetian sheets show a complete series from Permian upwards, including the Tertiary, in their frontal parts, but are nearly exclusively build up by the Verrucano in their backward parts.

The Axen sheet, called the Middle Helvetian sheet, is characterized by Lias, Dogger and Malm, its frontal part being complete from Liassic upwards to the Tertiary. Roughly speaking we can characterize the three units in this way:

Lower Helvetian sheets	——	Permian
Middle ,, ,,	——	Jurassic
Upper ,, ,,	——	Cretaceous

Since the excellent work of ALBERT and ARNOLD HEIM we know that the position of the thrustsheet units in their original basin was, from North to South as follows:

$N \rightarrow$ Autochtoneous Aarmassif with its sedimentary cover and par-autochtoneous sheets $\rightarrow$ Glarner sheet, Mürtschen sheet (Lower Helvetian)

→ Axen sheet (middle Helvetian) → Säntis, Räderten, Drusberg sheet (upper Helvetian) → *S*.

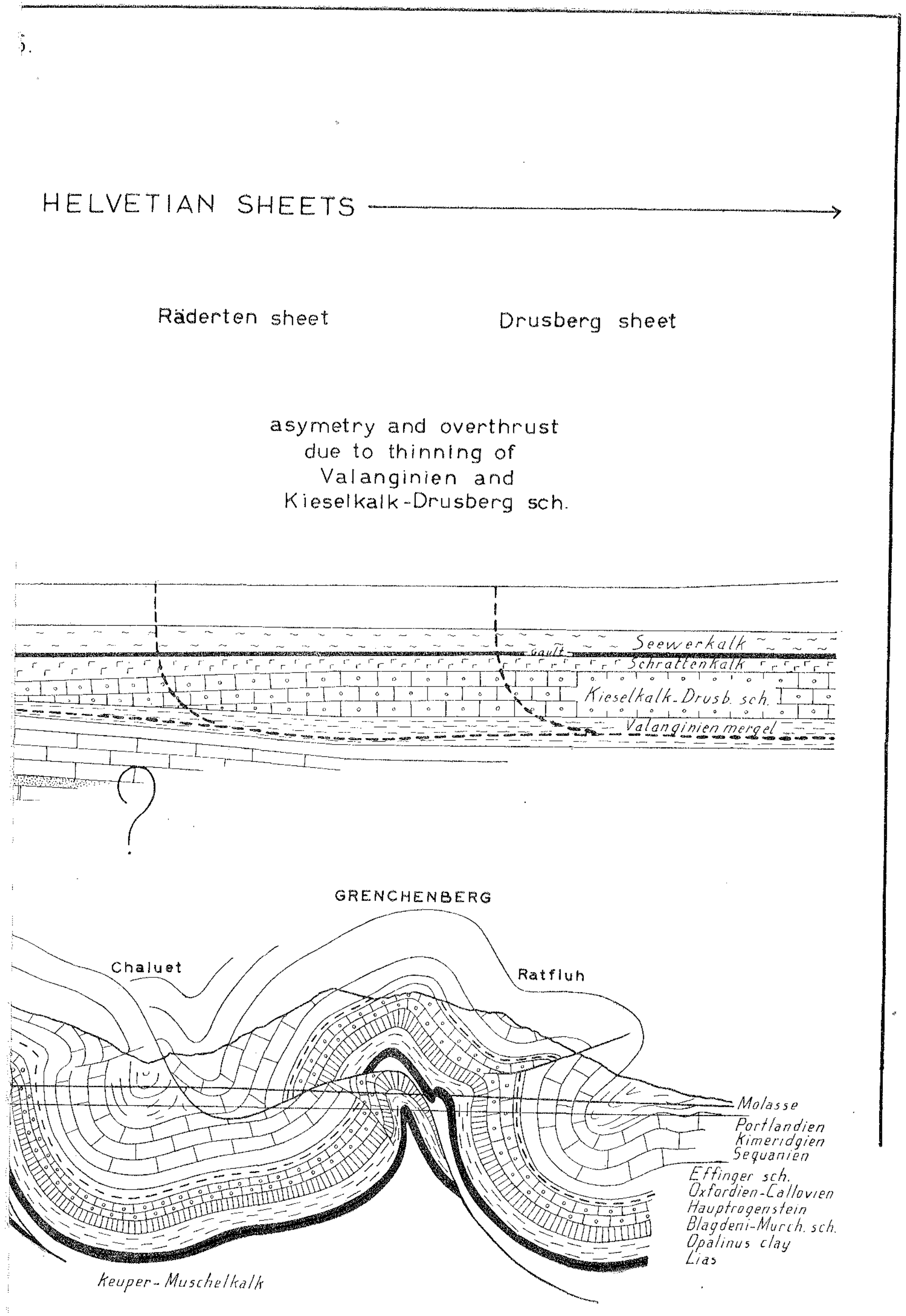
Figure 12, plate 1, represents the reconstruction of this Helvetian basin, along these lines, as accurately as possible. The accurate sections of OBERHOLZER (1933), of which we choose section 12 as the best disclosed one, formed the base of this reconstruction. The observed thicknesses have been rigoureously maintained even when OBERHOLZER supposed an attenuation, because it seems highly improbable that a hard formation as the Malm limestone will show the same attenuation as a soft Valenginien marl. Even in the thinnest part of the Glarner or of the Mürtschen sheet nearly the whole series is complete.

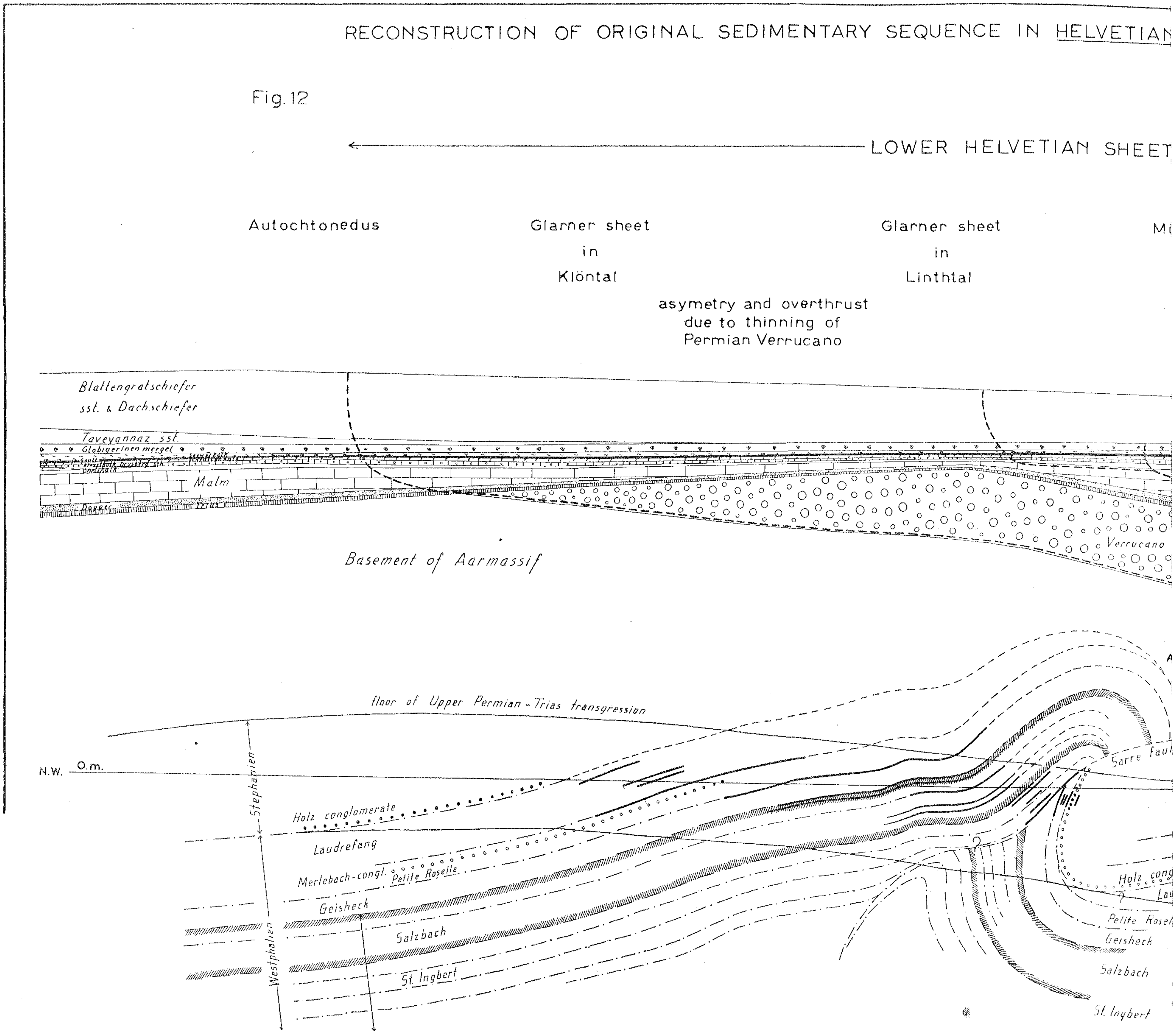
In studying the sedimentary conditions of the Helvetian basin we must realize that it represents only the Northern shelf of the Alpine basin. The Permian Verrucano and sernifite of the Glarner and Mürtschen sheets occurs in the same facies in the Southern Bergamasc Alps, in both localities thinning out and disappearing quickly Westwards. The Triassic sediments of the Helvetian shelf extend in the same facies Southwards in the Penninic sheets and acquire great thickness as limestones and marls in the southern Alps. The Liassic of the Helvetian basin is the shelf extension of the great filling up of the geosynclinal basin then situated in the Penninic centre of the Alpine basin. The Malm limestone extending a little further Northwards than the Liassic, probably continues below the Helvetian sheets even as the Liassic and the Dogger. In the Cretaceous period, however, this *S—N* movement of the subsidence has been arrested; the major subsidence is now found in the southern part of the shelf. In Tertiary times the whole basin was covered by Flysch sediments, the Pratigäu flysch of the Penninic sheets being very similar to the Wild flysch of the Helvetian basin.

By putting together the pieces of the different Helvetian sheets at their appropriate place the section of the original shelf was completed, but not everywhere with the same exactitude, due to the missing parts carried away by erosion.

The frontal parts of the sheets are best disclosed, their backparts often being doubtful, for instance the length of the Axen sheet is completely unknown as its backpart has been eroded away; we have drawn it at its minimum length. At the same time the future position of the thrustplane below every sheet has been drawn into the indisturbed sedimentary sequence. This could be done with great accuracy in the frontal parts and could often be followed rather far back with the help of the adjoining sections.

Studying this basin we notice first of all that the Lower, Middle and Upper Helvetian sheets are not only situated behind one another but also above one another. The Cretaceous of the U. Helv. sheets was situated *above* the Permian of the L. Helv. sheets and above the Jurassic of the



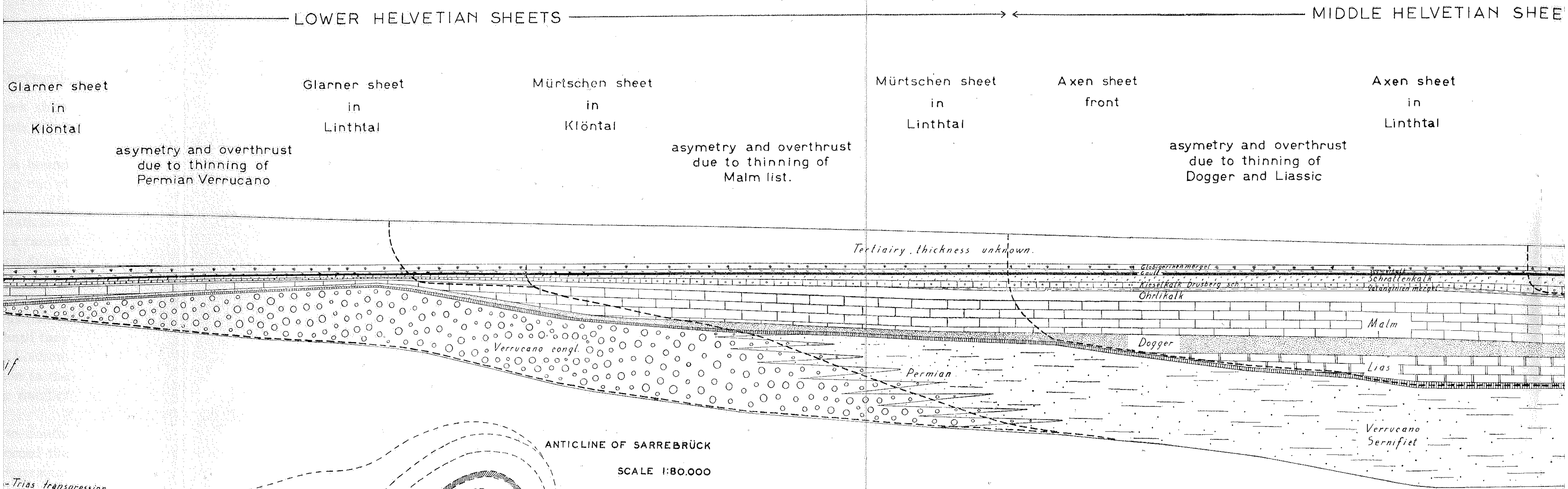

RECONSTRUCTION OF ORIGINAL SEDIMENTARY SEQUENCE IN HELVETIAN
Fig. 12
LOWER HELVETIAN SHEET
Autochtonedus
Glarner sheet in Klöntal
Glarner sheet in Linthtal
asymetry and overthrust due to thinning of Permian Verrucano
Blattengratschiefer
sst. & Dachschiefer
Taveyannaz sst.
Globigerinen mergel
Malm
Trias
Verrucano
Basement of Aarmassif
floor of Upper Permian - Trias transgression
N.W.
O.m.
Stephanien
Westphalien
Holz conglomerate
Laudrefang
Merlebach-congl.
Petite Roselle
Geisheck
Salzbach
St. Ingbert
Sarre faul
Holz cong
Petite Rosel
Geisheck
Salzbach
St. Ingbert

oncentric folding and the dependence of tectonical structure on original sedimentary structure.

N OF ORIGINAL SEDIMENTARY SEQUENCE IN HELVETIAN BASIN IN CROSS SECTION WITH THE HELP OF SECTION 12 AND ADJOINING SECTIONS OF OBERHOLZE

BY L.U. DE SITTER

horiz. and vertic. scale 1:100000



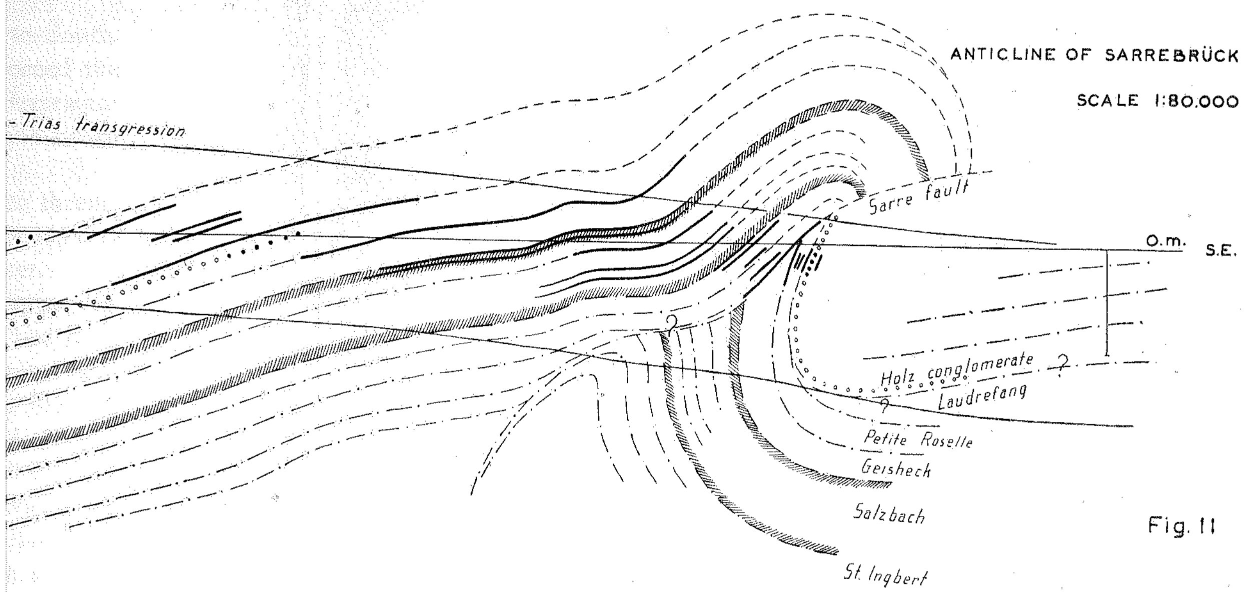


Fig. 11

ECTIONS OF OBERHOLZER, GLARNER ALPS, SHOWING POSITION OF FUTURE THRUSTPLANES.

IDDLE HELVETIAN SHEETS ⟶ ⟵ UPPER HELVETIAN SHEETS ⟶

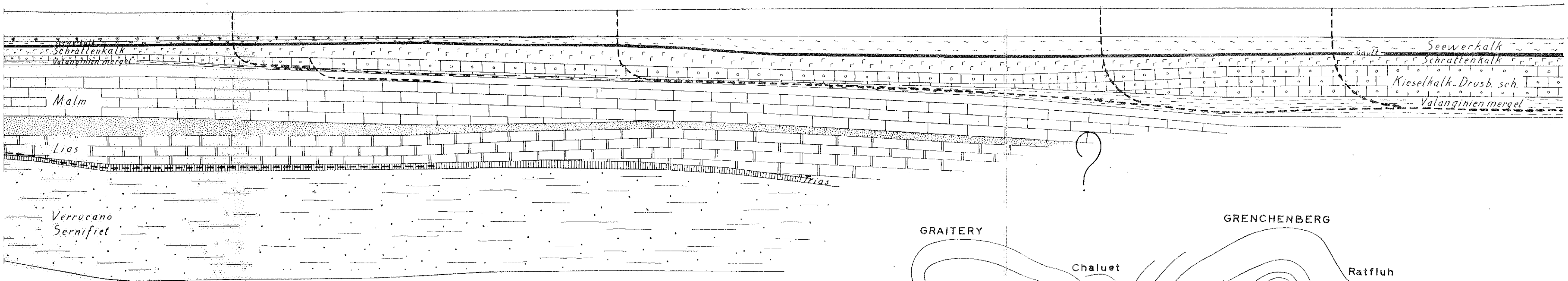
Axen sheet in Linthtal	Bächistock sheet in Glärnish	Säntis sheet	Räderten sheet	Drusberg sheet

ust

due to thinning of Schrattenkalk ?

due to thinning of Seewerkalk ?

asymetry and overthrust due to thinning of Valanginien and Kieselkalk-Drusberg sch.



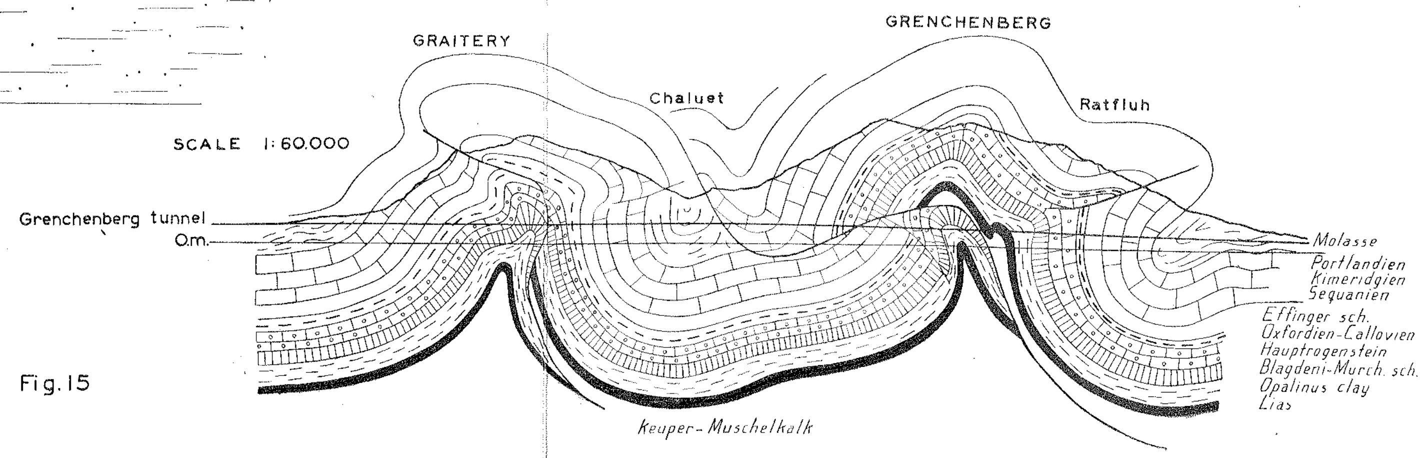


Fig. 15

M. Helv. sheet. Only the frontal parts of the different sheets were situated *behind* one another.

Another natural law concerning the position of the future thrustplanes is easily discernable. *Every thrustplane is bound to the thinning out of a conspiceous member of the sedimentary series.*

Thus:

The thrustplane of the	Glarner sheet	is bound to the thinning of the	Permian
„ „ „ „	Mürtschen „	„ „ „ „ „ „ „	Malm
„ „ „ „	Axen „	„ „ „ „ „ „ „	Lias-Dogger
„ „ „ „	Upper Helv. sheets „	„ „ „ „ „	Kieselkalk-Drusbergsch.

Doubtful is the connection of the thrustplane of the Bächisstock sheet with the thinning out of the Schrattenkalk and that of the Säntis sheet with the thinning out of the Seewerkalk.

There is no exception to the general rule; every thrustplane is bound to the thinning out of a special formation, and even every thinning out of a conspiceous member causes a major thrustplane.

We suppose that at the start of the folding process the anticlines became located above the irregularities of the sedimentary sequence caused by the thinning out of special members in a similar way as has been drawn in fig. 10*b* for the Hauenstein fold. The asymmetry of the folds was determined by the same factor and eventually developed in a thrusting movement directed towards the highest point of the basement rock. The thrustplanes cut down more or less perpendicular through the upper horizons until they found below their special thinning out member a suitable gliding horizon. The upper Helvetian sheets did possess an excellent gliding horizon in the Valenginien marls, which fact may be the cause of their greater number and shortness as compared to the other sheets.

Moreover, each subsequent thrustplane, reckoned from North to South, forced its predecessor further down, viz. the Axen thrustplane forced the Mürtschen thrustplane down through the Permian towards the basement rock; the Säntis thrustplane probably forced the Axen thrustplane down into the Permian.

When this forcing down cannot be effected because the lower thrustplane has reached already the basement rock, the lower thrustsheet is simply cut off from its back part as happened to the Glarner sheet.

This structural phenomenon explains why the highest sheets have moved furthest from their original position. As soon as the Glarner front had been cut off by the Mürtschen thrustplane its independent movement ceased and the Mürtschen sheet, which remained undamaged throughout the folding, passed over the inert mass of the remnant of the Glarner sheet. In the same way I suppose that eventually the Upper Helv. sheets cut off the Axen front and middle part, from its back part and left it, derived from its pushing block, as an inert mass where it had arrived before the mutilation took place. The only thrustsheet front that was not severed from its back part was that of the Mürtschen sheet, now reaching nearly as far North as the Upper Helv. sheets and still extending from root to front over the central granite mass.

This analysis shows that also in this case the tectonical structure is dependent wholly on the primary sedimentary sequence of the basin.

Lateral changes in the sedimentary sequence of the same basin must then also be followed by tectonical changes. Eastwards from the section which we chose (no. 12 of OBERHOLZER) the importance of the Lias-Dogger members decreases, consequently the Axen sheet disappears and the Upper Helv. sheets take over its function and become considerably broader in the Säntis Mountains. The disappearance of the Permian sediments Westwards mark the disappearance of the Mürtschen sheet and strong reduction of the Glarner sheet, the Axen sheet gaining in importance together with the growing mass of Liassic limestones.

The dependency of the tectonical units of the original sedimentary sequence is so clearly demonstrated in the instance of the Glarner Alps that I am confident that also elsewhere this line of research will throw unexpected light on the tectonical development of the origin of simple folds and thrustsheets.

III. 5. The development of a thrustfault out of an asymmetric anticline and eventually to a thrustsheet is a mechanical problem.

ALBERT HEIM largely guided by the structural features of the Säntis Mts in Northern Switzerland assumed that the thrustfaults were due to the extreme attenuation of the middle limb of a recumbent fold, BUXTORF (1916), familiar with the Jura Mts supposed on the contrary that a reverse fault gradually develops into a thrustfaulted anticline. He founded his opposition to HEIM's theory mainly on the fact that nowhere in the Jura Mts and neither in the Helvetian thrustsheets a single clear instance of a recumbent middle limb is known. The thrustplanes of the Helvetian thrustsheets follow over long distances the bottom of a single stratigraphical horizon, occasionally cutting obliquely through a part of the sedimentary series, but everywhere the lowest stratigraphical member of the upper sheet reposes directly on the stratigraphical highest member of the underlying tectonical unit. Sometimes the thrustplane is marked by a mylonite as the Lochsteinlimestone, but as often as not even a mylonite is absent.

The reasoning of BUXTORF would be sound, if we did not see in many instances, even in the Jura Mts, how an asymmetric anticline in lateral direction develops into an overthrusted one. It is difficult to understand how a primary reverse fault could ever develop in an unbroken anticline.

The logical conclusion of these facts is that the original structure was an asymmetric anticline, but the thrustplane coming into existence long before the fold has reached the recumbent state.

The necessity of overthrusting in a relatively early stage of folding is easily understood when we continue to apply the laws of concentricity and retention of volume.

In fig. 5 and the calculation of r, where r is the maximum thickness of pure concentricity, we have shown that only the upper half of the sedimentary series can be folded strictly concentrically. As soon as an extra steepening of one flank, due to the tendency of more equal loading of the uplift, happens, the radius of the curve at that place is decreased considerably e.g. the centre 0_1 (fig. 13) is replaced there by the centre 0_2. The lowest purely concentrically folded layer we call the lower concentricity boundary, which in the latter case is the horizon running through 0_2.

When we compare two layers, 1_1 and 1_2, 1_1 situated above 0_2 and 1_2 below this point, both of the same thickness, it is obvious that the volume of 1_1 has not changed during folding, but that of 1_2, as drawn in fig. 13

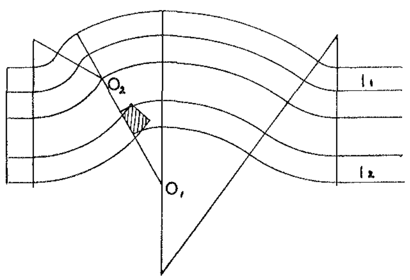


Fig. 13. Conventional way of section construction, disregarding lack of space in centre of anticline.

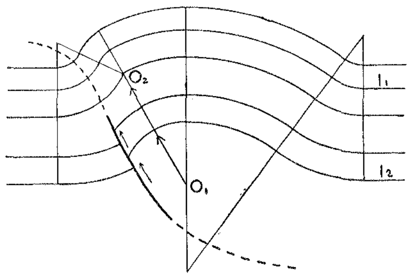


Fig. 14. The origin of an overthrust due to lack of space in centre of anticline.

has diminished by a considerable amount. This amount, hachured in fig. 13, can easily be calculated and increases downwards.

The construction method of fig. 13 is obviously wrong, although it is the usual way of construction (compare BUSK, Earthflexures, Cambridge 1929).

What really happens is this, that in course of the steepening of the dip in the left flank the centre 0_1 rises to the position of 0_2, and every layer it passes in its way upwards breaks through as it can no longer be folded and retain its volume at the same time. Thus the reverse fault originates just above centre 0_1 and follows the upward motion of the centre (fig. 14). The initial thrustfault may be nearly vertical. The strata above, and right of, the fault continue their folding movement, those left and below the fault are successively stopped in their folding as soon as they are ruptured. Finally the whole steep flank is broken by the fault along the broken line of fig. 14. The initial shape of the thrustfault is disclosed in every well developed front of thrustsheet, and always it cuts nearly perpendicular to the stratification through the sedimentary sequence, until it has found its gliding horizon. (Compare the Grenchenberg fold, fig. 15, plate 1).

We notice that the original position of the lower concentricity boundary and that of the gliding horizon determine the shape of the fold. When we deduced in II. 3 the size of the fold from the total thickness, we assumed a sedimentary series gliding over its granitic substratum. But in view of the predominant role of the position of the gliding horizon we must bear in mind that the total thickness only means the thickness of strata folded in one fold, and this thickness may be considerable less than the real thickness of the whole of the sedimentary series overlying a basement rock. Neither is it necessary that the highest concentrically folded horizon is the top layer of a sedimentary series.

Important gliding horizons here and there in the whole series may, and often will, separate horizontally the sedimentary series in tectonical units, each following, on its own terms, the laws of concentric folding and retention of volume, as shown by the superposed Helvetian sheets.

IV. 1. The principle that the depth affected by a fold can be calculated by measuring the uplift and the shortening has been evolved by R. T. CHAMBERLIN (1910). The difficulty for this author was the determination of the shortening. When, as in our conception, the original length of a layer has not changed we can measure the shortening accurately. In fig. 5 the shortening

$$s = A\,F\,A'' - A\,H\,A'' = a - b.$$

The uplift, y, is equal to the surface of $A'\,FA''\,H\,A'$ and can be measured from the section.

Obviously the product of depth affected by the folding, t, and the shortening, $a - b$, should equal the uplift y if no compression takes place.

$$t = \frac{y}{a-b}. \qquad (6)$$

The equation has the advantage that it can be applied to any reference surface, but we must bear in mind that we always have to consider a complete fold, measured from syncline to syncline. The curious way of CHAMBERLIN to divide his wellknown Appalachian profile in arbitrary sections resulted in the wedgeshaped folded triangle.

In order to check the validity of the equation (6) a few folds will be analysed.

IV. 2. The Grenchenberg and Graitery folds (fig. 15, plate 1), both cut by the Grenchenberg tunnel (BUXTORF, 1916) offer us the advantage that, the two folds being close neighbours, the calculated depth, t, calculated for each fold separately, must be sensibly equal. In table I the results of measurements and calculations are tabulated, reference horizon being the base of the Sequanien.

TABLE I.

	Graitery	Grenchenberg	Combined
Shortening $a-b$ in m	1530	3060	4590
Uplift in m^2	1917000	3566700	5483700
Depth of fold t in m	1253	1166	1195

The same calculation was executed for the neighbouring section of the Birscluse, the reference horizon being the top of the Hauptrogenstein some 150 m lower than the base of the Sequanien. The result is listed in table II.

TABLE II

	Les Raimeux	Vellerat	Combined
$a-b$ in m	840	580	1420
y in m^2	848000	560000	1408000
t Hauptrogenstein in m	1010	965	992
t base of seq. in m	1180	1115	1142

The four independent values of t compare very well, the extremes differing less than 6 % from the average.

It would be preferable to check the equation on a fold where we know by artificial or natural disclosures the actual depth of the basement, however, no such fold is known to me where both surface structure and basement rock are well enough disclosed, we will always have to compare neighbouring sections, the one checking the other.

IV. 3. In the same way we can apply the theory to different sections of the same anticline, showing varying shortening. This has been done by analysing a structure explored to great extent by drilling [1]). Fig. 16 shows three sections, A, B and C, A and B being only some 600 m apart, C some 15 km further on the plunge of the same anticline.

The shape of the reference horizon, p, in sections A and B, is specially well known. As can be seen on fig. 16 the top and bottom of this layer have a totally different shape in the zone of the overthrust, still the lengths differ very little, less than 1 % of the total length, proving to a certain extent the concentricity of the folding.

In table III the results of the analysis have been listed.

In all these sections the position of the syncline was a matter of conjecture. In section A, the bottom of the syncline was drawn as high as possible, resulting in a minimum value of both y and t. In section B, the depth of syncline has been drawn more liberally, whilst in section C, the depth was drawn at its probable depth according to that section itself.

Assuming the value of t = 1050 m of section C to be the true folding

[1]) The author offers his thanks to the board of Directors of the Bat. Petr. Co. for the use he was allowed to make of their geological files.

TABLE III

	Section A ref. hor. p	Section B ref. hor. p	Section C ref. hor. p
a	6250—6300 m	6450—6400 m	4500 m
b	4250 m	4200 m	3900 m
a—b	2000—2050 m	2200—2250 m	600 m
Y	1.633.500 m^2	2.014.000 m^2	1.280.000 m^2
t_q			2100 m
t_p	816 m	915 m	1050 m

depth, we can correct the measured values of uplift of sections A and B by introducing this folding depth.

$$Y' = Y + n\,(a\text{–}b) \quad . \; . \; . \; . \; . \; . \; . \; . \quad (7)$$

where n is the increase of folding depth, equal to 1050—816 = 234 m for section A, and 1050—915 = 135 m for section B.
We find:

$$Y' \text{ section } A = 2.101.500 \text{ m}^2$$
$$Y' \text{ section } B = 2.311.000 \text{ m}^2.$$

The value of the shortening, a—b, is hardly effected by increasing the folding depth, both a and b being lengthened by roughly the same amount.
In sections A and B the anticline is strongly overthrusted, the amount of overthrust being 1400 m in section A and 1550 m in section B, whereas in section C the thrusting movement has only just begun and can probably be disregarded.
Comparing the shortening in the three sections we see that the difference in amount of shortening is exactly equal to the respective amounts of overthrusts. (Table IV).

TABLE IV

Shortening section A	600 + 1400 = 2000 m	measured 2000 — 2050 m
Shortening section B	600 + 1550 = 2150 m	measured 2200 — 2250 m

From this feature we may conclude that section C represents an earlier stade of compression than the sections A and B.
A continued compression of section C, would then necessarily result in the shape of fold represented by sections A and B. When, m, is the increase of shortening then the resulting uplift will be

$$Y' = Y + t\,m \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (8)$$

However, before we can compare the sections we must calculate the

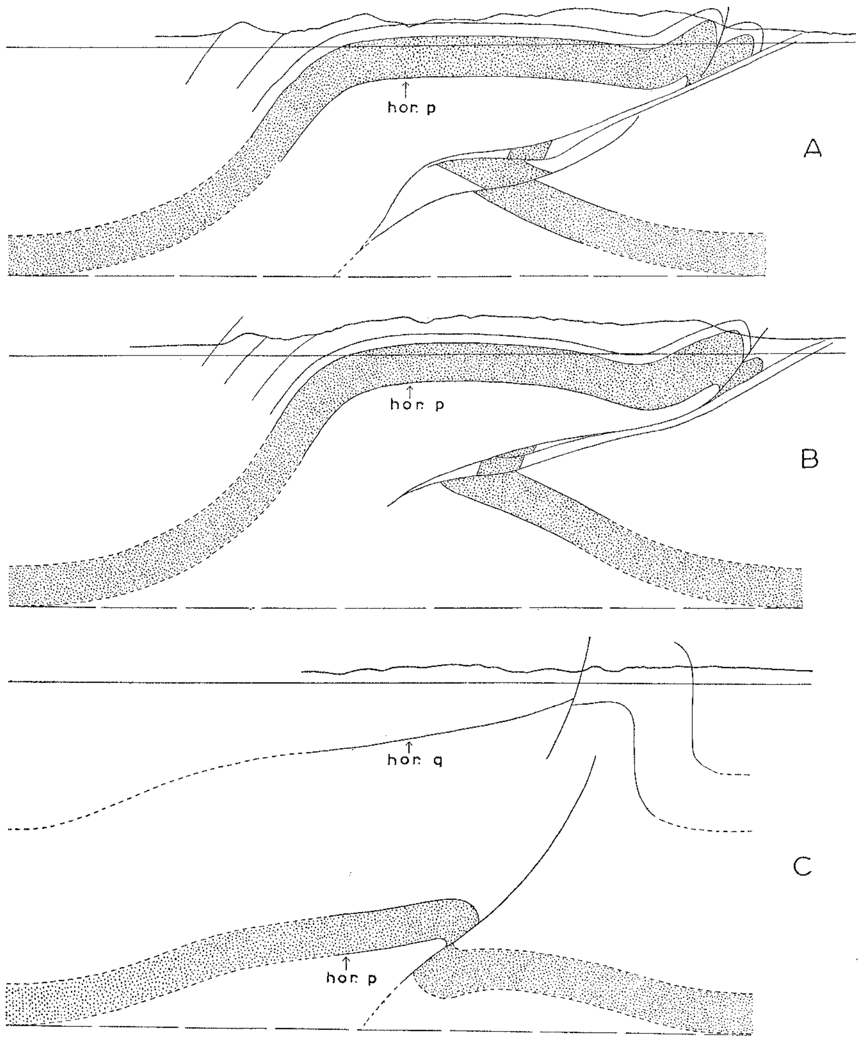


Fig. 16. Cross sections through a well explored anticline, based on drilling results.

uplift, Y_p, of the reference horizon p in section C by multiplying the folding depth t_p = 1050 m by the shortening a—b = 600, we find

$$Y_p \text{ in section } C = 630.000 \text{ m}^2.$$

Introducing this value of Y in eq. (8), and the values of 1400 m and 1550 m of m, for sections A and B respectively, we find:

$$Y' \text{ section } A = 2.100.000$$
$$Y' \text{ section } B = 2.257.500.$$

In table V the final comparison has been tabulated.

TABLE V

	Section A	Section B	Difference
Y' according to eq (7).	2101500 m^2	2100000 m^2	1500 m^2 0.07 %
Y' according to eq. (8)	2311000 m^2	2257500 m^2	53500 m^2 2 %

The very close agreement we notice in tables IV en V is a warrant of the validity of the theory.

We can conclude that without doubt the whole anticline has everywhere the same folding depth.

The practical value of this conclusion is manifold viz.:

1st Intermediate sections, which are badly disclosed, can be partly reconstructed by interpolating the values of Y and $a—b$; 2nd the folding depth itself may be of considerable interest; 3rd the prognose of the tectonical structure of the subsurface is much less a matter of conjecture because the length a and the shortening are known beforehand.

We must bear in mind, however, that the lower part of a fold is not necessarily folded concentrically. Already from the earliest start of the fold a part of the formation situated below the concentricity boundary must adopt itself to the available space, and this may be done by a compression fold comparable to fig. 3, or by faulting.

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Botany. — *Some remarks on the mechanism of spiral growth of the sporangiophore of Phycomyces and a suggestion for its further explanation.* By A. N. J. HEYN. (Communicated by Prof. G. VAN ITERSON.)

(Communicated at the meeting of April 29, 1939.)

The spiral growth of the spore bearing cell of Phycomyces, as first described by BURGEFF, 1915, and more especially studied by OORT, 1931, has become a phenomenon of more general interest later on in relation to the study of the mechanism of cell elongation.

During elongation this unicellular sporangiophore rotates round its long axis. OORT and ROELOFSEN, 1932, were the first to endeavour to give an explanation of the phenomenon. Referring to the old hypothesis of DIPPEL, 1868, and VAN ITERSON, 1927, on the relation between protoplasmic streaming and the orientation of new particles in the cell wall, these authors investigated whether a connection existed between the phenomenon of rotation and the direction of protoplasmic streaming in the spore bearing cell of this fungus. (A. *Theory of protoplasmic streaming*).

They were unsuccessful, however, in correlating protoplasmic streaming and spiral growth, no oblique direction of streaming being observed in the zone of elongation. These observations were confirmed later on by POP, 1938, who even described protoplasmic streaming as taking place always in a direction parallel with the long axis of the organ in the elongating zone. POP, however, adheres to the theory of protoplasmic streaming as the direction of streaming observed may in some undefined way result in *oblique* orientation of cell wall molecules on account of the asymmetry of the chitin molecules.

A study of the double refraction of the cell wall, by OORT and ROELOFSEN, revealed, that the wall consists of three different layers. The middle or main layer of the wall has positive birefringence, the long axis of the index ellipsoid forming a small angle with the long axis of the wall. Of the thin layer outside the main layer, the long axis of the index ellipsoid is almost perpendicular to that of the middle layer. The birefringences of these two layers compensate each other at a distance of about 2 mm from the sporogonium (the zone of elongation also laying within these 2 mm). Below these zones the birefringence of the middle layer preponderates, whereas above it the birefringence of the outer layer predominates [1]).

[1]) The conclusion of OORT and ROELOFSEN that in the older sporangiophore the middle layer is even completely absent in the zone of elongation does not of necessity follow from the optical data, as these data can be sufficiently explained by *a less complete crystalline structure* of the middle layer in the growth zone (as it follows from the X-ray observations to be referred to in the following).