Geology. — *Origin of the Jura Mountains.* By J. H. F. UMBGROVE.

(Communicated at the meeting of October 30, 1948.)

1. The oldest rocks in the Jura Mountains belong to one special stratum of the Mid-Triassic. Even in tunnels and in the core of deeply cut anticlines no older rocks appear to view. This layer of the so-called anhydrite group contains beds of rock-salt. Apparently, as suggested by BUXTORF since 1908, the anhydrite group played the rôle of a lubricant over which the overlying strata could glide and — detached from the underlying basement — were compressed into folds. Hence the Jura Mountains are considered as a surface phenomenon, a superficial type of folding which Swiss geologists have named *décollement*.

The arcuate chain of the Juras is framed by the basement blocks of Black Forest, Vosges, and Plateau Central. And in between the two last named the high situation of the basement is revealed by a few smaller outcrops of crystalline rocks (fig. 1).

Apparently the site and extern boundary of the Jura Mountains is in some way related to the surrounding "frame work" of high situated basement rocks the movement of the surface layers having been hampered by and becoming adapted to the updomed basement of the surroundings. In the depressed area of the Rhine graben the frontal chains of the Jura Mountains protrude farther northward than in the adjacent sectors which are opposite the higher situated blocks of Black Forest and Vosges.

On the other hand the whole arrangement of the Juras, as well as their time of origin clearly show a relation to the Alps. Two structural trends occur in the Jura Mountains. In the region between Basle and the Swiss plain [1]) the dominant pattern consists of longitudinal folds with E–W trends, the second feature is formed by several short anticlines with N.N.E. to N.E. trend. Thus the rectangular shape of the Delémont basin is due to a framework of folds consisting of these two elements. Another example is to be seen even as far south as the Verena anticline, a short and faulted anticline protruding from Molasse strata between Solothurn and the Weissenstein. The latter is one of the highest and southernmost longitudinal anticlines of this part of the Jura Mountains. To these examples many others enumerated by VONDERSCHMITT could be added. Moreover numerous faults run in the same direction. Now this direction is also displayed by the faults of the Rhine graben. Moreover they are of the same age, viz. they originated in Oligocene times, though some were rejuvenated in Miocene times. There even existed a connection between the Rhine graben and the Molasse trough across the present area of the Jura Mountains in Oligocene (Stampian) times, the so-called Rauracian graben (fig. 1).

[1]) See fig. 1 and also the tectonogram in UMBGROVE, op. cit. 1948, p. 764, fig. 1.

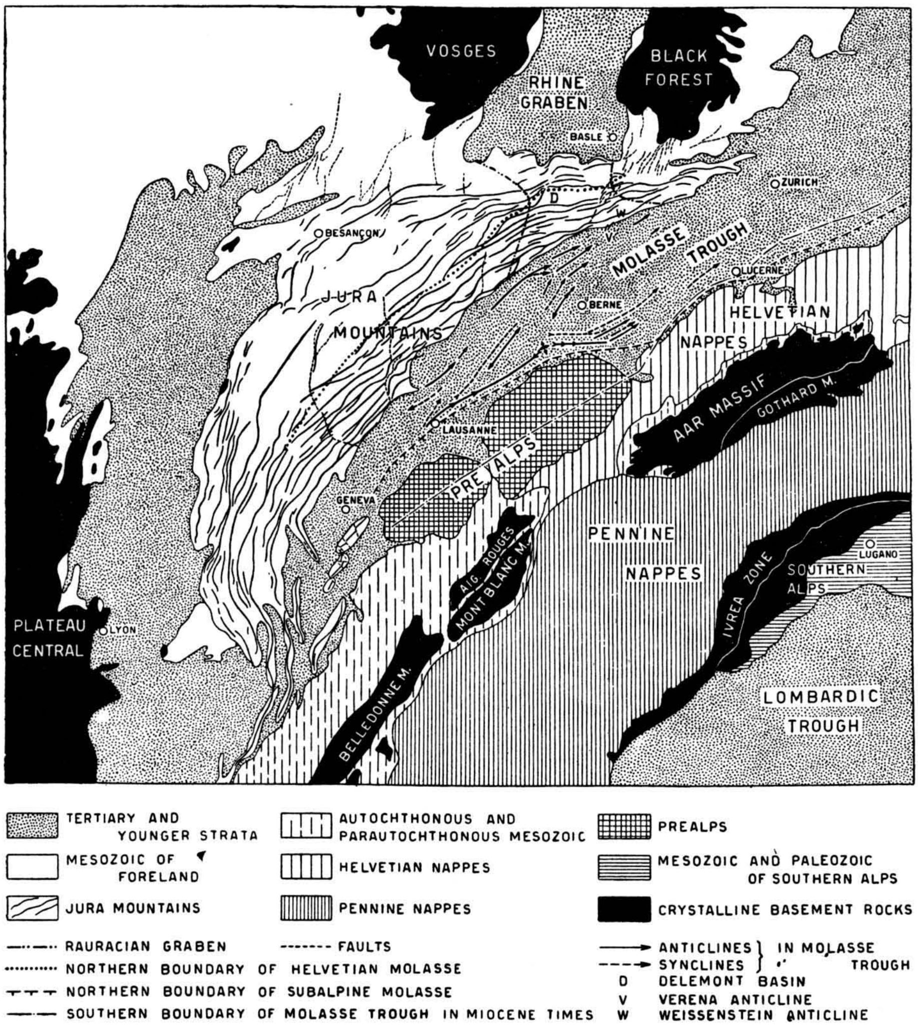

Fig. 1. Major structural elements of the Swiss Alps and adjacent areas.

Apart from the NE–SW system some faults originated at right angles to them and they often include small rift-like blocks, which GLANGEAUD called *pincées* [2]). The age of these is again Oligocene [3]).

On the other hand the longitudinal system of Jura folds originated towards the end of the Miocene. At that time the present pattern of two intersecting structural elements became completed. However, the transverse folds are quite different from the folds of the dominating longitudinal system. They are less numerous, they can be followed over a short distance only, and some of them show the characteristic arrangement which is called *en*

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[2]) GLANGEAUD, 1944, p. 27.

[3]) HEIM, 1919, p. 571, Taf. XXI; BUXTORF, 1934, p. 529, fig. 3, and GLANGEAUD, 1944, p. 24, 25 and fig. 2, 7 and 8.

échelon. After a discussion of several theories VONDERSCHMITT concludes these features can be best explained in the following manner. A system of short *en échelon* folds originated in the strata overlying the fault zone when adjacent blocks with their basement at different depth were subjected to differential movements.

Probably similar movements caused the Vosges to be moved relatively in a southern direction as compared to the Black Forest block which underwent a relative movement northward. However, the same final positions would result if all the blocks moved southward but over different distances.

The longitudinal Jura chains originated towards the end of the Miocene [4]). So they did not yet exist when the sediments of the Molasse trough accumulated. As a matter of fact Molasse sediments spread over large areas of the present Jura Mountains (fig. 3) and still occur in several synclines including the Delémont basin. With the exception of the area of the Rauracian graben their thickness is not appreciable if compared to the thickness of the deposits in the Molasse trough. Aquitanian strata of the Molasse trough overlain by Burdigalian still have a thickness of 400 m as far north as the southernmost Jura chain near Büttenberg (which is south of the Rauracian graben between Solothurn and Biel [5]). However, in the syncline of Tavannes-Court, which is about 8 km northward in the Jura Mountains, Aquitanian strata are lacking and the Burdigalian rests directly on Oligocene (Stampian) sediments. Hence the southern boundary of the Jura chains coincides approximately with the original outer boundary of the Molasse trough. A theory on the origin of the Juras ought to explain this coincidence.

2. ALBERT HEIM compared the Jura Mountains to a table cloth that being pushed to one side became rumpled into ridges and valleys. In his opinion the push came from the south. When the Alps were being compressed they are supposed to have pushed the Jura Mountains northward in front of them. Gliding over the lubricant layer of the Mid-Triassic the upper strata were pushed into folds over the unfolded basement consisting of Lower Triassic, Permian, and crystalline rocks. One wonders how this process took place, separated as the Alps are from the Weissenstein by a stretch of 20 miles of a low and rather flat country, the so-called Swiss plain which is the surface of the Molasse trough (fig. 2).

Undoubtedly the tectonics of the Molasse trough will prove more intricate the more detailed mapping, deep borings, and geophysical

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4) According to BUXTORF (1938, p. 381) the Upper Miocene folding probably can be devided into a pre-Pontian, and a post-Pontian phase. However, he remarked: "vielleicht gibt die künftige Prüfung die Notwendigkeit ihrer Verlegung in etwas frühere Abschnitte des Obermiocän". For the sake of arguement we will indicate the time of *décollement* as: Upper Miocene.

5) BAUMBERGER, p. 75.

investigations will be carried out. As a matter of fact a map of the western part of the trough published recently by KOPP shows several additional anticlines and synclines when compared to BAUMBERGER's map of 1934 (fig. 1).

Still, however, the fact remains that the moderate undulations of the Molasse strata form a strong contrast to the structure of the Jura Mountains. If a push from the Alps was transferred through the prism of Molasse sediments so as to cause the folding of the Juras why then was only the southern part of the trough strongly influenced by this pushing action, whereas the northern part remained nearly undisturbed? 6)

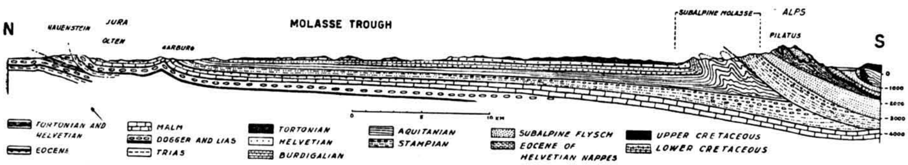

Fig. 2. Section across the Molasse trough (from BAUMBERGER).

This is still less comprehensible if downsliding was a main factor in the *mise en place* of the Helvetian nappes as is at present believed by some geologists.

Moreover the disturbed structure of the subalpine Molasse as well as the frontal parts of the Helvetian nappes are due to tectonic action of the basement according to several authors. In the central massifs the basement of both the Helvetian nappes and the Swiss plain is exposed. These massifs, consisting of a great number of wedges of crystalline rocks, were subjected to differential movements and the frontal parts of some of them reach as far as the Windgälle, Jungfrau, Breithorn and Muthorn, where they overthrust Mesozoic and Tertiary rocks of the High Calcareous Alps. It can hardly be denied that movements of similar wedges in the basement were responsible for the tectonics of the subalpine Molasse. This theory was offered by GÜNZLER (fig. 3), it was expressed by BERSIER 7) in a section across the Molasse trough near Geneva, (fig. 4 and 5) and again by HABICHT in his generalized section across the subalpine Molasse near Ricken—Speer.

Generally, the wedge-shaped elements have been considered as a result of northward overthrusting. More probably, however, the main factor responsible for their origin was a process of progressive underthrusting of the foreland towards the Alps, as was explained at some length by the present author in a previous paper.

6) Cf. BAUMBERGER, op. cit. p. 73, 74; BAILEY, op. cit. p. 33.

7) According to KOPP the Molasse in BERSIER's section is much too thick. Instead of 5000 metres he thinks about 3000 metres would be a more probable figure and more in accordance with seismic data.

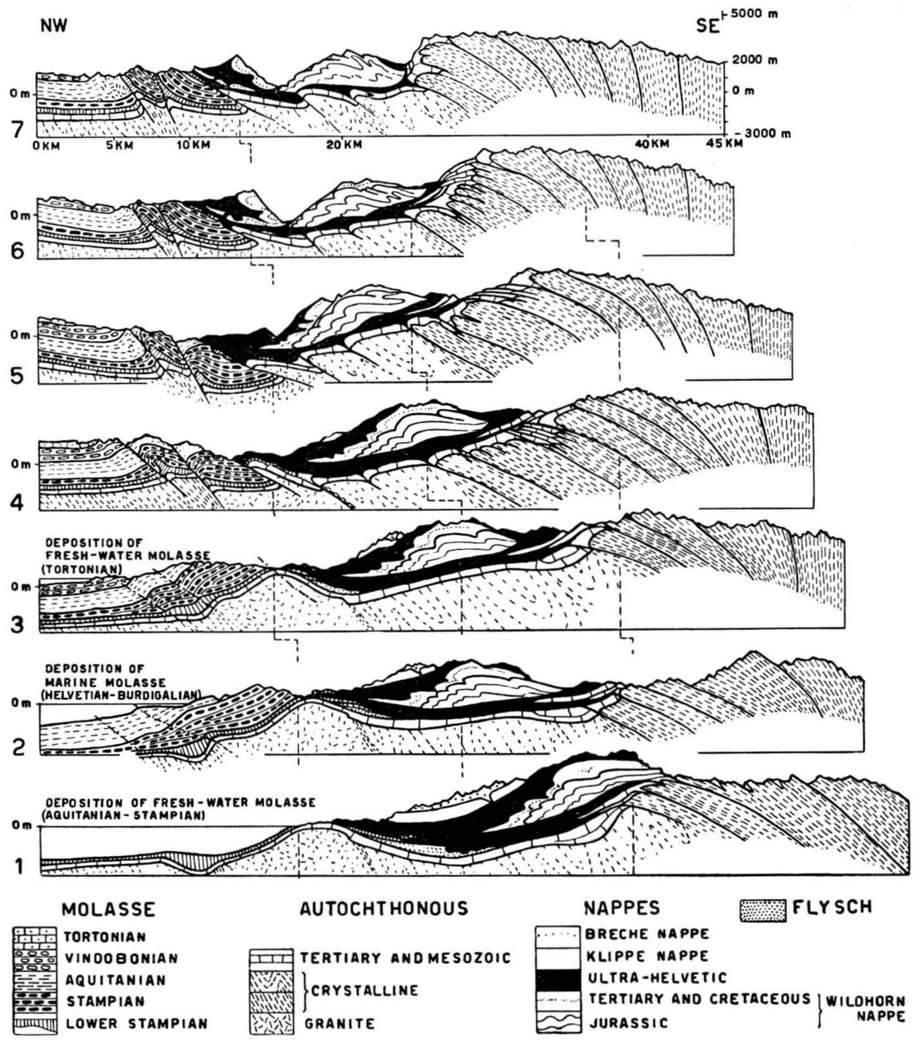

Fig. 3. Differential movements along basement wedges affecting the Central Massifs and the southern part of the Molasse trough (adapted from GÜNZLER).

3. BERSIER's profile (fig. 4) expresses a theory which is different from HEIM's inasmuch as a tangential push from the south is supposed to be transmitted underneath the Molasse trough towards its northwestern border where it caused the folding of the Jura Moutains. With respect to this representation the question again arises: why did the Juras become folded while an intervening pile of Molasse strata remained nearly undisturbed?

How far the typical sequence of Triassic and Jurassic layers extend beyond the Jura Mountains in S. and S.E. direction is unknown. The Trias of the Alps is developed in a quite different manner. However, to postulate that the lubricating layer coincides exactly with the present

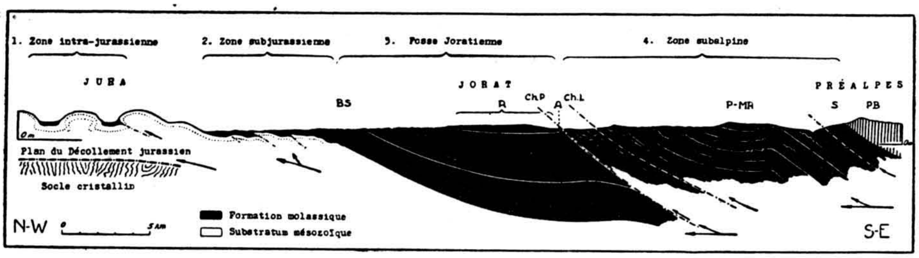

Fig. 4. Section across the western part of the Molasse trough (after BERSIER), compare fig. 5.

boundary of the Jura Mountains would be a too unsatisfactory theory. Besides it is not in agreement with known facts.

In the same manner the thickness and weight of the Molasse sediments cannot possibly furnish a full explanation because the Molasse trough extends much farther eastward than the easternmost Jura chains. Probably the processes involved were of a more complicated nature.

4. LUGEON went still further and considered the Jura Mountains as a nappe which slid into its present position under the influence of gravity. According to one suggestion a vertical uplift of the "central massifs" (Aar—Gothard, Aiguilles Rouges—M. Blanc) caused a downsliding of the plastic layers in N. and NW directions. The impulse is supposed to be transferred below the Molasse trough. The masses sliding and accumulating under the influence of gravity are supposed to have caused the *décollement* of the Jura Mountains and their adaptation to the surrounding framework of basement rocks. However, not only does the basement below the Jura Mountains dip towards the S and SE, i.e. in the opposite direction of the supposed gliding of the Jura strata, but one might reasonably expect an enormous gap either between the Juras and the Molasse trough or between the latter and the High Calcareous Alps.

Therefore LUGEON thinks the pressing out of plastic layers below the weight of sediments of the Molasse trough in an outward direction must have caused the folding of the Juras. Even this suggestion does not explain the shortening of the upper structure as displayed by the Jura Mountains. Moreover instead of folding in the Upper Miocene one might expect a gradual process keeping pace with the accumulation of Molasse sediments and causing the out-squeezing of the plastic layers along the outer boundary of the Molasse trough. According to LUGEON the extension of the Jura Mountains corresponds to the occurence of the series of Central Massifs. The latter disappear below the Helvetian nappes and possibly continue eastward in deeper realms. The point of disappearance would find its counterpart in the easternmost Jura anticline.

However, a line connecting the westernmost outcrops of the central massifs with those of the Vosges is far from parallel with a line which connects the easternmost outcrop of the central massifs with the eastern boundary of the Black Forest massif. This fact can easily be seen on a geological map and is clearly illustrated by OULIANOFF who also suggests an original connection between Vosges—Black Forest and central massifs, which was broken up subsequently. On the other hand there is a close relation between the extent and arrangement of the Jura anticlines and the situation of basement rocks along their outer boundary.

5. In short, in the simile of the table cloth being crumpled and forced over the table by some sort of pushing activety from the south, the following main problems remain unsolved: (1) what was the pushing element causing the *décollement,* (2) why does the inner boundary of the Jura Mountains coincide with the outer boundary of the Molasse trough, (3) why did the time of the *décollement* coincide with the Upper Miocene phase of diastrophism whereas such a phenomenon did not occur at the time of the much stronger Oligocene movements, (4) why did the greater part of the Molasse trough remain nearly undisturbed?

Theoretically there is a second possible way of crumpling a table cloth. Imagine we keep the cloth fixed at a certain point and then pull the table southward instead of pushing its cover northward, The result would be the same. Though an inconvenient manner of demonstration the simile is probably more relevant to what actually occurred when the Jura Mountains originated.

Our present knowledge of the structure of the Alps leads to the conclusion that a process of major importance was progressive underthrusting of both the northern and southern "forelands" towards the central belt of the Alps. The same process probably played an important part in the formation of the Jura Mountains.

Due to the process of the Miocene *décollement* the superstructure suffered a compression of about 6 to 10 kilometres or 25 percent. If we accept a process of southward underthrusting of the basement, one question still remains unanswered, viz. why did not the Jura strata slip under the Molasse trough, or more concisely what was the obstacle that kept the "table cloth" fixed at the present inner margin of the Jura Mountains?

The Oligocene movements in the Jura Mountains were contemporaneous with a phase of strong diastrophism in the Alps. However, only faults and some accompanying transverse folds came into being at that time. The dominating pattern of much stronger developed longitudinal folds originated during the more recent though not so strong phases of compression in the Upper Miocene. There must, therefore, be a reason not only why the longitudinal pattern originated in the Upper Miocene but also why it did not come into being with the much stronger Oligocene phase of diastrophism. Apparently the factor — or factors — which caused the upper layers to become stripped off from their basement so as to result in the Miocene *décollement* was — or were — not yet present during the Oligocene diastrophism. After the Oligocene diastrophism the Molasse trough came into being. Therefore it seems reasonable to consider the possible rôle played by this new element. Moreover the Rhine graben came into being in the Oligocene, though probably a first downward movement started already in the Eocene. However, the rising movement of the Rhine Shield which caused the formation of Vosges and Black Forest in the shape of high situated blocks took place in more recent times and had reached an appreciable amount in the Upper Miocene.

Hence the influence of the updoming basement of the foreland is a second factor which needs further consideration.

6. During the formation of the Molasse trough the basement under the trough subsided by an amount of about 3000 metres. In this movement the marginal flexures were the week strips predestined to become zones of tectonic disturbances during the subsequent epoch of diastrophism. Thus the tectonic disturbances along the inner boundary of the trough have to be considered as a necessary consequence of the general southward underthrusting of the basement during the Upper Miocene phase. Proceeding northward the next zone of weakness is the outer margin of the Molasse trough. Here, however, the situation was different inasmuch as the bottom of the trough slopes in the same direction as the underthrusting basement. Probably, therefore, the faults and crystalline basement wedges which originated along the outer margin of the trough were of minor importance if compared to those along the inner margin. A wedge-shaped element of the basement along the outer boundary of the Molasse trough was already drawn by STAUB [8]). BERSIER's profile (fig. 4) can be easily completed in a similar way (fig. 5).

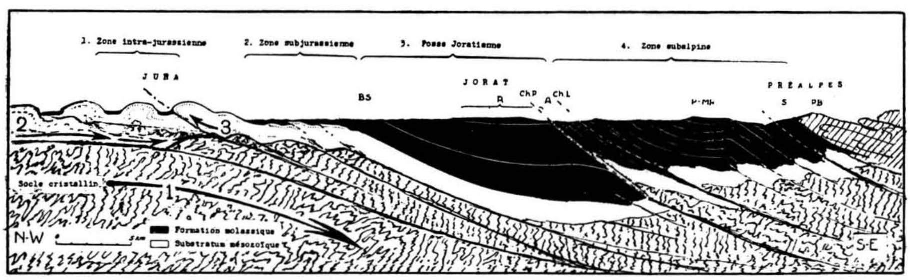

Fig. 5. The same section as fig. 4 with addition of basement. The arrow shows supposed direction of underthrusting.

Possibly the prism of Molasse sediments, if of a certain thickness and rigidity, formed in itself another and additional obstacle. Let us accept,

[8]) R. STAUB, op. cit. profiles 16—21. Wedges in the floor of the trough originated only where the trough is very narrow; see STAUB profile 21 (below the Salève fold).

for a moment, one or more obstacles along the outer boundary of the trough which prevented the upper layers of the Juras from being dragged along when southward underthrusting of the basement occurred. Even then the problem is not yet solved. For the Molasse trough extends much farther eastward than the Jura chains. Therefore the problem is only solved if there is a plausible reason for supposing the basement wedges not to have originated along the outer margin of the trough eastward of the present Jura Mountains.

7. I believe there is indeed a plausible reason for the origin of basement wedges along the inner side of the present Jura Mountains and their absence more eastward viz. the origin and extension of the other "new" element. Its influence was already mentioned in § 1. The shape of the Jura arc is adapted to the surrounding outcrops of basement rocks. Its eastward end corresponds exactly to the eastern boundary of the Black Forest (fig. 1), and the northernmost Jura folds protrude farther northward in the Rhine graben as contrasted to the adjacent sectors opposite Vosges and Black Forest. Hence it seems clear that without the presence of the highly situated basement rocks the Jura arc would not have formed.

It must be realised that only in some special areas the basement rocks have been elevated so high as to form large horst-like blocks like Vosges and Black Forest. However, a general tilting movement took place in a much wider surrounding area. Even in the Rhine graben the renewed movements along faults that occurred in Aquitanian times were accompanied by elevation according to VONDERSCHMITT [9]). So the surface of the basement under the Jura strata became gradually sloping upwards in an outward direction. This holds good also for the western part of the Juras. For even in this region, where the Juras are separated from the Plateau Central by the Saone-Rhône depression, outcrops of basement rocks are found along the outer margin of the Jura arc (fig. 1). Though the outer boundary of the Juras has the general appearance of a gently curved arc, it actually consists of two arcs (fig. 1). According to LUGEON a southwestern arc called *arc Lédonien* reaches as far as Salins from where a second arc, the so-called *arc bisontin* can be traced eastwards. Possibly this phenomenon is due to different amounts of tilt of the basement under the two respective arcs, the surface under the Lédonian arc dipping at a slightly greater angle if compared to the basement under the "arc bisontin".

Apparently subsidence of the Molasse trough was not sufficient to predestine the origin of basement wedges along its outer boundary. Only when, at the same time, the outer boundary of the trough became the inner boundary of an area with opposite movement —i.e. of an upward tilting of the present area of the Juras — the hinge line between the two opposed movements was weakened to such a degree that basement wedges

[9]) VONDERSCHMITT, 1942, p. 94.

and consequently a *décollement* could originate. Tentatively the situation is represented by blocks A—D of fig. 6. The tilted basement is shown by blocks A, B and C.

Block D represents a schematic profile east of the Black Forest. There the basement has not been tilted in an outward direction. Consequently no basement wedges originated and no *décollement* took place.

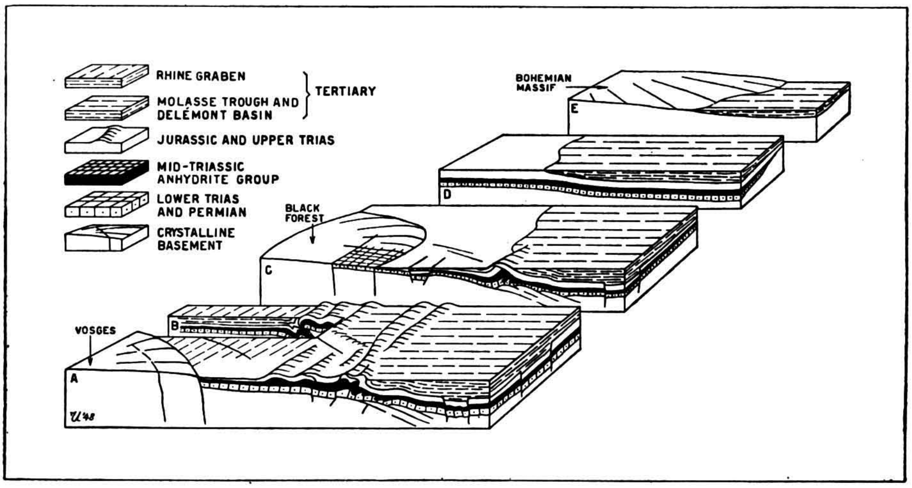

Fig. 6. Schematic representation of different sectors between Vosges and Bohemian Massif.

Still further eastward again there is a high situated block of basement rocks, the Bohemian massif (fig. 6, block E). There, however, neither Jura strata nor a lubricating layer are present. Moreover the prism of Molasse sediments is thinner and rests directly on the granites and gneisses of the Bohemian massif [10]).

Moreover, it is the upward slope of the basement that — combined with four other factors — was of deciding importance in controlling the outer boundary and shape of the Jura arc as well as the character of the folding.

The four other factors were: (1) the lubricating layer, (2) a certain thickness [11]) of the upper structure, (3) the limited space in transverse direction due to the obstacles along the outer boundary of the Molasse trough, and (4) Alpward underthrusting of the basement.

In the Rhine graben the basement is at a lower level than on the adjacent blocks. It is for this reason that *ceteris paribus* the outermost folds of the

[10]) See KOBER, op. cit. pp. 159 and 161; STAUB op. cit. profiles 1—3 (compare also profile 23). On STAUB's profiles no wedge-shaped obstacle of basement rocks is drawn along the northern margin of the trough.

[11]) The relation between the size of a fold and the thickness of the strata participating in the folding was discussed by DE SITTER (op. cit. 1929, with several examples from the Jura Mountains).

longitudinal system occur farther northward than on the higher blocks on either side (where similar conditions controlling the outer boundary of the arc are to be found more southward, see fig. 6, blocks A, B, C).

In short, the fact that a structure like the Jura Mountains is an exceptional feature means that its formation is due to the accidental presence and interaction of several factors. If we accept a southward movement of the basement the evident reason why the layers above the lubricant layer became folded within the limited space of the Juras is the presence of the upward slope of the basement rocks in an outward direction. In this process, however, one or more other factors were responsible for the coincidence of the inner margin of the Juras with the outer margin of part of the Molasse trough.

8. It seems improbable that the basement under the Juras is so smooth as was originally supposed. On the contrary structural elements of the basement dating from Oligocene times (some even from earlier times) presumably had a great influence in the development and arrangement of the Upper Miocene folds. Regarding the transverse elements this was already mentioned in § 1. Several transverse folds reveal the influence of an older pattern of the substratum in a convincing way. According to LINIGER the anticlines wich surround the Delémont basin existed even in pre-Stampian times, but they became rejuvenated subsequently, once in the Oligocene, and once again in the Miocene. Some of the Oligocene transverse faults became rejuvenated during the Miocene phases of movement. Among them is the well-known set of transcurrent faults. Probably, however, several longitudinal elements of the basement also had a great influence in the arrangement of the Upper Miocene pattern of folds.

The possible influence of basement wedges was suggested by AUBERT whose opinion is clearly represented in fig. 7. If such structures exist their

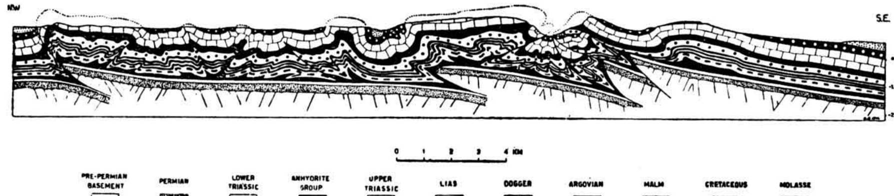

Fig. 7. Wedge-shaped structures in the basement of the Jura Mountains (after AUBERT).

origin is probably due to the same phenomenon of Alpward underthrusting of the basement that caused similar though larger wedges along the inner margin of the Juras. If so they must also have originated in the Upper Miocene. Another possibility is that longitudinal faults and relatively small graben-like structures (the *pincées* of GLANGEAUD, cf. § 1) dating from Oligocene or even older times had a great influence in the arrangement of the Upper Miocene pattern of the Juras. This idea is substantiated in the schematic and tentative blockdiagrams of fig. 6 and 8. Most probably both features played a rôle of importance.

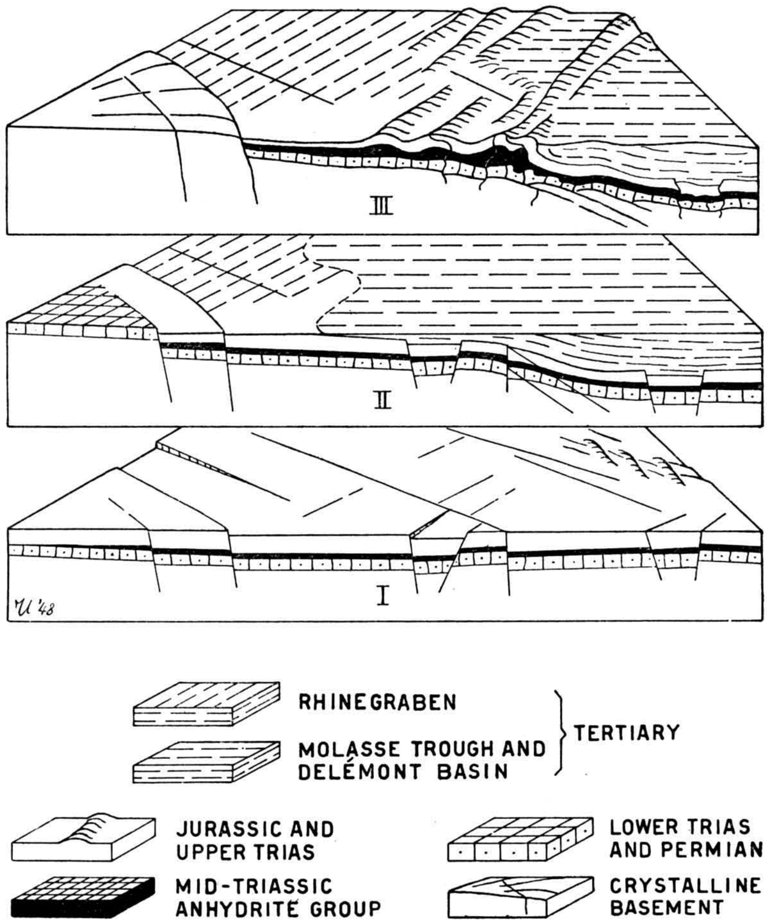

Fig. 8. The suggested sequence of events that gave origin to the Jura Mountains.

9. Finally, the suggested sequence of events that gave origin to the Jura Mountains is represented schematically by fig. 8 whereas a tectonogram showing the area under discussion in its coherence with the structural elements of the Alps, was published in my previous paper on *the root of the Alps.*

Block I of fig. 8 represents the situation after the Oligocene diastrophism. At a later stage the Molasse trough came into being (block II). The basement became gradually tilted outward and in part highly elevated to form the high situated blocks of the foreland (Black Forest, Vosges, Plateau Central) as well as the smaller outcrops in between them. During the

Upper Miocene phases of compression the inner margin of the trough became strongly influenced by movements along faults — parallel to the margin of the trough — which were due to a southward underthrusting of the basement and which caused the subalpine Molasse to become tilted and warped (fig 3). Due to the same general process of underthrusting another set of faults and intervening basement wedges originated along the next zone of weakness, viz. along the outer boundary of the trough (fig. 8, block III).

However, they originated only where the flexure became weakened by the upward tilting of the basement in the adjacent surrounding area. Without this additional weakening of the flexure no basement wedges and therefore no Jura Mountains would have originated (cf. fig. 6, A—D).

The wedges formed an obstacle which prevented the strata above the lubricating layer of the Mid-Triassic from being dragged along southward and downward so as to partake in the movement of the basement underthrusting towards the Alps. Possibly the prism of Molasse sediments formed an additional factor. The superstructure gliding over the lubricating layer became stripped off and rumpled into folds which in their general arrangement had to become adapted to the high situated basement. Possibly the connection between the lubricating layer below the Juras and its continuation under the Molasse trough was already broken or squeezed off during the subsidence of the trough and the additional tilting of the surrounding foreland. If so, this was a third reason for the coincidence of the outer margin of the Molasse trough and the inner boundary of the *décollement*. How far the sub-Jurassic layers extend under the Molasse trough is unknown. The manner in which they are drawn in fig. 6 is entirely arbitrary. The same holds good for the extension of the Jura-layers. The wedges are also drawn very schematically in the blockdiagram. Undoubtedly the situation is much more complicated, and possibly it would be better to imagine zones of imbrication instead of wedges which are a too simplistic representation. Among the Oligocene structural elements that became rejuvenated during the Upper Miocene phases is a set of transcurrent faults.

Though the major problematic points enumerated in § 5, seem largely cleared up by the suggested sequence of events, several questions need further examination. A better understanding of the complicated mechanism involved and a quantitative estimate of the rôle played by the interacting factors are wanted before the problem can be considered as solved. It may be expected that a thorough seismic investigation of the Juras and adjacent strips, combined with a gravimetric survey, will prove of great importance in this respect and, possibly, it will reveal also several unknown and unexpected features, and new problems.

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