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REPORT ON AN INVESTIGATION OF THE GEOLOGICAL STRUCTURE OF THE ALPS

BY

BAILEY WILLIS

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REPORT ON AN INVESTIGATION OF THE GEOLOGICAL STRUCTURE OF THE ALPS.[1]

By BAILEY WILLIS

Eight years ago I first had the pleasure of meeting Prof. Maurice Lugeon on the memorable occasion of his striking address and remarkable triumph at the Vienna Congress of Geologists in 1903. The subject of overthrusts which he then discussed so graphically and with so much force was not unfamiliar to me, that type of structure having been recognized first by the American geologist Rogers, whose observations I had had occasion to verify. I was, therefore, fully prepared to accept the view that the Alps had been overthrust. I did not then, and I do not now, doubt that they consist chiefly of overthrust masses. Nor do I question the amount of displacement. Even the greatest horizontal movements which are postulated to account for the various nappes that have been observed, are relatively small as compared with the long arcs of the earth's periphery, in which the movement must have originated; and the accumulated effect which we may observe in any case should not occasion doubt.

It is a pleasure to me to be able to agree with Prof. Lugeon in these fundamental conceptions of the importance and extent of overthrusting in the structure of mountain chains, and particularly of the Alps. I regret the more that there are differences of opinion between us as to the mechanics of overthrusts, and that this divergence of interpretation is such that I have not been able to accept his views on the structure of the Alps as cordially and fully as I should like to do. But, inasmuch as Alpine structure is one of the great types from which our science draws essential conclusions, I hold it to be important to reach a correct interpretation of it, and I have for some years assiduously endeavored to understand the basis of Prof. Lugeon's views and the grounds upon which they have been accepted generally by European geologists. Through the aid of the Smithsonian Insti-

[1] This investigation was carried on by means of a grant from the Smithsonian Institution in 1907.

tution, I visited, in 1907, certain critical districts in the Bernese Alps and was most courteously guided to significant localities in the Diablerets and near Château d'Eux by Prof. Lugeon and M. Jaccard. The observations which I was thus enabled to make confirmed my opinion that the visible structures must be essentially those which Prof. Lugeon had described as seen by him, but that his interpretation rests upon mistaken assumptions and is erroneous. The detail of his observations and the painstaking care with which they are made are worthy of the highest recognition, but, in my opinion, the purely hypothetical formula expressed in the conventional figure of a "pli-nappe" is incorrect.

In the interests of our science, I have sincerely hoped that Prof. Lugeon would explain the structure and movement of the "nappes de recouvrement" as he conceives them, and that his explanation would include such modifications of the accepted theory that it would not contradict the principles of mechanics. Particularly since the publication of the observations of Professor Rothpletz, in the section across Préalpes from Gurnigel to the Wildstrübel, it has seemed to me that the theory of the "nappes de recouvrement," involving the concepts of the "racine," the "carapace," and the "tête," must be justified or corrected. But, so far as I know, no adequate answer to Professor Rothpletz, nor any searching study of the mechanics of the "pli-nappe," has been made.

There is good ground, in my opinion, to question the following assumptions or inferences of the currently accepted theory of Alpine structure:

(1) That the overthrust masses of the Alps have all moved in one direction.

(2) That the so-called "racine" of a nappe de recouvrement is, in fact, the zone of origin of the thrust mass.

(3) That the supposed "tête" is that part of the structure which has advanced beyond the "carapace" and the "racine"!

(4) That the succession of overthrusts in the Bernese Alps has been as described, either in relations of space or time.

From the observations which I made in 1907, I infer that:

(1) Overthrusting in the zone of the Préalpes and Bernese Alps has proceeded at different epochs from opposed directions: namely, earlier from the northwest, later from the southeast.

(2) The so-called "racine" of the pli-nappe of the Wildhorn-Wildstrübel is, in fact, the southern and farthest advanced remnant of an overthrust from the northwest.

(3) The isolated masses of pre-Eocene strata, which have been called remnants of the tête or front of the same pli-nappe, and others which I saw near Château d'Eux, have been cut off by intersecting overthrusts. They first moved southward or southeastward and later northward or northwestward, in both movements rising on the inclined thrust planes. Their present position is thus above but not distant from that which they originally occupied. The same is true of the so-called "exotic" masses of the Préalpes which constitute the "têtes" of the hypothetical nappes des Klippes.

(4) The thrust which divides the pli de Morcles from that of the Diablerets is a minor thrust plane rising from a major thrust plane that underlies the Hautes-Alpes, and is one of a system of minor thrusts which, with the major thrust, constitute a single complex structure of the Scottish Highland type.

(5) Since the principal concrete example of a "pli-nappe" or nappe de recouvrement, that of the Wildhorn-Wildstrübel, is, according to my observation, not a pli-nappe but an effect of two intersecting thrusts, I am unable to accept the reconstruction of less complete nappes de recouvrement, which, according to modern theory, were once piled up, one overriding the other, to form the Alps. I regard it as probable that the recognition of intersecting overthrusts and of systems of major and minor thrusts of the Scottish type, combined with unusual but incidental folding, will eventually be found to explain a large part of Alpine structures.

The observations which led me to these views were as follows:

First, as to the existence of thrusts from opposed directions. The evidence of that fact I first observed near Lenk, in the valley and heights, up to and including the base of the Wildstrübel. It is stratigraphic, structural, and physiographic. For identification of strata in the field on paleontologic evidence I am indebted to Professor Rothpletz, whom I chanced to meet at Zweisimmen and with whom I examined the locality. We there discussed and verified our observations of structure. The physiographic relations, which had great weight with me because I had seen similar effects in the Lewis Range of Montana, were unfamiliar to him as a basis of inference, and may be regarded as an independent line of reasoning.

The stratigraphy of the district of Lenk, which lies in the southern Préalpes, is well established. The Triassic, Jurassic, and Eocene are more or less fully represented by very distinctive formations which, in the order named, are essentially gypsiferous shales or gypsum (Triassic), blue marine limestone (Jurassic), and sandy brown shales

(the facies of the Eocene, commonly called "Flysch"). The Cretaceous is scarcely present, there being a marked hiatus between the Jurassic limestones and the earthy red lime-shales that correspond to its highest horizon. The Flysch, which was originally a very thick formation, has been thickened by folding and thrusting, so that it constitutes the dominant rock of the hills. The Jurassic limestone and the Triassic gypsiferous shales occur in the Flysch as fragments which have been separated from their original connections by thrusting.

The internal structure of the Flysch is obscured by sward, but its principal features may be traced by the fragments of pre-Eocene formations. Where Jurassic or Triassic rests upon Flysch, the contact of the older upon the younger formation is obviously a thrust plane. Where two or more such contacts, though somewhat apart, fall into a common plane of dip, they may reasonably be connected as belong-

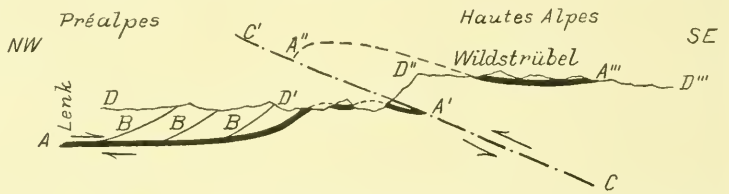

FIG. 1.—Diagram of intersecting thrusts observed near Lenk and in the Wildstrübel.

AA'A''A''' = plane of a major thrust from the northwest. *B, B, B,* = minor thrusts branching from the major thrust *AA'* and belonging to one system with it. *CC'* = thrust from the southeast, intersecting and disturbing the older thrust *AA'A''A'''*. *DD'* and *D''D'''* = surface of erosion developed after the thrust *AA'A''A'''* and before the thrust *CC'*; dislocated by the latter and involved in the elevation of the Hautes-Alpes.

ing to one and the same thrust. And where several such planes lie parallel one to another, they form a system of thrusts; such, for instance, as that diagrammatically represented by the minor thrusts *B, B, B* in Fig. 1.

Near Lenk, in the hills which rise on each side of the valley that is eroded across the strike, this structure is clearly represented by the fragments of Jurassic limestone that form little scarps in the smooth grass-grown slopes of Flysch. Having traced out the several parallel thrusts on one side of the valley, one may identify each one on the other side by corresponding features of the hills and slopes. This Professor Rothpletz and I did, and we observed that the planes of these parallel thrusts dip northwestward at moderate angles. Our observations

have been fully described by Professor Rothpletz in the article already referred to. (See p. 2.)

Beneath the valley and adjacent hills is a thrust plane which is nearly horizontal. It is exposed near Lenk in the very bottom of the valley, and has long been recognized by Swiss geologists as one of the major structural features of the "zone des Cols" and of the "Niesen." We observed that the Flysch at this contact rests upon the nummulitic Eocene; that is to say, that the terrigenous sandy shales had been thrust upon the marine limestone of the same general period.

The relation of this nearly horizontal thrust plane to those which, at steeper inclinations, traverse the hills on either side is that of a major thrust to minor thrusts of the same system, as shown by *B, B* to *AA'*, Fig. 1. The general dip is northwestward. In that direction the minor thrusts join the major thrust and the system is represented farther northwest by other minor thrusts.

In a region like the Alps, where thrust planes have been folded, the direction of thrusting cannot safely be inferred from the dip of a single plane. But granting this, it is quite a different matter when the inference rests on the agreement of several minor thrusts and the major thrust from which they spring. The system of major and minor thrusts to be seen at Lenk demonstrates that the Flysch of that region and the fragments of older strata included in it moved from northwest toward southeast.

This observation is surprising, because it is in such marked contradiction to the fact that European geologists have in recent years given up the idea of movements from the north or northwest. They appear to have abandoned the field too readily to those who assert that the Alps have been pressed northwestward only. At Lenk there is clear evidence of southeastward movement.

It will be necessary to identify this mass which has been thrust southward, in its southern extension. But before doing so, it is desirable to refer here to the great thrust that underlies the Wildstrübel and other portions of the Bernese Hautes-Alpes (*CC'*, Fig. 1). It is, of course, well-known. With the superb recumbent fold which is so magnificently exposed in the face of the Wildstrübel, it constitutes a most striking example of that structure which is now described as a "pli-nappe," and which Rogers first recognized in the Appalachians as an overturned anticline and reversed fault. Heim elucidated the mechanics of the structure. It has been experimentally reproduced. The overturned anticline precedes displacement on the thrust plane when a couple of opposed forces develops in strata in

the zone of moderate load and folding; but when dislocation originates in the deeper zone, where excessive load prevents competent folding, the movement, on being transmitted to strata in the zone of folding, may produce a recumbent anticline as an incidental structure. Displacements of the former class are usually of moderate horizontal throw, rarely more than ten or twenty kilometers, but they may be features of a very extensive general movement. Such I take this pli-nappe of the Wildstrübel to be: an overturned anticline which has been pushed far enough to dislocate the middle limb, although not necessarily to a great distance. It is, however, a striking feature of the pronounced movement of the mass of the Alps from southeast toward northwest. Since there is no question of this movement toward the northwest, we may accept it without discussion.

I must here advert to the difference of facies between the strata of the Préalpes and those of the Hautes-Alpes. The former is an incomplete sequence, comprising but a few of the Mesozoic stages and the Eocene. The latter is a very complete succession from Triassic to Eocene inclusive. The one is composed chiefly of sands and muds, the other of marine limestones. The contrast could scarcely be more marked.

Accepting this well-known distinction, we may say that the two facies are superimposed, each on the other, by the thrusts from opposite directions. The Flysch of the Préalpes, in being thrust toward the southeast on the major thrust plane, came to rest on the surface of the marine nummulitic Eocene of the facies of the Hautes-Alpes. This contact is seen in the valley floor near Lenk, as already described. The marine strata which form the Hautes-Alpes may, in turn, be seen superimposed on the Flysch at the base of the great cliffs which form the face of the Wildstrübel south of Lenk. The contact marks the thrust plane, which dips southeast and on which movement was toward the northwest.

Having become convinced, contrary to my expectations, but by my own observations, that the structures of this district comprise two intersecting systems of overthrusts, I sought to determine which might be the older system. The evidence on this point is unequivocal.

Going from Lenk southward to the base of the Wildstrübel one may observe that the major and minor thrusts of the system on which displacement was southward rise in the hills. Near Lenk the planes dip nearly uniformly. Near the base of the Wildstrübel they are folded into anticlinal and synclinal structures. Although long fa-

miliar with folded thrust planes as they occur in the Appalachians and have been described by Keith, I have never elsewhere seen such clear and convincing examples as are to be found here. The anticline of the Iffigental, which shows a superb arch of Jurassic limestone overlying the Eocene Flysch, is without an equal in my experience for perfection and simplicity; and the folded thrust planes of the foothills north of the Wildstrübel (Oberlaubhorn and Laufbodenhorn), though more intricate, are no less clearly defined. At the immediate base of the Wildstrübel the disturbance of the thrust planes is more intricate and minute. They are affected by shearing as well as by folding; and tracing these minor secondary structures directly to the great overthrust on which movement was from the opposite direction, one cannot doubt that they were produced by that movement. Hence, the thrust from the southeast is younger than that from the northwest.

A method of investigation which has been more widely adopted by American geologists than by those of Europe, is based upon the relation that may exist between structures, such as folds or thrusts, and the features developed by erosion. I know many mountain ranges whose internal structures are older than the erosion of the surface. I know others whose relief is an effect of relatively recent folding or thrusting. On examining the Préalpes and Hautes-Alpes with this relation in mind, I found a clear distinction between the movement from the northwest, which is older than any recognizable erosion of the region, and the movement from the southeast, which is younger than the earliest erosion cycle that I could recognize. The succession of events was: (1) movement from the northwest; (2) erosion to a mature stage, with moderate relief; (3) movement from the southeast, resulting in dislocation of the older structures and also of the mature erosion surface, together with the elevation of the Hautes-Alpes; (4) erosion of the younger features of topography as they now exist.

The observations which I made on these points were as follows:

In the Préalpes I detected features pertaining to two different cycles of erosion. The more recent is represented by the deep valleys and slopes of the present stage. The other is an older, mature surface, which may be seen in the long ridges and summits of the Préalpes. It is extensively and generally dissected by the later valleys, but there are many flat areas which are not the result of any structure or of any recent condition of erosion. They represent the lower levels of the mature surface in which the present valleys are

so deeply cut, and they are being destroyed by current activities. The hills that rose above these old levels were of moderate altitude, 200 meters, more or less, and were maintained by the relatively hard limestone fragments involved in the overthrust masses of the Flysch. The old topographic surface thus resulted from differential erosion of a region which had already been disturbed by movement from the northwest. The thrusts had brought up the limestone fragments, but any ridges which may initially have been produced by thrusting had been eroded and replaced by hills adjusted to the the relatively harder rocks. This mature topographic surface is well seen in the Hahnenmoos and surrounding hills above Lenk, and may be recognized from that point of view as an obvious landscape of the summits of the Préalpes.

A mature erosion surface of parallel development to that just described is to be seen in the Hautes-Alpes. I would cite the ice-covered flat of the Plaine Morte as an illustration of its development in the Wildstrübel. This basin, though now the gathering-ground of a glacier, is not due to glaciation; nor is it due to structure of the rocks. It is an erosion surface of gentle grade, with more or less surviving relief worked out before it was elevated to its present position. Where it now lies, its destiny is to be cut to pieces by the development of ravines in the mountain mass of the Wildstrübel. It lies a thousand meters above the homologous surface in the Préalpes and is separated from it by the thrust plane on which the Wildstrübel moved northwestward. The thrust plane rises in that direction; the mass of the Wildstrübel must have been raised in advancing up the incline, and the altitude of the Plaine Morte above its homologue in the Préalpes may, with reason, be attributed to that upward movement.

From these relations I draw the conclusion that the thrusting from the southeast occurred after the erosion cycle had advanced to maturity on the overthrust masses that had previously approached from the northwest.

Since structural and physiographic evidences show that the more recent thrusting was from the southeast, we are led to look for displacement of the older structures by the younger. I have already described the folding of the older thrust planes at the base of the Wildstrübel on the northern side of the younger thrust, by which they are there cut off. When we cross to the southern side of that younger thrust any part of the older major thrust which may exist on that side must lie at some higher level in the elevated mass of the Wild-

strübel. It is found in the summit and is traced down the southern slope to the valley of the Rhone.

This statement rests upon Prof. Lugeon's own observations. He has traced this overthrust from the Rhone valley over the Wildstrübel to the Préalpes near Lenk, and has identified the overthrust mass as a nappe de recouvrement having its "racine" in the Rhone valley, its "carapace" on the summit of the Wildstrübel, and its "tête" near Lenk. We may accept the identification of the several sections as parts of a whole structure, for it rests upon that detailed stratigraphic and structural study which Prof. Lugeon has pursued with minute care. But, misled by the erroneous assumption that thrusting proceeded from one direction only, Prof. Lugeon has, I believe, mistaken the relations of the parts to the whole. The so-called "racine" is the tête and the "tête" is the racine, if we can apply these terms at all. The great major thrust from the northwest can be recognized from Lenk to the base of the Wildstrübel and from the summit of the Wildstrübel to the Rhone valley. It is dislocated between the base and the summit of the Wildstrübel by one younger thrust from the southeast, and is finally cut off by another south of the Rhone.

Having been obliged by my observations to recognize the preceding statement of the structure of the Préalpes and Hautes-Alpes as correct, and feeling sure that the concept of superimposed "pli-nappes" or "nappes de recouvrement" should be replaced by an explanation based on intersecting major thrusts, minor thrusts, and folds, I ventured to consider the supposed sequence of pli-nappes which Prof. Lugeon has described as forming the Hautes-Alpes from the Rhone valley eastward. He distinguished the "pli de Morcles," the "pli de Diablerets," and the "pli de Wildhorn-Wildstrübel," and others, in the order named from west to east, and showed that the pli de Morcles pitches under that of the Diablerets, the latter pitches under the pli-nappe of the Wildstrübel, and so forth, each folded and overthrust mass disappearing under the one to the east of it. I accept this observed structure, a portion of which I had the pleasure of seeing with Prof. Lugeon in an excursion to the Diablerets. According to the current interpretation, which I cannot accept, each of these pli-nappes developed as a distinct overthrust, one after the other, each older one having a "racine" south of the next younger, and each having been thrust over the preceding. They would thus have been piled up, as shown in various hypothetical sections, in such, for instance, as profiles I to IV of the Géologie de la Suisse, by Dr.

Schardt.[1] The total altitude would then have been not far from 12,000 meters.

Were this view correct, there must be a notable difference in age between the successive overthrusts, and particularly between the earliest and latest of the series. Since they have been exposed to erosion, and by hypothesis some have been exposed longer than others, we should expect the older masses to be more eroded then the younger; as, for instance, in the case of older and younger volcanoes of the Canary or Hawaiian Islands. Such is not the case in the Alps. The Hautes-Alpes constitute a physiographic unit, although they are structurally complex. Considering them for the moment also as a structural unit, and recalling the great recent thrust plane up which they have advanced as a whole from the southeast, we may recognize that the altitude of the chain above the Préalpes is due to the rise on the inclined thrust plane, while the superb scarp which they present to the northwest and north is the effect of consequent erosion on the front of the rising mountain mass. This scarp is of uniform physiographic age from one end of the chain to the other, it being everywhere in a stage of extreme youth.

Having studied a similar scarp and structure in the Lewis range of Montana, where Pre-Cambrian rocks were overthrust on Cretaceous, probably during the Miocene, I judge by comparing the effects of erosion in the two mountain ranges that the elevation of the Hautes-Alpes by advance on the thrust plane occurred not earlier than the Pliocene and possibly in the early Quaternary. However this may be, the scarp is very young, and uniformly young from end to end.

At certain points a lesser scarp branches from the great front of the range and turns back into the heights. As the front faces north by west, these lesser ones face westerly. They also are physiographically young. Indeed, they are distinguishable from the great scarp only by their branching off and having less altitude. Each of these minor scarps is the western face of a segment of the range which Prof. Lugeon has described as a distinct pli-nappe. The cliffs of the Diablerets thus overlook the segment which is called the pli de Morcles. Each minor scarp is based on a thrust plane, dipping easterly, just as the major scarp is based on the major thrust dipping southeasterly. Each minor scarp is related to its minor thrust as the major scarp is related to the major thrust. They all form one system and are of one and the same age.

[1] Schardt, H.: Géologie de la Suisse, article extrait de "La Suisse"; Publications de la Dictionnaire Géographique de la Suisse, Neuchatel, 1908, pls. 22-23.

Thus I regard the Hautes-Alpes of the Bernese chain as consisting structurally of a great overthrust mass whose general movement was north by west or northwest on a major thrust plane. There developed simultaneously a number of minor thrusts on which movement was toward the west, at an angle to the general motion of the mass. It is an example of major and minor thrusting, with two somewhat divergent directions of displacement and with diversities of folding in the several segments.

It was at the suggestion of Prof. Lugeon that Dr. Jaccard courteously conducted me to the vicinity of Château d'Eux, where he showed me a typical example of the " tête plongeante " of a nappe de recouvrement in the Rhetic limestone of the Pte. de Cananéen. The annexed diagram is taken from Dr. Jaccard's paper.[1]

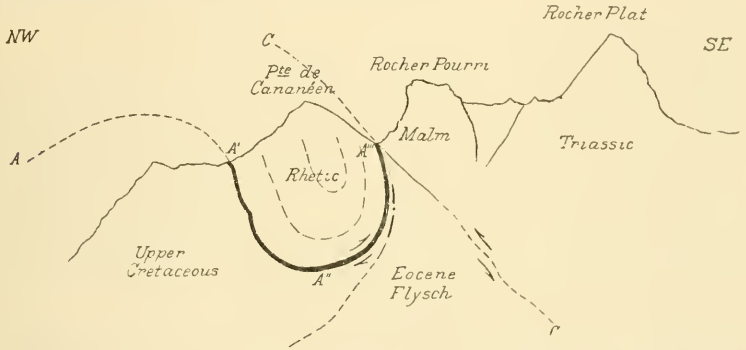

FIG. 2.—Préalpes near Château d'Eux. Characteristic " tête plongeante " of a supposed " pli-nappe " represented by the " Brèche de Chablais-Hornfluh " (Rhetic) infolded in Cretaceous and Eocene. Otherwise interpreted as a mass overthrust from the left (*NW*) on the plane *AA'A''A'''*, which now appears folded back by the later thrust *CC'* from the southeast. (Adapted from sketch by Jaccard, pl. 34.[1])

The limestone (" Brèche de Chablais-Hornfluh ") is of Rhetic age, according to Jaccard, and the fragment that forms the Pte. de Cananéen is an isolated synclinal mass, resting upon and enveloped in Upper Cretaceous strata, which in turn overlie the Eocene Flysch. In this inverted order and synclinal structure we may certainly see the plunging head of a great overthrust sheet that has come over all the Alps from the far southeast and buried itself in the Flysch—if such a head and such a sheet have, or possibly could have, any actual existence. I could not, however, accept that concept. I saw, instead,

[1] Jaccard, Frédéric: La Région Rubli-Gummfluh; Bull. de la Société Vaudoise des Sciences Naturelles, Vol. 43, 1907, pl. 34.

a complex thrust, composed apparently of two related planes, which had been folded back upon itself in a later movement from the opposite direction. The later movement had also resulted in a thrust, dislocating the former one and superimposing the Jurassic and Triassic strata of the Rocher Pourri and the Rocher Plat upon the Eocene and the Rhetic mass infolded in it. To the southeast of the Rocher Plat we crossed another fragment of the Brèche de Chablais-Hornfluh, also superimposed upon the Flysch by thrusting from the northwest, and observed that the thrust plane was closely folded and cut off by the Jurassic of the Gummfluh, again overthrust upon it by the later movement from the southeast. (See the sections in Jaccard's paper, pls. 36-38.)

The structure involves one thrust plane from the northwest and two later parallel thrust planes from the southeast. The strata involved in the movements have also been closely folded.

This structure is one of the most complex I have ever seen, and I could not have understood it, as I believe I do, had I not been prepared by the observations on folded and intersecting thrusts which I had made at the northern base of the Wildstrübel, in the Laufbodenhorn, etc. During the two days that I was guided by Dr. Jaccard, between Château d'Eux and Zweisimmen, I saw repeatedly the evidence of older thrusts from the northwest and of younger thrusts from the southeast intersecting and dislocating them.

In the tête plongeante of the Pte. de Cananéen we have an excellent illustration of the structure of those masses which were described by Querreau and later by Prof. Lugeon as being isolated and "without roots." To satisfy myself on this point, I studied the Mythen above Schwyz, and the Brèche de Hornfluh near Zweisimmen. I have no doubt that these masses and others described by Prof. Lugeon, including the Brèche de Chablais, are actually underlain throughout by younger strata and are without any connection with the like formations in place. It is well known that some of these isolated masses, those of the Klippes, are "exotic"; that is to say, no strata of the same facies have ever been found in place. Hence, it is supposed that they must have come from a distant zone south of the Alps. An earlier and, I think, a more correct view was that they came from strata deposited in the zone of the Préalpes, where they are now found. That view was discarded because there was no explanation of the manner in which these isolated masses might have risen through and have become superimposed upon the younger (Eocene) strata which now so widely cover that zone. But let us consider the mechanical effects of intersecting thrust planes.

Let a rock mass start at a and be thrust to a'. Then let a later thrust carry it to a''. It will be isolated by two thrust planes and will be superimposed on younger strata more or less nearly over the place from which it started. One has but to think of a person mounting a stairway which turns back on itself. The " exotic " masses have

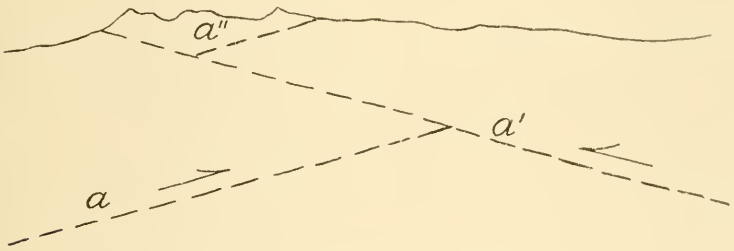

FIG. 3.—Intersecting thrust planes.

gone upstairs, some in one direction only, some in two; and the strata have been folded and squeezed into most complex and irregular forms in the successive movements.

In conclusion I desire to express my appreciation of the able and painstaking investigations of Prof. Lugeon, and to repeat an expression of regret that it is impossible for me to accept the theories of structure which have been developed from his studies.