Geology. — *The root of the Alps.* By J. H. F. UMBGROVE.

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Introduction.

1. A prominent feature in ARGAND's tectonic synthesis of the Alps is the suggested northward overthrusting of the southern "hinterland" of the old Tethys geosyncline. In its most extreme expression this theory was formulated as overthrusting of Africa over Europe, the crystalline cores of the Austro-Alpine nappes being regarded as frontal overthrust parts of the hinterland. This theory has been generally accepted by Swiss geologists [1]). It is the leading theme in STAUB's "Der Bau der Alpen" and it was also propagated by COLLET in his well known book "The Structure of the Alps". So, for example, COLLET wrote: "the higher Prealps, that can be seen from Geneva, Lausanne and Berne, represent a small part of Africa resting on Europe or Eurasia".

2. However, recent investigations clearly show this idea to be untenable. In the first place the counterpart of the *Préalpes medianes* are known from French territory where they are called *zone briançonnaise et zone subbriançonnaise*. French geologists, however, always had good reasons for accepting a quite different view. In their opinion these masses originated from troughs along the external or convex side of the Pennine zone. Opinions changed so to speak at the SWISS frontier mainly under the influence of the tectonic interpretation of ARGAND and STAUB, but recently, TERCIER, was one of the first Swiss geologists to dissent. On account of detailed stratigraphic investigations in the *Préalpes medianes* — he presented strong arguments in favour of the opposite French theory. The sediments of the Prealps and the "klippes" are supposed originally to have accumulated somewhere in the northern part of the Pennine region.

3. Crystalline schists of the Ivrea zone (cf. fig. 7) were considered by ARGAND as the roots of the Prealps, which also were called lower East-Alpine nappes by STAUB. A quite different interpretation of the Ivrea zone was given by NOVARESE who considers this zone of schists as a mass of pre-Triassic rocks more or less comparable to the Aar-Gothard massif from a structural point of view. The northern boundary of the Ivrea zone is characterized as a strongly mylonitized zone of tectonic movements. His conclusion was adhered to by E. NIGGLI when this author attempted to give an explanation of the strongly positive anomalies of gravity found in the eastward continuation of the Ivrea zone near Lake Maggiore.

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1) One will find the same ideas in a recent paper by LOMBARD.

Apparently the Ivrea zone is not a zone of roots of nappes and E. HAUG was right when, as early as 1925, he tried to make clear that Switzerland never was covered by East-Alpine nappes. Results obtained in the Lombardic Alps have given conclusive evidence.

In this paper I hope to make clear that a dominating process in the formation of the Alps was progressive underthrusting towards the central belt from either side of the mountain-chain. This view was expressed by VENING MEINESZ in 1933 and it was also accepted by HESS in 1938. In order to examine the shape and dimensions of the resulting mountain-root geological as well as geophysical data will have to be taken into consideration.

Geological evidence.

4. The tectonic crush-zone along the northern boundary of the Ivrea strip can be followed eastward where it is generally called the Insubric line. The East-Alpine nappes occur north of the Insubric line whereas the Lombaric Alps are to be found south of the same line.

Recently de SITTER published a synthesis of the work of the Leyden School, carried out in the Lombardic Alps during the last decades. Here I want to stress only a few aspects of his results. In the first place so much seems to be established without doubt: the region south of the Insubric line did not give origin to overthrust sheets towards the north or northwest. Switzerland is not a tectonic "half window" in the sense of STAUB. *A fortiori* there is no question of overthrusting of a hinterland over the Alps. Whatever the interpretation of the East-Alpine nappes they originated from the Tethys geosyncline itself which apparently consisted of an intricate pattern of troughs and intervening ridges.

In the second place the results of the geological survey of the Lombardic Alps and the Orobic zone are in accordance with the interpretation of the Ivrea zone by NOVARESE. As a major feature the region south of the Insubric line is comparable to the northern Hercynian massifs like Aar-Gothard and Aiguilles Rouges-Mont Blanc. Both are blocks of the basement divided into numerous wedges showing differential movements and as a whole dipping towards the original geosyncline. Minor differences are due to their respective situation, the Ivrea-Insubric-Orobic region being at the concave, the "central massifs" at the convex side of the arc. According to LUGEON, GAGNEBIN and others down-sliding of nappes over rather great distances must have been a frequent process in the Helvetian Alps and the Prealps. Looking for similar features elsewhere we might expect to find them in the Lombardic Alps. Now, indeed, it seems to me hardly possible to show a more convincing example of down slided nappes than those shown in sections published by DOZY and DE SITTER.

5. Unrolling of the Alpine nappes reveals a shortening of the whole chain by a considerable amount. According to CADISCH an original width

of 630 km has been reduced to the present width of 150 km in post-Carboniferous times. Other estimates made by various authors vary between 200 km and more than 1000 km shortening. SONDER, however, who published a critical study on this subject agrees with 200 km as the minimum estimate allowable. Evidently the crystalline basement must have suffered the same shortening as the superstructure because autochthonous sediments are directly connected with the crystalline basement in the north (Aar massif) as well as in the South (Lugano-Lombardic region). The total mass of basement rocks incorporated in massifs and crystalline cores of nappes is far from sufficient to explain a crustal shortening of 200 kilometres even if the original crust was comparatively thin [2]). Hence the basement must have slid downward under the Alps so as to form a sialic mountain-root.

The question how the assymmetrical structure of the Alps originated above a symmetrical root was ably discussed by BUCHER. According to his opinion the asymmetry results from the arcuate shape of the geosyncline. Folds and thrustplanes will show overthrusting mainly towards the convex side of the arc because a movement meets less resistance towards the convex side than towards the concave side. Asymmetry is the rule, even in the rectilinear part of a geosyncline [3]).

Due to thermal processes in the root a migmatite front rises upward (cf. fig. 7). It is locally revealed at the surface by granite masses like the Bergell and Adamello massifs.

The situation of the young plutonic bodies along the Insubric zone or in its northern vicinity as well as their absence along the boundary of the belt of northern or so-called central massifs may be also due to the assymmetry. For the southern zone of basement rocks is much steeper than the central massifs and so facilitated the ascent of plutonic processes.

6. Considering the structural history of the Alps one notices an outward progression of tectonic action resulting in the addition of more and more structural elements. The complicated system of Mesozoic troughs and intervening ridges in the Pennine region was bounded on one side by the deeply subsiding Helvetian trough on the other side by the sedimentation troughs of the Southern Alps.

After the Oligocene paroxysm two new troughs came into existence, one further to the north (the Molasse trough) one to the south (the Lombardic trough). Probably the subsidence of these troughs kept pace with the rising movement of the folded belt in between them, due to a cause and effect relation. In the mean time denudation products from the Alps filled up the subsiding troughs on either side of the rising mountain-chain.

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[2]) This question is discussed at greater length in § 13.

[3]) "No wrinkle, however formed, would be expected to remain poised in perfect symmetry. As soon as it begins to lean, the bulk of further deformation is transferred to one side" (BUCHER, op. cit. p. 261, see also p. 483).

Due to a renewed compression towards the end of the Miocene Tortonian strata of the Lombardic trough were overrun by Triassic rocks of the Bergamask Alps, and the Helvetian nappes came to rest on Molasse deposits. Moreover differential movements along planes separating wedge-shaped parts of the basement caused the southern boundary zone of the Molasse trough including the frontal part of the Helvetian nappes to become tilted and adjusted into their present position.

Usually the crystalline wedges of basement rocks have been regarded as upthrust or even squeezed out masses due to pressure from the Pennine nappes. Though it is not denied that such a process may have played a role of some importance it should be granted that underthrusting towards the Alps might also be the main factor. This holds even for intricate situations such as those represented in the Windgälle and Jungfrau. Moreover the elevated position of the basement rocks is due to the same factor that was responsible for the great altitude of the Pennine nappes viz. a subsequent isostatic rise of the mountain-chain.

7. During the diastrophic phase of the Alps which ended in the Oligocene the region of the present Jura Mountains was affected by differential movements along basement blocks. The movements caused a roughly NE–SW pattern of faults and short anticlines as well as a number of small faults and intervening grabens in a longitudinal direction. However, the dominating pattern of longitudinal Jura folds originated with the Upper Miocene phase. Apparently renewed southward underthrusting of the basement was an important factor in the formation of these folds. Several other factors cooperated in the formation of the longitudinal folds and evidently these factors were not yet present in Oligocene times. Doubtless the high situated basement in the northern and western foreland

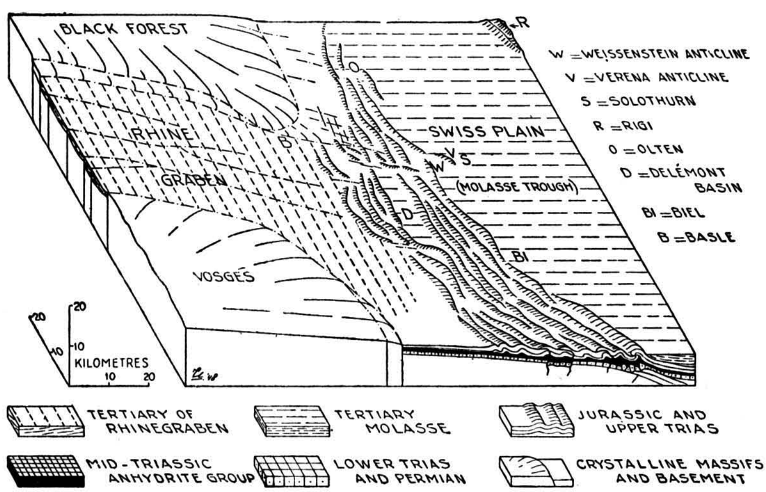

Fig. 1. Tectonogram of the Jura Mountains between the Rhine graben and the Swiss plain.

of the Juras was a factor of importance. The external shape of the Jura Mountains and the available space for the folds was controlled by it.

However, due to the general phenomenon of southward underthrusting a set of faults and intervening basement wedges originated on either side of the Molasse trough. The extern set of these tectonic elements probably caused the *décollement* of the Jura folds as they formed an obstacle against which the surface layers abutted. These layers became stripped off from the basement thereby gliding over the lubricating medium of the Mid-Triassic anhydrite group (fig. 1).

Other structural elements dating from Oligocene times (some even from earlier times) were active in the region of the present Jura Mountains. Several transverse folds reveal the influence and rejuvenation of an older pattern in a convincing way. Probably, however, several longitudinal elements of the basement had also a great influence in the arrangement of the Upper Miocene pattern of folds [4]).

Thus the Jura Mountains again reveal the progressive outward migration of tectonic activity in the basement [5]).

The Jura folds show a crustal shortening in the order of 10 kilometres, i.e. about 25 percent. However, it follows from the above given considerations that this does not imply a proportional amount of shortening for the whole Alps during the Upper Miocene phase of compression. For probably the greater part of the compression was taken up by the outer zones of the Alps and their foreland.

Geophysical evidence.

8. Uniting the results arrived at so far, a schematic and generalized section across the Alps ought to express a progressive underthrusting towards the mountain-chain from both the northern and southern foreland.

Evidently the two girdles of massif-like wedges were zones of very high friction and stress, especially their inner sides where they are bounded by the huge Pennine nappes and their roots. Probably the same strips were predestined to become major zones of movement during the subsequent process of restoration of isostatic equilibrium of the Alps. This suggestion finds a good confirmation by the distribution of seismic belts. In the western Alps ROTHÉ found two belts of seismic activity (fig. 2). The northern belt corresponds to the inner side of the zone of "Central Mas-

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[4]) The possible action of basement wedges was suggested by AUBERT. If sortlike structures exist their origin is probably due to the same phenomenon of Alpward underthrusting of the basement that caused similar though larger wedges along the intern margin of the Juras. If so they must have originated in the Upper Miocene. However, it seems to me very probable that longitudinal faults and graben-like structures of the type, which were called "pincées" by GLANGEAUD, and which date from Oligocene or even older times, were rejuvenated and had a great influence in the arrangement of the Upper Miocene pattern of folds.

[5]) A full discussion of the intricate problem of the origin of the Jura Mountains will be given in a separate paper.

sifs". The massifs themselves are practically aseismic. The conspicuous accumulation of epicentres between the massifs apparently means that similar tectonic elements are present at a lower level where they are buried in the intervening area of axial depression. The southern seismic belt corresponds to the boundary of the Pennine roots and the Ivrea zone which is characterized geologically as a steeply dipping zone of mylonitisation and greats faults (Ivrea, Tonale, Orobic and Insubric belts).

I cannot agree with OULIANOFF's criticism of ROTHÉ's interpretation. On the countrary, the two seismic zones can be followed eastward as far as the Eastern Alps [6]).

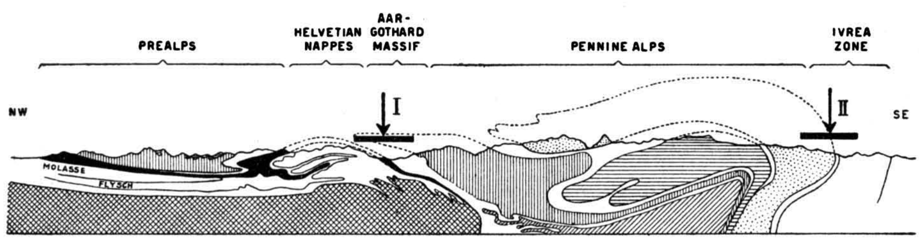

Fig. 2. Position of seismic belts (I and II) in the Alps (After ROTHÉ).

9. One of the principal conclusions arrived at so far leads us to deep reaching problems in a literal sense. For if underthrusting of the foreland towards the Alps took place from both the northern and the southern sides a sialic root of large dimensions must have been forced downward under the present mountain-chain.

Indeed, gravity anomalies found in the Alps clearly demonstrate the existence of a root of comparatively light material below the mountain-chain.

NIETHAMMER's map of Bouguer anomalies shows isanomale curves roughly parallel to the general trend of the mountain-chain. The anomalies gradually increase from zero along the northern margin of the Jura Mountains up to about — 150 in the Pennine Alps, whence they decrease again to zero when proceeding towards the southern margin of the Alps.

SALONEN's curves of Bouguer anomalies constructed at right angles to the trend of the Swiss mountains reveal an additional steepening below the Pennine Alps apart from the general increase of the anomalies towards the centre.

This feature is especially clear in profiles of the Eastern Alps constructed by HOLOPAINEN with the aid of a modified Bouguer reduction. The same phenomenon appears in all his curves of isostatic or Airy anomalies based on various assumptions of the thickness of the crust (T) and the degree of regional compensation (R). One of HOLOPAINEN's profiles is reproduced in fig. 3.

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[6]) See HOLOPAINEN op. cit. 1947, p. 90 and also WANNER 1945.

The general conclusion deduced from studying these anomaly curves is: (1) the presence of a broad root of light material below the Alps and the adjacent regions gradually increasing from the northern and southern boundaries represented by the profiles towards the central belt of the Alps, (2) an additional root of light material below the central belt.

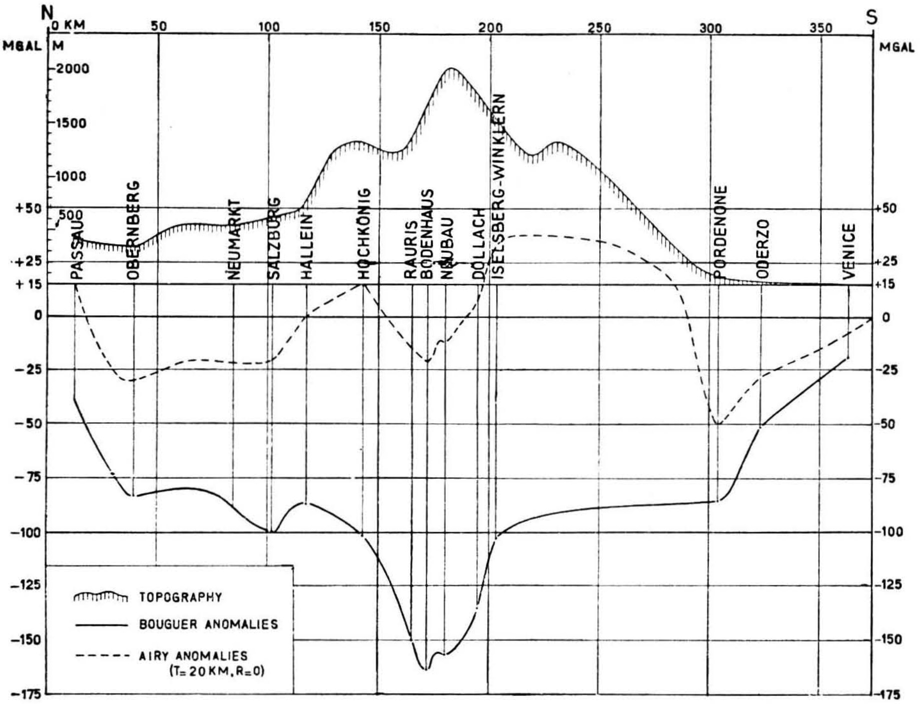

Fig. 3. Gravity profiles across the Eastern Alps (after HOLOPAINEN).

10. From a purely physical point of view numerous, not to say an infinite number of suppositions about the position of the light masses might be put forward.

The question now arises what the most probable distribution is. The relatively sharp peaks of the curves furnish a means of limiting the number of suppositions considerably. For they make clear that most probably the disturbing masses occur in comparatively shallow levels. A comparison to the geological features at the surface furnishes a further means of arriving at an explanation, which in some cases seems highly probable. Thus, for example, one sharp downbending of the isostatic anomaly curves (fig. 3) corresponds exactly to the site of Molasse trough and a similar downbending corresponds to the Lombardic trough. Evidently the northern and southern strips of negative anomalies are due to the presence of the Molasse and Lombardic troughs. HOLOPAINEN thinks the negative anomaly is due either to the prism of young and light sediments with density of about 2.37 or to the non-equilibrium of the area or to a combination of both factors.

11. It is difficult to locate the disturbing mass which causes the negative bulge below the central belt. Tracing the structural history of the Alps we found that underthrusting towards the central belt was a dominating process. Hence the theory of a root of light material was postulated as a logical and necessary consequence. However, geological data cannot possibly furnish any evidence about the shape and dimensions of the root.

HOLOPAINEN's attempt at interpretation of the gravity data is based on several uncertain premisses.

His theory starts from two fundamental assumptions. One is a "normal anomaly" of + 15 milligal for the whole area of western Europe, as based on a formula accepted by HEISKANEN in 1938. The meaning of this positive anomaly is a mystery [7]). Moreover a different value may result

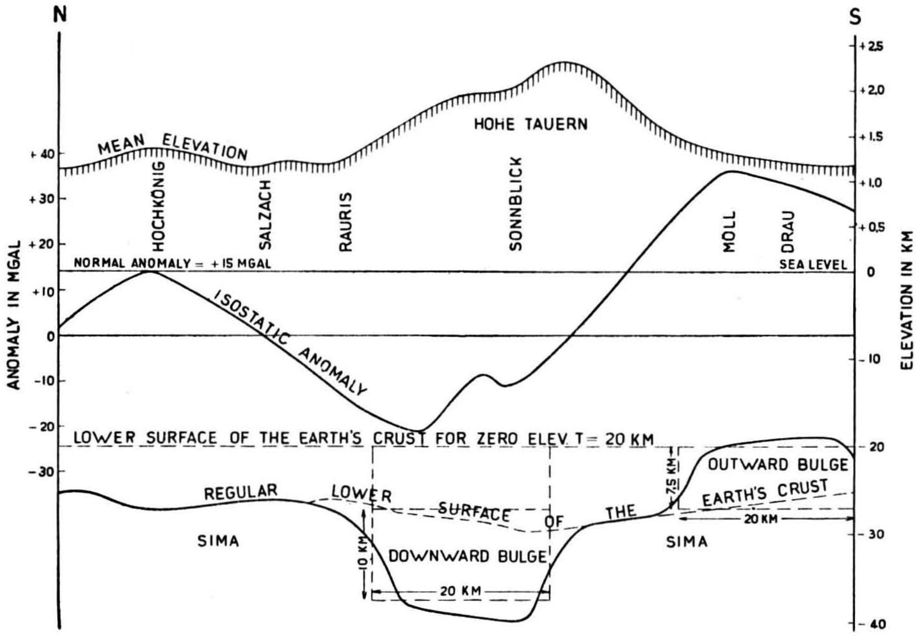

Fig. 4. Interpretation of isostatic anomalies in the Eastern Alps (after HOLOPAINEN).

if future investigations enable us to compute the "normal anomaly" on more numerous and more accurate data. The weight of this uncertainty will be clear if we realise that a second assumption is intimately connected with it, viz. the supposed thickness of 20 km of the earth's crust for zero elevation ($T = 20$). For the sake of simplicity HOLOPAINEN accepts the following model of the earth's crust. A crust 20 kilometres thick and with a density of 2.67 floating on a substratum with density 3.27. In his opinion these figures represent the most probable assumption. Of course the

[7]) The writer feels sincerely indebted to Professor VENING MEINESZ for his elucidating and stimulating discussion of the gravity anomalies of the Alps.

negative values partly depend on the accepted "normal anomaly". If the normal anomaly were to prove less than + 15 m.gal the result would be a corresponding increase of the thickness of the crust in HOLOPAINEN's model.

Moreover it seems more probable that the crust consists of several layers of varying density. For evident reasons the simplification introduced by HOLOPAINEN in his one layer model is another factor that affects the conclusions based on it. Fig. 4 clearly shows what his conclusions are. The lower surface of the crust would occur at a depth of 20 kilometres for zero elevation. An additional root of about 7,5 to 10 kilometres is drawn below the central Alps corresponding to the mean elevation of about 2 kilometres. Hence, a value of about 30 km would be probable for the thickness of the earth's crust under the mountain range. An additional root, called downward bulge, increases the thickness under the central belt by an amount of about 10 km over a north to south distance of about 20 km. According to HOLOPAINEN the downward bulge originated by a proces of downbuckling as suggested by VENING MEINESZ for the belt of strongly negative anomalies in the East Indies. It would be premature, however, to consider this model as a picture of the real situation.

12. Fig. 5 represent a crustal model built up of a granitic layer and intermediate layers above the substratum. The density of the intermediate layers is supposed to be greater than of the granitic layer and to be surpassed by the density of the substratum, though no special values will be introduced. The upper part of fig. 5, the geological profile, is based on STAUB's profile no. 4. which coincides with HOLOPAINEN's profiles II and II*a* (our fig. 3 and 4). Sedimentaries are marked by dots, crystalline cores of nappes are left white. Evidently the negative anomalies observed at the surface result from the combined influences of the sediments indicated by s and the roots r, r_1 and r_2. Probably the highly elevated pile of comparatively light sediments indicated by s in the geological section has a marked influence on the gravity curve. It is suggested that after its substraction from the total effect the resulting curve would coincide approximately with the dot-dash line. Hence the remaining negative must be due to the roots r, r_1 and r_2.

The downward bulge r is narrower than r_1 which in turn is narrower than r_2, but it is impossible to decide on the real magnitudes of the respective downward bulges, because data on the thicknesses of the crustal layers and their specific densities are still too few and of a too uncertain character.

Mutatis mutandis the same holds good regarding the outward bulges a, a_1, a_2 and b, b_1, b_2 which correspond at the surface respectively to the zones of central massifs and southern basement rocks.

Possibly the positive belts are due to the higher level at which deeper and denser rocks became situated automatically when they had to follow the upward movement of the northern and southern belts of basement rocks to their present high situation. Of course, other factors may have been of additional importance. Intrusion of basic magma may be responsible for the relatively high positive anomalies in some areas, as suggested by E. NIGGLI for the region near Lake Maggiore.

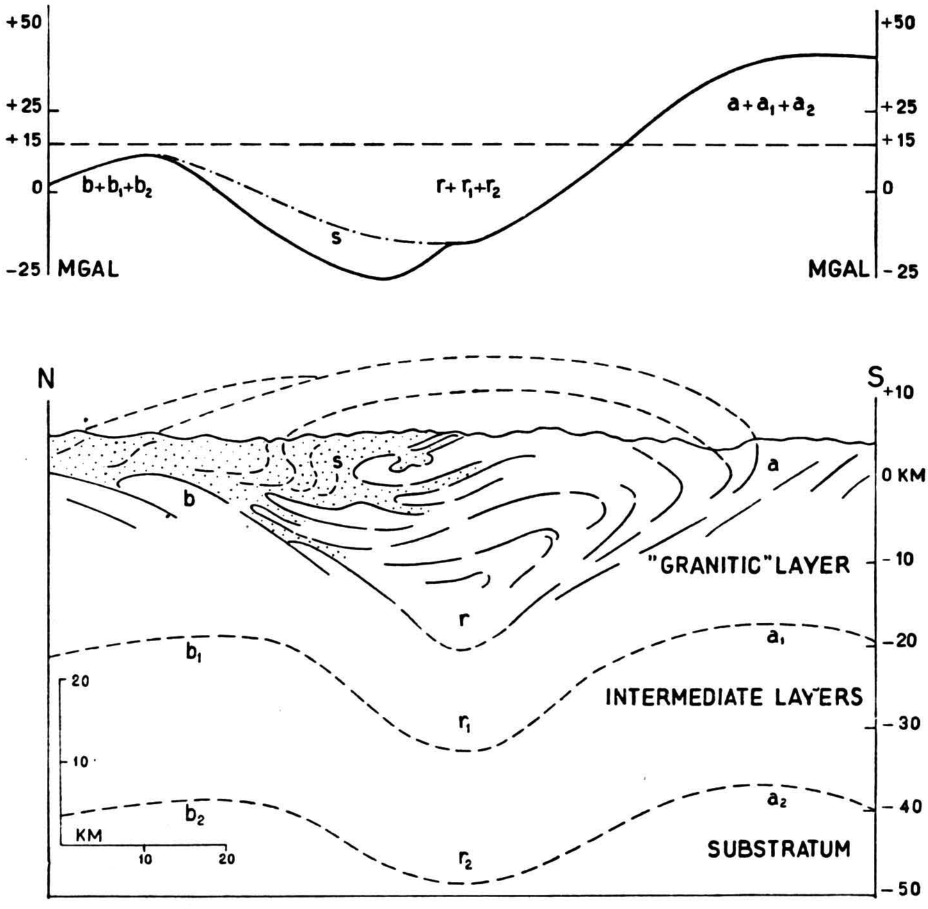

Fig. 5. Attempt at interpretation of isostatic anomalies in the Eastern Alps.

A geological conclusion which seems to be warranted and to be sustained by gravimetric and seismic data is that during the long history of the Alps the crust became thickened due to progressive underthrusting towards the central belt, and that part of the thickened crust formed a central downward bulge, though it remains uncertain which crustal layer formed the main part of the root. Moreover it seems highly probable in such a process that the phenomenon of underthrusting gradually migrated in a direction from the centre towards the "foreland" on both sides of the chain [8]).

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[8]) In the East Indies a process of down-buckling of the crust was advocated by VENING MEINESZ in order to explain the occurrence of the belt of strongly negative

13. Possibly several problematic questions will be solved if more seismic data become available. What is known from seismic evidence about the thickenesses of the crustal layers in Europe was summarized by GUTENBERG in 1943 (Table I).

Though these data are too few for furnishing a final solution of several problems the seismological evidence is important in more than one respect. In the first place GUTENBERG's conclusion is in agreement with the geological and gravimetric evidence. "For Europe", he writes, "the maximum depth of the Mohorovičić layer is undoubtedly under the region of the Alps which means that the Alps have a root".

TABLE I.
Approximate thickness in km of crustal layers in Europe (after GUTENBERG).

Region	„granitic" layers (d_1)	intermediate layers (d_2)	Total
Northwestern Europe	30	10	40
Schwaebische Alb	25 — 30	20 — 25	50
Northern Alps and foreland	35	20 — 25	55 — 60
Tauern	35 — 40	20 — 25	55 — 65
Southern Carnic Alps	40	20 — 25	60 — 65
Yugoslavia	15	25	40

After this conclusion GUTENBERG continues [9]): "This root is mainly a result of a greater thickness of the uppermost (granitic) layer."

The total thickness of the upper layer under the central belt of the Alps consists of two parts, viz. (1) the crystalline cores of nappes and (2) a downward bulge. On the other hand the thickness of the intermediate layers under the Alps (20—25 km) is of the same order as the thickness of the intermediate layers under the foreland. Still, it is self-evident that during the process of down-buckling the intermediate layers must have formed an additional downward bulge similar to that of the upper layer. Therefore it appears logical to conclude that the root of the intermediate layers at any rate the bulk of it has disappeared by melting and spreading in the substratum [10]).

anomalies. The negative belt corresponds to a zone of strong diastrophism. Remarkably enough the negative belt is comparatively narrow, in spite of the fact that strong compression and possibly a corresponding rejuvenation of the sialic root occurred at several epochs. Apparently the processes involved in the formation of the root of the Alps were similar in so far as a central root originated and was perhaps rejuvenated eventually. But they were different in as much as the Alpine root grew ever broader during subsequent phases of diastrophism.

Perhaps this also explains why the negative anomalies of the central belt of the Alps are much smaller than those of the negative belt of the East Indies. (See also KUENEN, op. cit. 1936, pp. 202, 203.)

[9]) GUTENBERG, op. cit. 1943, p. 487.

[10]) See in this connection JEFFREYS, op. cit. 1929, pp. 295—296; and UMBGROVE, op. cit. 1947, pp. 85—86.

It is worth while to deduce the amount of basement rocks in the Alps before and after the crustal shortening of the Alpine cycle from a cross-section of 150 km of the present mountain-chain. Let us assume a crustal shortening of 200 km and a crustal thickness of 30 km at the beginning of the cycle in Triassic times.

From these minimum estimates follows that the original profile ought to show a total of crustal material in the order of 30×350 km^2 = = 10500 km^2. During the process of crustal shortening part of the crystalline basement became incorporated in massifs and the crystalline cores of nappes. In the profile represented by fig. 5 this amounts to 1500 km^2 above the zero line. This is a maximum estimate and it includes the part that disappeared by erosion. Allowing for a thickening of the crust under the whole area of the Alps in the order of 10 km below the zero line the total amount of crustal material now present, with the exception of the downward bulge, would amount to $1500 + (40 \times 150) = 7500$ km^2. Therefore a downward bulge with a profile in the order of $10500—7500 =$ $= 3000$ km^2 must have formed during the several epochs of compression of the Alpine cycle [11]). The figures chosen are unfavourable for finding a large downward bulge. Even if we would allow for still more unfavourable assumptions it seems inevitable to conclude that during the Alpine cycle crustal material formed a downward bulge which for the greater part has spread in the substratum. The only means of escaping this conclusion would be to start with a much thinner pre-Alpine crust and to allow for a much greater thickening of the crust under the whole area of the Alps. For the time being these seem very unprobable assumptions.

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[11]) As a consequence of the process of crustal shortening HOLMES is inclined to conclude that the continents must have grown progressively thicker and covered an ever smaller area in the course of geological history. As suggested by HOLMES this would involve a progressive increase of the rate of denudation and geosynclinal sedimentation as well as a progressive speeding up of orogenic processes. The theory of a remarkable acceleration of these phenomena, representing a genuine departure from the theory of uniformitarianism has been advocated by several authors. It is in good agreement with HOLMES' geological time curve based on the most probable ages of radioactive minerals and the maximum thickenesses of the geological systems. Still, however, the effect of the acceleration must not be overrated. For as far as can be ascertained the major cycles of diastrophism do not display a marked speeding up of their rhythm. As a matter of fact minor cycles plotted on the time scale show an increasing frequency but probably this phenomenon is due to the fact that unravelling the earth's structural history becomes ever more difficult the farther we try to penetrate into the past! Moreover one should not forget that after a phase of diastrophism, when the mountain belt regains isostatic equilibrium, part of the detritus is transported to the deep-sea and is forever lost from the continents. This amount should be taken into account when estimating the progressive thickening of the continents.

One of the most baffling problems of earth science is to find the motor of the deep seated processes which cause a rhythmic shortening of the earth's crust (and the earth's radius?). A vast increase of geological and geophysical data are needed before these problems can be attacked without entering into the realm of mere speculation.

14. In a far distant future one may expect the upper roots (r and r_1) to disappear due to the combined effect of continued denudation at the surface and isostatic rise of the root.

In this connection it is interesting to compare the seismic evidence found in the Sierra Nevada.

"All results available indicate that the root of the Sierra Nevada is due rather to an increase in the thickness of the deeper intermediate layers than in the thickness of the uppermost (granitic) layer" [12]. However, the Sierra is much older than the Alps.

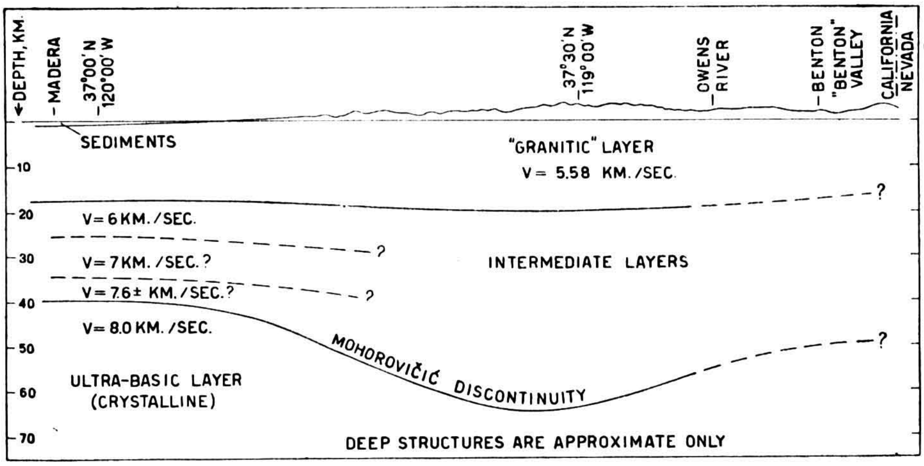

Fig. 6. Crustal layers in the Sierra Nevada (after GUTENBERG).

Fig. 6 shows the granitic layer without an appreciable root [13]) as contrasted to the large and broad root of the intermediate layers. The absence of a "granitic" root is what one might expect in a structure of great age, where there was ample time for an original root to disappear by the combined effect of isostatic rise and denudation. The presence of a root of the intermediate layers is an unexpected feature if it is true that it has already disappeared in the Alps.

If more seismic data confirm the marked difference between the Alps and the Sierra Nevada the cause of the different features must be sought in fundamental differences in the structural history of these mountain-chains.

For the time being, however, we must wait for more reliable data. As to the Alps GUTENBERG wrote: "More and better data on the velocities in the intermediate layers are necessary to find out how far an increase in the thickness of the intermediate layers contributes to the result."

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[12]) GUTENBERG, op. cit., p. 492.

[13]) "The results of a more detailed study now in progress, seem to exclude a root of the granitic layer extending below a depth of 30 km under the Sierra" (GUTENBERG, op. cit. 1945, p. 492).

Moreover, one may expect the boundaries between the crustal layers to be very irregular, especially under a region like the Alps. Therefore many more data are needed before one can construct a satisfactory picture of the thickness and distribution of crustal layers in the Alps.

A tentative and very schematic interpretation, taking into account the available geological and geophysical data is given in the tectonogram fig. 7.

REFERENCES.

ARGAND, E., Sur l'arc des Alpes occidentales. Ecl. Geol. Helv. 14 (1916).

———, La tectonique de l'Asie. C.R. XIIIe Congr. Geolog. Intern. (1924).

AUBERT, D., Le Jura et la tectonique d'écoulement. Mém. Soc. Vaud. Sc. Nat., vol. 8, no. 4, 20 pp., 3 figs. (1945).

BEARTH, P., Ueber den Zusammenhang von Mt. Rosa und Bernhard Decke. Eclogae Geolog. Helvetiae 32 (1939).

BUCHER, W. H., The Deformation of the Earth's crust. Princeton Univ. Press (1933).

CADISCH, J., On some problems of Alpine Tectonics, Experientia II, (1946).

COLLET, L. W., The Structure of the Alps, E. Arnold, London (1927).

GÜLLER, A., Zur Geologie der südlichen Michabel und der Monte Rosa-Gruppe, Eclogae Geol. Helvetiae, vol. 40, 39—161 (1947).

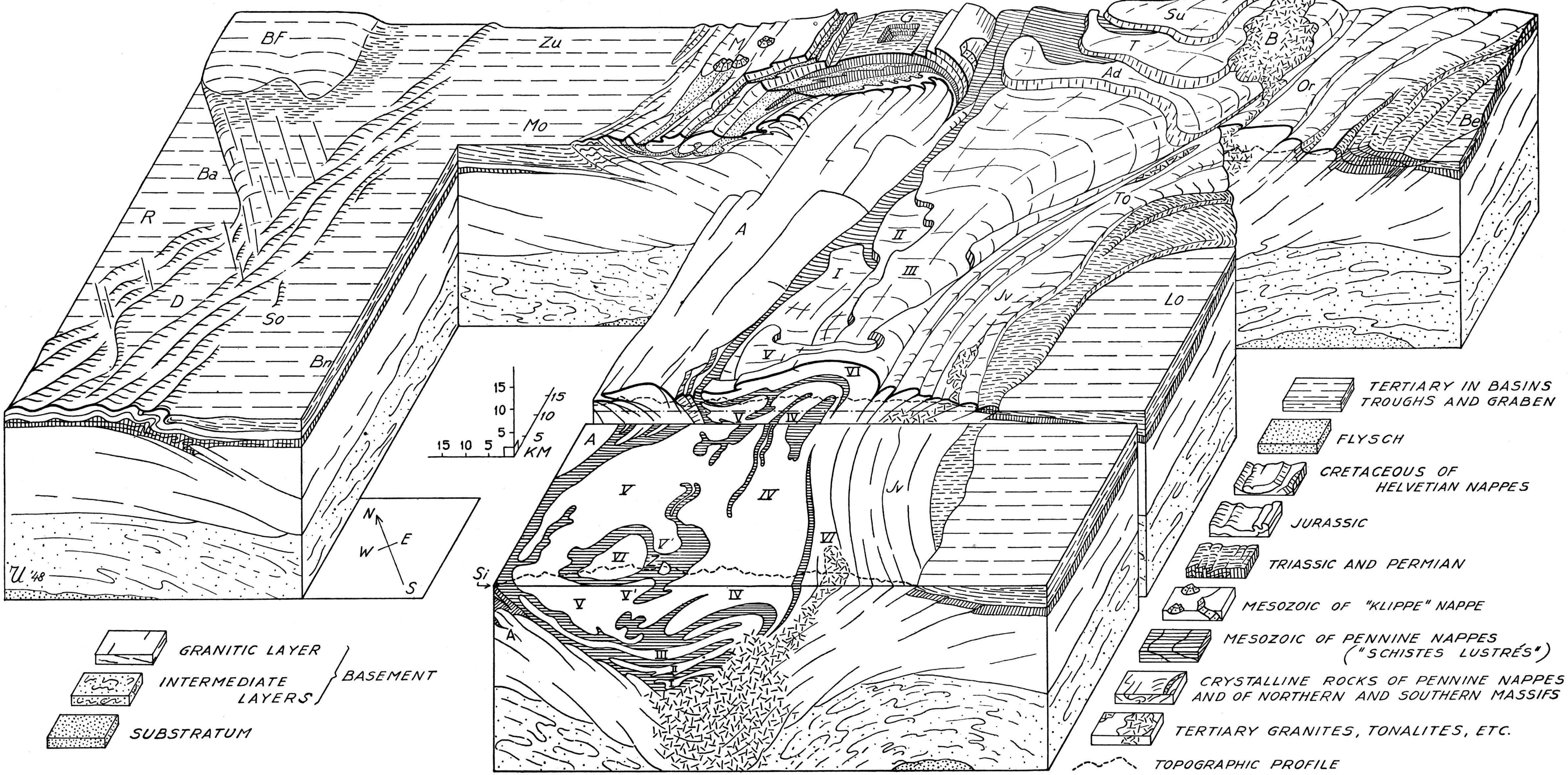
DOZY, J. J., Beitrag zur Tektonik der Bergamasker Alpen, Leidsche Geol. Mededeelingen VII, 63—84 (1935).

Fig. 7. Tectonogram of the Swiss Alps.

The left-hand part of the tectonogram shows the southern part of Rhine graben (R) and Black Forest massif (BF). South of them the Jura Mountains are represented schematically. The continuation of the section through the molasse trough (Mo) passes approximately along the famous "Axenstrasse". This part of the tectonodiagram, showing the structure of the so-called Helvetian Alps and remnants of the "Klippe" nappe (M) is largely based on a well-known blockdiagram by ARBENZ. The northern and southern massifs (A and Iv) as well as the Pennine nappes (I—VI, ad, T, and Su) are drawn in a very schematic manner, as is the whole blockdiagram. For the sake of clearness no "schistes lustrés" have been drawn between the Pennine nappes on the main block in the centre. They are shown, however, in the foreground block which is largely based on ARGAND and BEARTH. The profile on the right-hand part of the tectonogram, passing through the Orobic zone (Or) and The Lombardic Alps (L), is based on sections published by DOZY and DE SITTER. South of them follows the Lombardic trough (Lo).

A, Aar-Gothard massif; Ad, Adulla nappe; B, Bergell granite massif; Ba, Basle; Be, Bergamo; BF, Black Forest massif; Bn, Berne; D, Delemont basin; G, tectonic window of Glarus; L, Lombardic Alps; Lo, Lombardic trough; M, Mythen and Rotenfluh "Klippe"; Mo, Molasse trough; Or, Orobic (Insubric) zone; R, Rhine graben; So, Solothurn; Si, Sion; Su, Suretta nappe; T, Tambo nappe; To, Tonale zone; Z, Zermatt; Zu, Zurich.

VI	Dent Blanche nappe		
V'	St. Bernard nappe (backfold)	Michabel nappe	Pennine nappes
V	St. Bernard nappe	Michabel nappe	Pennine nappes
IV	Monte Rosa nappe	Michabel nappe	Pennine nappes
III	Monte Leone nappe	Simplon nappes	Pennine nappes
II	Lebendun nappe	Simplon nappes	Pennine nappes
I	Antigorio nappe	Simplon nappes	Pennine nappes


BF
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S
GRANITIC LAYER
INTERMEDIATE LAYERS
BASEMENT
SUBSTRATUM
TERTIARY IN BASINS TROUGHS AND GRABEN
FLYSCH
CRETACEOUS OF HELVETIAN NAPPES
JURASSIC
TRIASSIC AND PERMIAN
MESOZOIC OF "KLIPPE" NAPPE
MESOZOIC OF PENNINE NAPPES ("SCHISTES LUSTRÉS")
CRYSTALLINE ROCKS OF PENNINE NAPPES AND OF NORTHERN AND SOUTHERN MASSIFS
TERTIARY GRANITES, TONALITES, ETC.
TOPOGRAPHIC PROFILE

Fig. 7.

GAGNEBIN, E., Les idées actuelles sur la formation des Alpes, Actes Soc. Helvet. Sci. nat. pp. 47—53 (1942).

GUTENBERG, B., Seismological evidence for roots of mountains, Bull. Geol. Soc. America **54**, 473—498 (1943).

HAUG, E., Contribution à une synthèse des Alpes Occidentales. Bull. Soc. Geol. de France, 4e ser., Vol. XXV, 97—244 (1925).

HESS, H. H., Primary peridotite magma. Americ. Journ. of Sci., **35** (1938).

HOLMES, H., The construction of a geological time-scale. Transact. Geol. Soc. Glascow, **21**, part 1, 117—152 (1947).

HOLOPAINEN, P. E., On the Gravity Field and the isostatic structure of the Earth's crust in the East Alps. Ann. Acad. Sci. Fennicae, Serie A, III, Helsinki (1947).

HORTON, C. W., Gravity anomalies due to extensive sedimentary beds. Bull. Geol. Soc. America, **55**, 1217—1228 (1944).

JEFFREYS, H., The Earth. Cambridge Univ. Press, Sec. Edit. pp. 295—296 (1929).

KUENEN, PH. H., The negative anomalies in the East Indies. Leidsche Geolog. Mededeelingen, VIII, 169—214 (1936).

LEHNER, M., Beiträge zur Untersuchung des isostatischen Kompensation des Schweizerischen Gebirgsmassen. Verh. Naturf. Gesellschaft, Basel, Bd. XLI (1930).

LOMBARD, A. E., Appalachian and Alpine structures — A comparative study. Bull. Americ. Assoc. of Petrol. Geolog., **32**, 709—744 (1948).

NIETHAMMER, TH., Die Schwerebestimmungen der Schweiz. Geol. Kommission. Verh. Schweiz. Naturforsch. Gesellsch. (1921).

NIGGLI, E., Ueber den Zusammenhang zwischen den positiven Schwere anomalien am Südfuss der Westalpen und der Gesteinszone von Ivrea. Eclog. Geol. Helv. **39**, 211—228 (1946).

NOVARESE, H., La zona del Canavesa e le formazioni adiacenti. Mém. descrittive della carta geolog. d'Italia **22**, 66 (1929).

OULIANOFF, N., Infrastructure des Alpes et tremblement de terre du 22 Janvier 1946. Bull. Soc. Geol. de France, 5e. 17. 39—55 (1947).

ROTHÉ, J. P., La seismicité des Alpes occidentales. Bull. Soc. Geol. de France, 5e ser. II, 295—320 (1942).

SALONEN, E., Ueber die Erdkrustendicke und die isostatischen Kompensation in der Schweizer Alpen. Annal. Acad. Sci. Fennice, Serie A, vol. 37, no. 3, Helsinki (1932).

SITTER, L. U. DE, La Geologie des Alpes Meridionales d'après des levés recentes. Geologie en Mijnbouw I, 68—91 (1939).

————, Antithesis Alps Dinarides. Geologie en Mijnbouw, **9**, 1—147 (1947).

SONDER, R. A., Ueber das Ausmass des Alpinen Krustenzusammenschubs. Eclog. Geolog. Helvetiae, **33**, 353—362 (1940).

STAUB, R., Der Bau der Alpen. Beitr. Geolog. Karte der Schweiz, N.F. 52 Lief. (1924).

TERCIER, J., Le problème de l'origine des Préalps. Bull. Soc. Fribourgeoise des Sci. Nat., Vol. 37, 125—140 (1945).

UMBGROVE, J. H. F., The Pulse of the Earth, Sec. Ed., Nijhoff, The Hague (1947).

VENING MEINESZ, F. A., The mechanism of mountain-formation in geosynclinal belts. Proc. Kon. Akad. v. Wetensch., Amsterdam, **34**, 375—376 (1933).

VENING MEINESZ, F. A., J. H. F. UMBGROVE and PH. H. KUENEN, Gravity Expeditions at Sea II, 129—131 (1934).

WANNER, E., Die Erdbebenherde in der Umgebung von Zürich. Eclog. Geologicae Helvetiae 38, Nr. 1 (1945).