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The Insubric Line, a Major Geotectonic Problem

By *A. Gansser* (Zürich)*)

With 8 figures in the text

Abstract

From Ivrea in the west to Dimaro in the east, the Insubric Line represents the most important Alpine structural feature. It separates the Southern from the Central Alps and sharply divides Pre-Alpine structures and metamorphism in the south from Alpine structures in the north. From Locarno to the west, with the appearance of the Ivrea Zone south of the Insubric Line, the structural and metamorphic differences diminish, reflected by the Upper Paleozoic conglomerates which transgress the Pre-Alpine Sesia Zone and also contain Ivrea pebbles. These sediments belong to the base of the Canavese Series, which follows the Insubric Line in the western section mostly on its northern side, while similar non-metamorphic sediments occur east of Locarno as a steeply-dipping and irregular band on the south side of the Line, here called the Tonale Line.

Within the South-Alpine "basement", the Ivrea Zone is cut out and is missing from Locarno eastwards. This coincides with a sharp decrease of the large gravity anomaly. In the Ceneri Zone high-grade metamorphic rocks form a complicated Pre-Upper Carboniferous core. The metamorphism diminishes eastwards over the meso-grade Morbegno schists into the epi-grade Edolo formation. The concentration of high-grade though polymetamorphic rocks south of the Tonale Line is sharply opposed to the equally polymetamorphic but Alpine-influenced rocks of the Ticino uplift.

North of the Tonale Line, a conspicuously constant and parallel band of schists and gneisses with pegmatites and marbles follows the Line, forming the Tonale Zone from Locarno to over the Tonale Pass. Only north of this band do various structural units with varying metamorphism appear, including the southern Bergell tonalites.

The Tonale Line itself is surprisingly sharp, with banded mylonites and sometimes horizontal striation indicating some lateral slip as the latest movement. In spite of its young aspect and structural importance, it is now seismically inactive, a surprising fact in contrast with similar features the world over.

Differences north and south of the Tonale Line are further corroborated by isotopic ages. Hornblendes, only 100 m south of the Line (Val Morobbia), are still Paleozoic, while north of it Alpine metamorphic ages range between 15 and 25 million years. Striking are preliminary hornblende data suggesting a Cretaceous age for porphyrite dikes which cut discordantly through the Verrucano and are restricted to the south of the Tonale Line.

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The Insubric Line may be an old, but late- to post-Alpine strongly rejuvenated deep geotectonic feature (deep fracture type). Large sections of Alpine "roots" must have been engulfed by north/south compression. Likewise, the complete Ivrea Zone is cut out east of Locarno. Important source areas for detrital sediments, such as Molasse deposits, must have disappeared. The assumption of lateral displacement is tempting (clockwise movement), but so far no relations exist between north and south elements all along its trace.

Introduction

From Ivrea in the west to Dimaro in the east, over a distance of 280 km, the Insubric Line¹⁾ forms the most conspicuous structural feature in the Alps. Cut by the Giudicaria Line in the east, its eastern equivalent can be observed in the Puster Line, where conditions are remarkably similar to those of the Insubric Line west of the Tonale Pass. At Lienz, the east-west running Puster Line turns east-north-east and splits into two tectonic features: the Drau Line in the north and the Gail Fault in the south, with the Gail Alps in their middle and the Carnic Alps to the south. From Villach to the east, diverging elements begin to appear, with a branch line following in a east-south-east direction south of the Steiner Alps, while south of the northwards-thrusted Karawanken the east-west direction is maintained.

From Locarno westwards the Insubric Line is tectonically less conspicuous than its eastern branch. To the south-west the Ivrea Zone begins as a new element south of the Line. The contrast of high Pre-Alpine against Alpine metamorphism disappears towards the equally mainly Pre-Alpine metamorphosed Sesia Zone to the north-west of the Line. Recent investigations have shown that the Ivrea and Sesia Zones were neighbouring Pre-Alpine crystalline masses in Pre-Upper Carboniferous times, though indications of a tectonic contact were already apparent (CARRARO 1966). Upper Paleozoic to Mesozoic sediments follow as a conspicuous band north of the Insubric Line. They have been included in the Canavese Zone. East of Locarno similar sediments comparable to the Canavese follow as a more or less reduced strip on the south side.

In the following, the Insubric Line will be discussed in two main sections, an eastern one from Locarno to the Tonale Pass, here called Tonale Line, and a western one from Locarno to Ivrea, with main emphasis on the eastern section. New investigations have shown that a subdivision into quite distinct western and eastern branches is justified.

¹⁾ The name "Insubric Line" proposed by SPITZ (1919), is applied here for the complete structure. From Locarno eastwards the older name "Tonale Line", introduced by SALOMON (1890), is maintained. West of Locarno the Insubric Line was called "Canavese Line" or "Canavese Zone" (NOVARESE 1929), but since the name "Canavese" has to be restricted to the sedimentary cover only, it should not be used as a structural unit.

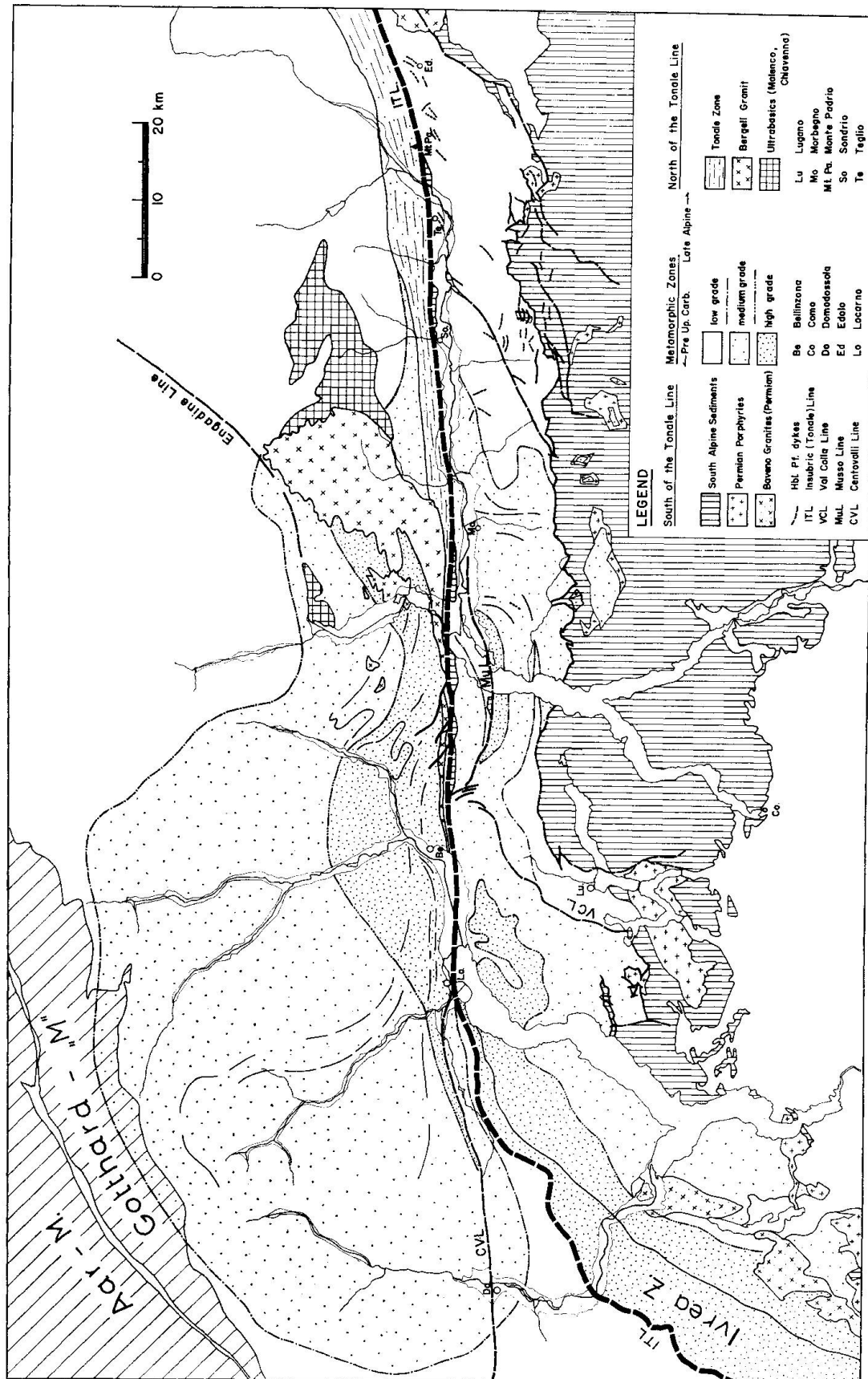


Fig. 1. The Insubric Line and the adjoining metamorphic zones: Alpine in the north, Pre-Alpine in the south (by GANSSEK).

It is not intended to enter into a detailed description of the many facts related to the Insubric Line. Only some of the important features are mentioned and discussed in a more regional frame. Published informations and the writer's own observations form the basis for the present paper.

A. The eastern Insubric Line or Tonale Line from Locarno to the Tonale Pass

It is along this section that the Insubric Line is particularly well defined, and no doubt exists as to its trace in the field (Fig. 1).

1. The sediments and the crystalline rocks south of the Tonale Line

It is a peculiar fact that along the south side of the Tonale Line outcrops a more or less well preserved belt of non- or only weakly metamorphosed sediments, ranging from Carboniferous to probable Liassic. These sediments appear in a more constant facies compared to the primarily oblique isoclinal folds of the South Alpine sedimentary cover, which transgresses the crystalline "basement" further south (DE SITTER 1949, 1963). However, based on the available facts we cannot decide whether apparent local facies changes along the Tonale Line reflect different depositional basins or if the frequent tectonic complications (repetitions, cutout etc.) must be held responsible for these changes.

Just east of Locarno the Tonale Line is covered by the alluvial deposits of the Magadino plain. Its trace can be inferred from the exposures of the Val Morobbia in the east and the outcrops west of Locarno (WALTER 1950). Below this same plain the Ivrea Zone is completely cut out towards the east, and with this the marked gravity and magnetic anomaly decreases rapidly eastwards (NIGGLI 1946). It is planned to investigate this plain geophysically in the near future.

The outcrops of the Tonale Line along the Val Morobbia are well known (KNOBLAUCH 1939, WEBER 1957). The discordance with the Pre-Alpine "Schlingen" structures south of the Line and the constantly east-west striking Tonale schists and tonalites to the north is remarkable. The Pre-Alpine metamorphism is well documented by a hornblende isotope-age investigation from hornblende-biotite-gneiss approximately 100 m south of the Line in the Val Morobbia. Potassium/argon dates indicate $326 \cdot 10^6$ years (McDOWELL 1968), suggesting a lack of Alpine metamorphism practically at the Line itself, while just north of it the Tertiary tonalite is changed to augengneiss, and the potassium/argon age of an amphibolite 500 m north of the Line gives $26 \cdot 10^6$ years. This knife-sharp jump of $300 \cdot 10^6$ years between Pre-Alpine and Alpine influences is one of the most remarkable features of the Tonale Line.

The lack of Alpine metamorphism opposite a highly metamorphic Alpine

area (Ticino Dome) is well supported by the Triassic outcrops which occur south of the Tonale Line from the Val Morobbia to the region west of Sondrio. The dolomites are sometimes fossiliferous and their metamorphism is negligible to altogether lacking. In the Val Morobbia (Alpe Giggio), in the Sasso Pelo area as well as in Dubino a stratigraphic succession is indicated including mostly the Lower Triassic, with the *rauhwacke* of Carnian age as the youngest Triassic horizon (CORNELIUS 1930). This may suggest a Triassic „Unterbau“, from which the upper horizons have been sheared off along the plastic Carnian. The facies seems to resemble mostly the Lombardic Trias with some East-Alpine affinities. Where the Triassic horizons are present they are sharply cut by the Tonale Line, and usually the youngest layers border the steeply faulted zone. This fact is corroborated by the underlying Permian deposits, preserved in the form of Verrucano-type elastics and occurring further away from the Line. This is the case in the Upper Val Liro east of the Iorio Pass and at the outcrops of Dubino. Most of these sedimentary relics are steeply-dipping, frequently heading northwards and with the oldest exposures outcropping towards the south. Of particular interest is a section in the Upper Val Liro, already described by CORNELIUS (1930), where diaphthoritic sericite phyllites are bordered northwards by sheared black schists with quartzites and conglomerates containing fist-size quartz pebbles. Since these conglomeratic horizons are followed northwards, after a short intercalation of schists, by wine-red conglomerates and red schistose sandstones of most likely Permian Verrucano type, it seems probable that the lowest conglomerates may belong to the Carboniferous. Over red sandstones of „Buntsandstein“ type the section grades into Lower Triassic carbonates. Here again the youngest sediments border the Tonale Line, which is followed by sheared granitic gneisses to the north.

A widespread development of Triassic dolomites forms further east the well known Sasso Pelo, which borders the Tonale Line in a most spectacular gorge with well exposed knife-sharp contacts (FUMASOLI, in preparation) (Fig. 2, 3). Well exposed, but still stratigraphically disputed are the Permo-Triassic outcrops of Dubino, in the western Valtellina (CORNELIUS 1930, VENZO and FAGNANI 1954). The first outcrops in the southern foothills are mylonitic white to greenish granitic gneisses rich in quartz and poor in mica. They strongly resemble the gneiss chiari, which should be regarded rather as an old basement surface or a basal unit of the sedimentary section covering the crystalline “basement” than a granitic intrusion (TAHLAWI 1965). This suggestion is further supported by the fact that here the gneisses grade into schistose red and green Verrucano-type conglomerates. These are followed by green schistose quartz-porphyrries, black carbonaceous shales and quartzites, which form the base of a Lower to Middle Triassic section. Towards the Tonale Line the thick Middle Triassic dolomites become more and more fractured.



Fig. 2. The Tonale Line forming a gorge east of Livo. View to east. Sasso Pelo dolomites to the right, fractures tonalited and squeezed Tonale Zone to the left (Phot. GANSSEER).

They border muscovite gneisses and muscovite schists of the Tonale Zone. The Verrucano and the dolomites strike east-north-east and dip 60 to 80° to the north-north-west. This slightly oblique strike may be responsible for the gradual pinching-out of this section towards the east.

Highly questionable are the sediments along the Tonale Line at the south end of the Val Masino, north of the Culmine di Dazio. At the Culmine the Valtellina makes a most conspicuous bend. The core of this resistant hill consists of a granitic biotite-gneiss poor in alkali feldspars, flanked by meso-grade Morbegno schists. The schists to the north of the hill are followed by a thick section of dark phyllonites, which CORNELIUS correlates with a possible disturbance related to the Tonale Line (1930, p. 224). They contain some fluidal marbles and lime-silicate bands more characteristic of the Tonale Zone than of the Morbegno-type schist. They border banded amphibolites and diorites, not unlike some basic non-granulitic rocks of the Ivrea Zone. Northwards they are chloritized and grade into green chlorite phyllites. These are in sharp contact with about 10 m of a yellow, somewhat brecciated non-metamorphic dolomite with thin-bedded to banded limestones, cut by steeply-dipping black phyllonites denoting strong tectonization. Platy, quartzitic



Fig. 3. The Tonale Line cutting the more gently dipping Triassic dolomite of Sasso Pelo (left). Gorge east of Livo. View to west. To the right relictic Tonale Zone (Phot. GANSSER).

micaschists form the outcrops to the north, and continue on the north side of the Masino river with some marble intercalations recalling the Tonale Zone south of the gneissic tonalites, which appear with a sharp contact further up the Val Masino (FAGNANI 1952).

The non-metamorphic dolomites and platy limestones with shales are most likely Triassic relics, and the Tonale Line might be traced to the north of these outcrops along the black phyllonites. This would still place the Trias on the south side of the Line. On the other hand the marbles and lime-silicates, most likely Pre-Triassic carbonates, resemble similar intercalations of the Tonale Zone and are rare in the Morbegno-type schists. Recent mapping of the Sondrio sheet may clear up some of the still unsolved problems (VENZO and FAGNANI 1954). Dolomites, banded marbles and fluidal limestones outcrop just south of the villages of Gatti and Trangia west of Sondrio. Some appear within Edolo-type schists. As in the Masino section, their direct relation to the Tonale Line is obscured by tectonic complications.

From here to the Tonale Pass, Permo-Triassic sediments are rarely in direct contact with the Tonale Line. Large tracts are covered by glacial drifts and huge alluvial cones. Dolomites in small irregular lenses do appear directly

within the phyllonites of the main disturbance. Strong boudinage is often characteristic. Along the steep foothills south of Tresivio (south of the Tonale Line) outcrop Verrucano conglomerates, alternating with sandy layers. They show a marked east-west directed lineation with stretched pebbles parallel to the Tonale Line and are discordantly cut by hornblende porphyrite dykes which are not tectonized and cut the lineations. The contact with the Tonale Line is not exposed. Only at Stazzona, below Tirano, where the so far east-west running Valtellina turns north-east and the Tonale Line crosses the main valley do Triassic dolomites outcrop south of the Line again. The light yellow, non-metamorphic thick-bedded dolomites are locally penetrated by tectonized black schists. They border several meters of a phyllite breccia with a sandy carbonaceous matrix, which suggests a *rauhwacke* rich in phyllites rather than Verrucano as suggested by CORNELIUS. Southwards the dolomites are in direct contact with quartz-phyllites of the Edolo type, which are locally sub-folded along a west-north-west directed gently-dipping fold-axis.

The Tonale Line is again excellently exposed in the summit of Monte Padrio, south-east of Tirano. Yellow dolomite lenses form boudins within black phyllonites along the Tonale Line. To the south the phyllonites develop into intensely folded quartzitic sericite-phyllites. They exhibit two phases of folding. One observes sharp folds with an axis plunging gently to west-south-west and which have been refolded along a steep north-west-plunging axis. Both fold-phases are older than the discordant dykes of fine hornblende porphyrite, which occur frequently in the quartz-phyllite belt of the Edolo-type schists.

Sedimentary sections are less frequent further to the east. The Edolo schists form most of the southern border of the Tonale Line. Sporadic outcrops of dolomites (some with phlogopite), *rauhwacke*, banded marbles and some quartzites occur within phyllonites along the Tonale Line east of Ponte di Legno and are difficult to date. Their facies resembles Middle Penninic Trias and they should be distinguished from Triassic sediments south of the Tonale Line. They are not unlike the sediments just north of the Tonale Pass, where some of the dolomitic rocks are surprisingly little metamorphosed. East of the Tonale Pass, the continuation of the Tonale Line is masked by large slumps, and outcrops are not in normal position. Banded marbles follow the Line, together with carbonate rocks containing siliceous concretions notably similar to the still disputed carbonate rocks at the base of the Grosina nappe in the Grosina valley.

If we review the crystalline rocks to the south of the Tonale Line, we note the rapid decrease in Pre-Alpine metamorphism from west to east. The least affected formations are the *Edolo schists*.

Their intense tectonization does not allow one to establish a clear lithological subdivision. Some authors believe a large part of the phyllites to be diaphtho-

ritic and to consist of phyllonitized rocks originally of a higher grade of metamorphism such as gneissic types of the East-Alpine nappes (KÖNIG 1964). The clearly defined lithological units of the low-grade Edolo schists suggest rather thick sections of argillaceous and sandy deposits. Phyllonites can be recognized where present, and they are restricted to the Tonale Line and to secondary tectonic zones.

The main rock-type of the Edolo schists is sericitic phyllites. With increasing quartz content they grade into well banded quartzitic phyllites with layers of very fine and well bedded quartzites. A slight carbonate content does occur, but carbonate horizons are rare, with a few exceptions, such as conformable banded, slightly marmorized limestones within the phyllites of the Teglio region, south of the Tonale Line. Further intercalations are dark gray to black graphitic phyllites, distinct from phyllonites and most likely normal stratigraphic intercalations. Chloritic horizons are not frequent. They are often intensely subfolded. In spite of the monotonous aspect of the Edolo schists, a detailed stratigraphic investigation may eventually produce interesting results. The possibility of a Lower Paleozoic age for part of this section is not out of the question.

Most characteristic are the already mentioned hornblende porphyry dykes. They are widespread in the Edolo schists but also cut sharply through schistose Verrucano without being affected tectonically. Some are found in the Triassic of the Bergamasc Alps. They have been regarded as of Tertiary age and related to the Adamello massif (DE SITTER 1949). The dyke system of the Adamello pluton is, however, much more variable in composition and should be distinguished from the widespread and uniform porphyrites. It is interesting that preliminary potassium/argon ages of hornblendes from hornblende porphyrites south of Teglio have given a Middle Cretaceous age (analysis by McDOWELL).

Towards the west, the east-north-east striking Edolo schists become more metamorphic. The low-grade rocks change through garnet-phyllites into staurolite-two-mica-schists with intercalated biotite-albite-gneisses which regionally are called the *Morbegno schists*. With this change in metamorphism, tectonic complications increase, and the original composition of the altered sediments seems more complex. Argillaceous graywackes must have played here a rather important rôle, differing from the cleaner sand and shale deposits from which the Edolo schists derived. Local granitic gneisses seem to represent older intrusions. Abnormal north-south trends appear, well exposed in the valleys south of Morbegno and towards Monte Legnone. Fold axes change from a gentle northerly dip to steeper north-east trends. The north-south trend is partly reflected in the distribution of the overlying sediments, in particular the Permo-Carboniferous (TROMP 1931, DE SITTER 1949, 1960—1963).

Further west the metamorphism increases, and at the same time the general

picture becomes more and more complex. Secondary fault-zones appear, and these fault lines coincide with sharp changes in metamorphism. One such fault-zone is the east-west running *Musso Line* (TAHLAWI 1965), which on the east shore of Lake Como brings sillimanite gneisses to the south against low-grade phyllites to the north together with a complete change in structural alignment. The sillimanite-bearing schists and gneisses belong to the well known Olgiasca Zone, cut by numerous pegmatites, which, on the basis of recent age-dating, have turned out to range from 200 to $250 \cdot 10^6$ years. K-Ar and Rb-Sr ages of the muscovites agree, and this may suggest a thermal event at the end of the Permian (HANSON et al. 1966). Eastwards the Musso Line passes south of Colico and disappears below the alluvial plain of the Lower Valtellina. In this section low-grade phyllites border the Tonale Line. This situation changes on the west shore of Lake Como between Musso and Dongo where the low-grade phyllites are gradually replaced by medium-grade schists. No trace of metamorphism is noticeable in the Triassic cap covering the hill south-west of Dongo, at the base of which unmetamorphosed Carboniferous shales occur, squeezed into the Musso Line (LEPORI 1961). The contrast with the high-grade marble zone intercalated in the vertical gneisses is most striking.

Little is known about the western continuation of the Musso Line (STAUB 1958). The trend is towards the Iorio Pass, where a steep locally north-south directed fault-zone, which is cut in the north by the Tonale Line, separates the Musso Line from the very similar Val Colla Line. The latter is well known from the Val Colla to its disappearance below the Caslano Trias hill. As with the Musso Line, a marked change in metamorphism is noticeable with low-grade rocks to the east and medium-grade ones on its west or north-west side. The well known non-metamorphic Carboniferous at Manno is faulted along this tectonic trend.

The crystalline rocks to the north and north-west of the Val Colla Line are well known (REINHARD 1964). Characteristic are the medium- to high-grade Ceneri gneisses. A complicated core of high-grade rocks seems evident in the Ceneri/Tamario region. Its outline is complicated by the „Schlingen“ tectonics proper to this part of the South Alpine crystalline complex. The concordance of the metamorphic isograds with the structural pattern is, however, only apparent. Already REINHARD (1953) drew attention to the striking similarity of the wider Ceneri zone with the East-Alpine Silvretta nappe. Petrology, dyke intrusion as well as the tectonic style are the same in both areas, a fact not to be neglected in the genetical approach to the Tonale Line.

2. The region north of the Tonale Line

In striking contrast to the sediments and crystalline rocks south of the Tonale Line are the formations to the north of it. Here the Tonale Line is

followed by a most conspicuous band of complex rock formations, which are mostly vertical or dip steeply to the north, and which more or less parallel the Line. They consist of high- to medium-grade metamorphics such as banded gneisses, schists, amphibolites and conspicuous marble horizons frequently cut by pegmatites. Called the *Tonale Zone*, this band borders the root-zones of the Lepontic, Penninic and Lower East-Alpine nappes to the south.

Lithological composition and metamorphism of the Tonale Zone are surprisingly constant, and contrast with the more complex structural elements to the north of it. It is therefore most unlikely that the Tonale Zone forms a root, and it is not related to the various tectonic elements to the north of it. Some of these are directly connected as root-zones to the respective nappes, some show most complicated fold and thrust features, which have previously been regarded as root-zones but which, on the basis of recent information, exhibit a tectonic style such as closed antiforms from which no nappes could have been derived (WENK 1956). Direct connections to nappes are more evident where the Ticino Dome plunges eastwards and westwards. This is well visible when following the antiform of the Pizzo Ragno south of Centovalli towards the west through the Val Anzasca (BLUMENTHAL 1952, BEARTH 1956). Here, at Bannio, one can observe the change from an antiform to the Monte Rosa nappe. This would indicate an eastern limit for this tectonic unit. We seem to have proof that at least the middle Penninic nappes did not cover the western Ticino Dome. Similar antiforms have been detected in the east, north of Gravedona (northern Lake Como) (FUMASOLI, in preparation). These, together with ultrabasic rocks, have no relations to the Adula and Tambo nappes further to the north (Fig. 8). Visible root-zones of these nappes do not exist at present.

In the Ticino Dome itself we recognize the wellknown domal configuration of the zones of Alpine metamorphism (WENK 1962, JÄGER et al. 1967). In the region east of Locarno, the highest-grade rocks border the Tonale Line, but their young Alpine metamorphism is strictly related to the north of the Line. The high-grade rocks south of it, excluding the Ivrea Zone, sharply oppose the Ticino Dome, but, as we have seen, their metamorphism is Pre-Upper Carboniferous.

Highly disputed are some of the carbonate rocks within the Tonale Zone. Some, in the form of lime-silicates, indicate medium- to high-grade metamorphism. In the carbonates of the Tonale Zone north of the Valtellina, banded marbles and dolomites resemble somewhat a metamorphic Pennine Trias. In addition, rather dense, often bituminous limestones are intercalated. Their relatively weak metamorphism is believed to be selective (recrystallization hampered by bituminous matter) (GANSSEER and DAL VESCO 1962). Others may be calcareous ultra-mylonites. The latter are well exposed along some sections of the Tonale Line (gorge east of Livo, north of Gravedona). Here, the Tonale

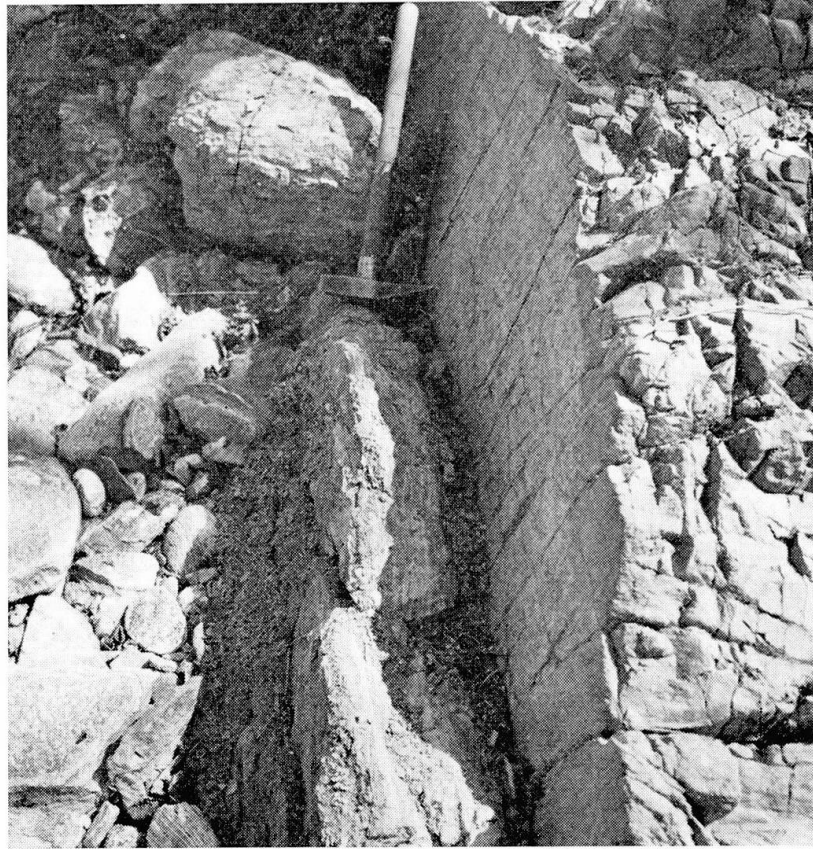


Fig. 4. Banded mylonite (at hammer) along trace of Tonale Line. Liro Valley. To the right Lower Triassic calcareous quartzites (Phot. GANSSEK).

Line separates the Sasso Pelo dolomites in the south from a reduced Tonale Zone and fractured tonalites in the north. Carbonaceous and argillaceous ultramylonites are well preserved as a 30 cm thick, well laminated band in which marked horizontal east-west striations are visible (Fig. 4, 5). Of special interest are, however, carbonate intercalations in the Tonale Zone which show a most conspicuous flow texture. They occur in steep layers usually 5–20 m thick, often within banded biotite gneisses or amphibolites. Lime-silicate layers form marginal bands, while the central part consists mostly of an irregularly banded, grayish limestone conspicuous in small and larger fragments of crystalline rocks including lime-silica minerals. Of particular interest are the flow features of the limestone and the drawnout gneisses and quartzites. Some appear as angular fragments, other are boudinaged, some show fluidal aspects. Surprising are quartzites with flow striations as if squeezed through a harder environment, while completely surrounded by fluidal limestone. Fold axes trend in all directions giving the aspect of a type of convolute folding not unlike that seen in the fluidal limestones of the Lochseitenkalk at the base of the Glarus thrust. The explanation for these most peculiar carbonate layers is not easy. Intense tectonization under pressure and relatively high temperature

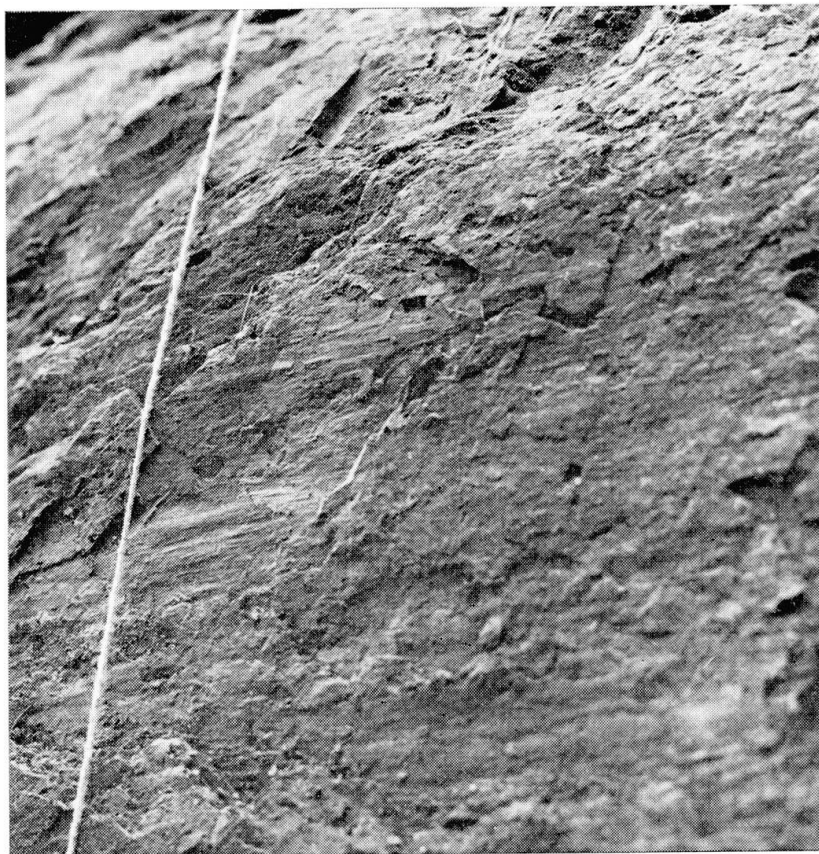


Fig. 5. Horizontal striations in mylonite along trace of Tonale Line (string indicates NS line). Gorge east of Livo (Phot. GANSSER).

is suggested and this movement must have been in some way restricted to the carbonate zone, while the surrounding gneisses are often only steeply-dipping without excessive stress effects. These fluidal limestones are rather widely distributed. The best outcrops within the Tonale Zone have been observed north of Monte Padrio, north of Tegliò and just south of the local tonalite body at Trangia (west of Sondrio). They have also been observed from Locarno westwards and certainly deserve special investigation (Fig. 6, 7).

B. The Insubric Line west of Locarno

With the appearance of the Ivrea Zone west of Locarno, the striking contrasts south and north of the Insubric Line become less pronounced. The Ivrea Zone borders the Insubric Line with rocks metamorphosed in a granulite facies during the Pre-Upper Carboniferous (WALTER 1950, SCHILLING 1957, SCHMID 1967). The latest results of isotopic dating indicate moreover that the Ivrea Zone has undergone a later event around $180 \cdot 10^6$ years, for which no reasonable explanation is so far possible (GRAESER und HUNZIKER 1968). North of the Line are low-grade schists, representing a diaphthoritic band of

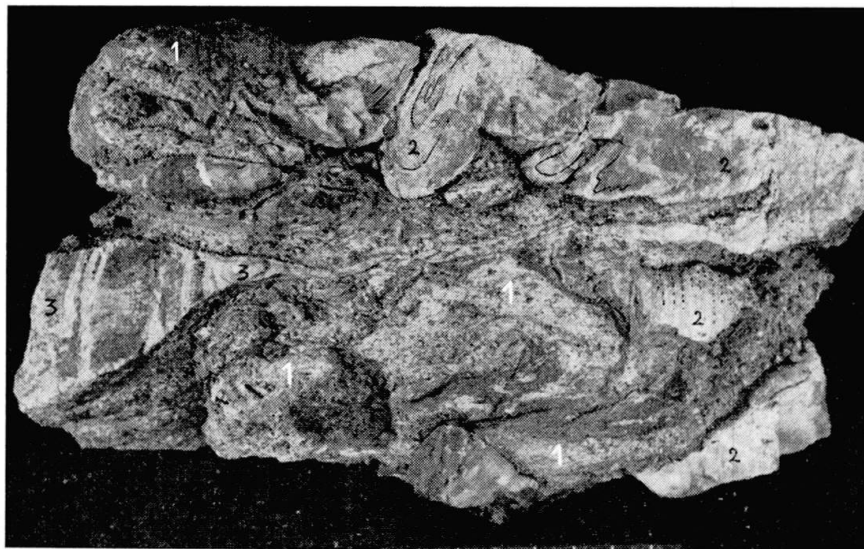


Fig. 6. Fluidal limestone with limesilicate fragments (1), folded quartzites (2) and stretched biotite gneiss (3) (scale in cm). Near Trangia, Valtellina (Phot. Geol. Inst.).

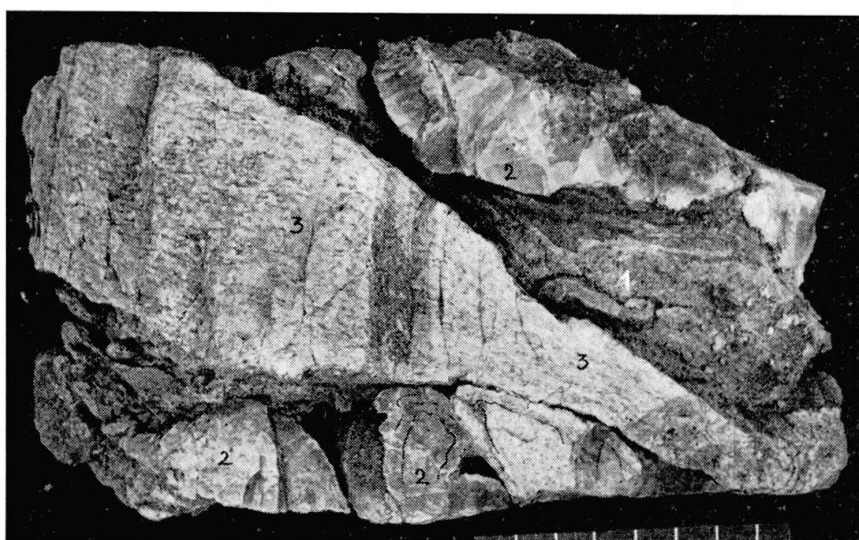


Fig. 7. Fluidal limestone (1) with stretched biotite gneiss (3) and folded quartzites (2). (Back side of Fig. 6) (Phot. Geol. Inst.).

the Sesia crystalline rocks, the metamorphism of which is also predominantly Pre-Alpine.

Along the tectonic contact between the Ivrea and Sesia Zones tectonized sediments are often to be observed; they are mostly steeply-dipping, and are generally restricted to the south border of the Sesia Zone and to the north of the Insubric Line, in contrast to the sedimentary belt east of Locarno which borders the Tonale Line to the south. Sediments and underlying low-grade schists have usually been referred to as the Canavese Zone (NOVARESE 1929). Since these schists seem, however, strictly related to the Sesia Zone and do

not include a retrograde facies of the Ivrea Zone as some authors have suggested (BAGGIO 1968) they should not be included in the Canavese Zone. Assuming that the latter only consists of cover sediments, one should speak of the Canavese series with sediments from Upper Carboniferous to at least Jurassic (BIANCHI and DAL PIAZ 1963, CARRARO 1966, REINHARD 1966). It is, however, questionable if the Canavese sediments are directly related to the South-Alpine sedimentary cover (ELTER et al. 1966).

Unlike the eastern part of the Insubric Line, the Sesia Zone with its marginal belt of low-grade schists is often thrust, with dips as low as 20° , over the Ivrea Zone. This fact is well visible in the Upper Strona Valley. For this reason the trace of the Insubric Line is less straight in the western sector than in the eastern one, while east of Locarno only very steep upthrusting but not overthrusting towards the south must be assumed (Fig. 1).

In spite of the considerable difference between the eastern and western section of the Insubric Line rock-types typical for the Tonale Zone can be observed even west of Locarno. Apart from some basic intercalations, which should be distinguished from the Ivrea Zone, bands of fluidal limestones, identical to the common occurrences in the Tonale Zone, have been observed in various places. They can be seen north of the Insubric Line, north and north-west of Ronco. Further outcrops occur at Loro in the Ossola valley together with basic rocks and schists. Fluidal limestones are again well exposed just north of the Insubric Line in the Upper Strona valley west of Campello Monti. They occur in an extremely tectonized zone just at the base of the low-grade Sesia thrust sheets.

Some of the thrusts and fault-zones become quite complex, and the sharp outline of the Insubric Line is somewhat lost towards the west. Secondary fault-zones, most probably of different ages, accompany the main tectonic features; some branch off, some run parallel. This fact may eventually cause repetitions in the form of imbrication of the main units, as is the case in the Biella-Ivrea region (BAGGIO 1965). The most striking example of a branching fault-zone is the mylonitic zone of the Centovalli. It begins in Locarno, but its direct relation to the Tonale Line is masked. It is responsible for the morphology of the Centovalli, where the mylonite-zones are well known and where a complicated system of secondary fracture-zones is visible (KNUP 1958). The mylonitic zone can be followed over Domodossola into the Lower Bognanco Valley. Here small dolomite lenses occur along its trace. This fact may be accidental, since along the Centovalli the fracture-zone cuts through rocks of the Orselina Zone without any marked displacement. Rock formations to the south and north of this fracture-zone are identical, in sharp contrast with the Insubric Line. The Centovalli fracture-zone seems to be considerably younger than the main alignment of the Insubric Line and may be a Post-Alpine fracture-zone.

C. General Conclusions

The main and still unsolved problem is the striking difference in structure, lithology and metamorphic age of the rock formations north and south of the Insubric (Tonale) Line. That this difference coincides with the separation of the Central Alps from the Southern Alps is well known, but the many related detailed facts such as mentioned above are still puzzling the geologist (Fig. 8).

Nowhere do we find rock-types north of the dividing Line which could be compared with rocks to the south of it. The Central Alps have undergone a very pronounced Late-Alpine metamorphism, which is exposed in the well known metamorphic Dome of the Ticino. The highest grade of this metamorphism occurs to the south and is now sharply cut off by the Tonale Line and opposed by rocks with a metamorphism $300 \cdot 10^6$ years older. That these age differences can be measured within a few 100 m only (and by more detailed investigations over an even smaller stretch) seems a unique fact in isotope geology. During this Late-Alpine metamorphism rock-types originally south of the Ticino Dome must have equally been affected, but where have they gone after the main formation of the Insubric Line?

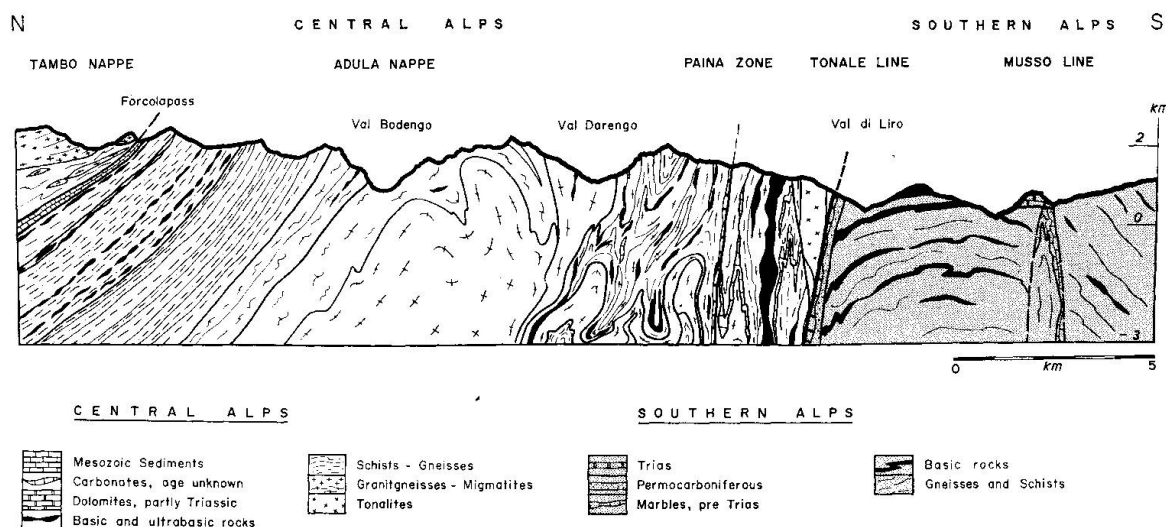


Fig. 8. Composite section from Tambo Nappe over Tonale Line to Musso Line. Based on new investigations of Geol. Inst. Zürich.

We have noted that from Locarno eastwards the complete Ivrea Zone and part of the adjoining Lake Crystalline Complex have been completely cut out, a fact corroborated by the sudden disappearance of the marked gravity and magnetic anomaly. We have further noted that large parts of roots of Alpine nappes cannot be found. They may have been engulfed in a zone which is now mostly outlined by the Tonale Line. This involves considerable compression (Southern Alps against Central Alps). During this process certain areas

may have been squeezed downwards, areas which have once been the source rocks for detrital sediments now found in the South Alpine Molasse, and for which so far no direct origin is known. Even the large granitic boulders in the Como Molasse (LONGO 1968) are difficult to trace directly from the Bergell massif, considering the complicated transport involved, in spite of their petrological identity.

Some good outcrops of the Tonale Line show a horizontal striation in the mylonitic members (Fig. 5). Detailed studies along the Tonale Line in the western part of Upper Lake Como (FUMASOLI, in preparation) indicate a possible relative horizontal movement in a clockwise direction. It is most tempting to postulate considerable lateral displacements along the Insubric Line, but so far we have not the slightest proof for any relation between corresponding rock-types north and south of the Line. (Conclusions drawn from spotty paleomagnetic measurements are too uncritical and cannot be seriously considered, until much more precise data are available (DE BOER 1965, DE JONG 1967).) A juxtaposition of the Bergell and the Adamello intrusive massifs, which, apart from the coarse granitic rock-types, are strikingly similar in age, structural and petrological composition, would suggest horizontal displacement in an anticlockwise sense.

Along the whole Insubric Line many indications point to relative vertical movements of considerable extent. Upthrusting from the northern Alpine block over the South-Alpine one must be assumed. West of Locarno, actual thrusting to the south is well exposed. This vertical movement, subsequent to or even simultaneous with a considerable south to north squeeze, may explain some but by far not all the problems of the Insubric Line.

Detailed studies in the western part (Biella-Ivrea region) have shown that an ancient alignment of the Insubric Line may be Pre-Upper to Middle Carboniferous (CARRARO 1966). In this respect it is interesting to note that parallel southern features such as the Musso and Val Colla Lines have played a considerable role in Pre-Upper Carboniferous times and have only been weakly affected by later tectonic events. The peculiar trend of mostly Permo-Triassic sediments of a rather independent facies along the Insubric Line (Canavese north of the Line, west of Locarno and South-Alpine-type sediments south of the Line east of Locarno) further indicate structural influence during the late Paleozoic and Mesozoic. The Giudicaria Line, which cuts off the Tonale Line in the east, is believed to have acted as a facies divide since Permian times. Here again vertical movements dominate horizontal displacements (VECCHIA 1957).

The Insubric Line has been rejuvenated during various geological events, and here isotope geology may eventually make important new contributions to this problem. During the Alpine orogeny the Insubric Line must have been sufficiently outlined to form a frame for the intrusion of the Bergell and

Adamello plutons, the structure of which, in particular within the tonalites, reflects the Tonale Line as well as the Giudicaria trend (Adamello). The strongest event along the Insubric Line was Late- to Post-Alpine, cutting off sharply the young Alpine metamorphism, leaving, as far as is known, no trace of transitional features. This event was mainly characterized by vertical movements. Horizontal displacements of minor importance may reflect the late history of the Insubric Line. It is however surprising that, considering these young movements, the Insubric Line is now seismically inactive, a fact in contradiction with many similar features the world over.

From all available facts the Insubric Line is a deep-seated structural element, a deep fracture-zone, probably affecting most of the crustal section. In spite of its very marked Alpine rejuvenation it is somewhat surprising that alpine-type ophiolites are missing along its trend. Large ultrabasic masses (Chiavenna-Malenco) appear to the north of the Tonale Line, but their Alpine age is not yet confirmed (Fig. 1). The preliminary geophysical model suggested for the western part of the Insubric Line and including the extraordinary Ivrea body, does not conform to the geological picture of a deep-seated and steep geofracture (ANSORGE, 1968).

The morphological aspect of the Insubric Line is much stronger along its eastern part (Tonale Line) than along the western extension. Some clearly visible scars do reflect soft mylonitic rocks rather than subrecent to recent movements. Larger morphological discrepancies along the Tonale Line are, however, present in the Valtellina and to the east of it. How much they are directly related to movements along the Tonale Line may be revealed in recent investigations (MASONI, in preparation).

The Insubric Line is a most tempting subject for detailed structural studies and isotopic age investigations of minerals and total rock. Paleomagnetic studies, carefully undertaken and interpreted, as well as deep seismic investigations may give us further data. It seems to me that research along these lines will provide most valuable information. Such facts will eventually enable us to understand this most enigmatic and important geotectonic feature of our Alps.

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