Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 73 (1980)

Heft: 2: Symposium alpine geotraverses with special emphasis on the Basel-Chiasso profile : Lausanne, 4-5 October 1979

Artikel: Tectonophysics of the Western Alps

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DOI: https://doi.org/10.5169/seals-164964

Eclogae geol. Helv.	Vol. 73/2	Pages 425-436	2 figures in the text	Basle, July 1980

Tectonophysics of the Western Alps[1])

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ABSTRACT

The Western Alps are firstly seen through the results of dynamic geodesy. At the scale of the whole alpine belt, deep-located density contrast(s) disturb(s) the trajectories of the satellites but at the European scale, only the topographic effects seem to exist. This contrasts with seismological results. The Bouguer anomaly maps show three main anomalies ("penninic" minimum, Ivrea maximum and "padane" minimum). The obliquity of the first two zones on the superficial structures is underlined. A schematic profile of the crust is presented; it shows the relations of the Ivrea body to its neighbourings. It is noticed that there are no determinant proofs showing that there is a large thrust of the Briançonnais on its foreland; on the opposite, it seems more likely that the external crystalline massivs are allochthonous. The data on the Moho's depth in the Western Alps show that the central part of the chain is inserted between two accidents (Tonale in the north; Stura in the south) which also limit the Ivrea body. A schematic map summarizes the essential data and the dynamic equilibrium of the belt is described. Simple computations show that the present primordiale phenomenon is there the subsidence of the Po plain. A kinematic model of the recent evolution is lastly presented.

RÉSUMÉ

Les Alpes occidentales sont d'abord examinées à travers les résultats des études de géodésie dynamique. Les trajectoires des satellites sont perturbées par un (ou des) contraste(s) de densité situé(s) dans le manteau, à des profondeurs de l'ordre de la centaine de kilomètres. Ce contraste intéresse l'orogène alpin dans son ensemble. Mais à l'échelle de l'Europe, les Alpes occidentales ne sont marquées, semble-t-il, que par leur effet topographique. Il n'y a donc pas là de contraste appréciable de densité dans la partie superficielle du manteau alpin, ce qui contraste avec les données de la sismologie.

La carte d'anomalies de Bouguer montre trois principales anomalies (minimum «pennique», maximum d'Ivrée, minimum «padan»). L'obliquité des deux premières sur les structures superficielles est remarquée. Un profil schématique de la croûte est présenté. Il est remarqué qu'il n'existe pas d'argument déterminant démontrant que le Briançonnais est largement charrié sur son avant pays; il semble par contre mieux «établi» que les massifs cristallins externes sont allochtones. L'examen des données sur la profondeur du Moho dans les Alpes occidentales montre que la partie centrale de la chaîne est encadrée par deux accidents (Tonale et Stura) qui limitent aussi le corps d'Ivrée, au sens géophysique classique.

Une carte schématique résume les principales données acquises. L'équilibre dynamique de la chaîne est décrit. Des calculs simples montrent que le phénomène actuel primordial dans cette région est la subsidence de la plaine du Pô. Un modèle cinématique de l'évolution récente (néogène) de la chaîne est enfin présenté.

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[1]) The principal data given in this paper were commented in the Symposium on Alpine Geotraverses (Lausanne 1979); most of the illustrations then presented, are published in the references listed here.

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The upper mantle

The perturbations of the satellites' orbitals above the alpine orogen correspond to a relative maximum of the geoid undulations (WAGNER et al. 1976); this maximum shows lateral gradients higher in the Middle East than in the western zones (CORON et al. 1977, Fig. 3). The cause(s) of this anomaly can be density variation(s) lying in the mantle, at depths of the order of 100 km. The width of the structure(s) is also of an order of 100 km; it is the one of the whole alpine belt.

It is noticeable that all the European Alps do not appear on a map of the residual geoid undulation (CORON et al. 1977, Fig. 5). On this map, only the outlines of the Po plain are sketched. So, the structures shown by seismological studies in the upper part of the mantle do not necessarily correspond to perceptible density contrasts. However, these contrasts can exist in the mantle, but be compensated at greater depths, with few measurable effects on the earth surface.

On the detailed map of the geoid undulations (DESVIGNES & GUILLAUME 1978) the effect of the topography is clear in the Western Alps, but the undulation is more complicated in the Central-Eastern Alps. The seismology shows another difference between these two parts of the Alps: the upper mantle has a low velocity channel under the Western Mediterranean Sea and the Western Alps (KNOPOFF et al. 1966, POUPINET 1976, PANZA & MÜLLER 1978), but a high velocity zone is found under the Central-Eastern Alps (MILLER et al. 1979). If there are no perceptible density contrasts in the alpine upper mantle, these differences on the velocities can be principally due to differential orientations of crystalline networks, under the influence of a global stress field (see also MEISSNER & FLÜH 1979).

The heat flow seems to be lower in the Western Alps than in Central-Eastern Alps. Moreover, the heat flow isolines are generally oriented E-W and seem to be uninfluenced by the Western Alps (map in ČERMÁK & RYBACH 1979). On the other hand, recent seismological studies (POUPINET 1976) consider that the upper mantle is at higher temperature under the Western Alps than under the Po plain. It must be underlined that geothermal data are not numerous in the Western Alps and that there are often some difficulties to make detailed comparisons from one place to another. Seismic velocities, and eventually the temperature distribution, can obviously support fascinating but hypothetical considerations on the places of phenomena (subduction and others) with respect to the mantle. We also note that if the lithosphere's base is a thermal boundary, old structures are not easily fossilized.

The base of the crust

Recently, over 6000 gravity measurements were made in the Western Alps. They had allowed to draw a rather precise map of the Bouguer anomalies (GUILLAUME & GUILLAUME 1979*a*). This map reflects the variations in depth of the Moho. Three principal zones are classically distinguished, from west to east: the "penninic" negative anomaly (under −165 mgal), the positive Ivrea anomaly (over 50 mgal) and the "padan" negative anomaly (under −140 mgal). The first two anomalies lie obliquely to the main geological units; the third seems to be independent of the alpine structures. The seismological results confirm that the thickness of the crust is rather high in the Pelvoux-Briançonnais and Grand Saint-Bernard zones (about 45 km). Under the Ivrea zone, a body of anomalous mantle-like material appears between 5 and 8 km of depth. The Po plain anomaly is not only due to the great thickness of the light sediments.

The Ivrea body and the internal Alps

The analysis of the gravity and seismological results allowed to propose many velocity/density distribution models (CLOOS & LABROUSTE 1963; Symposium Ivrea 1968). The now classical model presents the profile of the Ivrea body as a "duck head" one, having a crest. The beak points towards the west under the penninic units. The crest induces high lateral superficial gravity gradients (CORON & GUILLAUME 1968); it corresponds to rocks of Lanzo type and to subvolcanic basic masses (cf. Canavese andesites). One of the most recent models is based on the classical velocity/density relations; it considers that there is a low density (resp. low velocity) level not only under the Ivrea body but also in the crust of the external zones (CHENOT et al. 1978, Fig. 2). Another model, besides taking into account the astrogeodetical data, proposes the existence of a relatively homogeneous upper crust and a connection of the Ivrea body with the astenosphere (CHENOT et al. 1978, Fig. 3). The lack of a crustal density inversion is not inconsistent with the seismological models. Indeed, if it exists, the velocity inversion near 15 km depth does not necessarily correspond to an appreciable density reduction. Moreover, the mechanical properties of the rocks change considerably at this depth, and the expression "zone dynamosensible" (GLANGEAUD 1946) adequately denotes this level. It is also known that the velocity changes in the gneisses with the orientation of the mica planes relatively to the direction of propagation.

The Briançonnais and the external zones

Presently the extent of thrusting of the Briançonnais basement on its foreland is little known. The seismological experiments (1956) found level(s) with relatively high velocities under the Briançonnais which can represent the external basement as well as the Briançonnais basement itself. The precise levelling (FOURNIGUET 1977) seems to show that the external Briançonnais, Pelvoux and Belledonne massifs are now jointly uplifted; it fortifies the first hypothesis. On the other hand, rather high horizontal (E-W) gravity gradients exist some kilometers backward the penninic front (heavy rocks injected into the Briançonnais front?), but these observations are quantitatively near the limit of significance.

The direction of the "remanent" magnetization of the Guil andesites had been used to invoque a rotation of the "Briançonnais bloc" relatively to the "European bloc". In fact, the magnetization is here in the schistosity plane (HENRY 1976); moreover, the direction of magnetization for the Marinet andesites is globally the same as that of the Guil rocks, and the magnetization vector is in the schistosity plane of these very tectonized rocks (B. Henry, pers. comm.). So it is not possible to consider on the basis of these data only that the Briançonnais s.l. was formerly a unit completely independent from the European bloc.

The isostatic anomaly maps (Airy system) obtained for three compensation depths (20, 30 and 60 km) are similar and show that the Briançonnais and more external Alps are globally compensated at the scale of 10 km. A positive anomaly (over 40 mgal) exists in the Aoste valley and corresponds nearly to the Dent Blanche nappe; caracterized by relatively small lateral gradients (about 1–1.5 mgal/km), it is probably connected with a rather deep structure. Lying in an essential alpine zone, it merits detailed studies, especially since seismologists have detected there a structure which they had considered as an uplifted Moho (LABROUSTE et al. 1968, map).

The position of the external crystalline massivs had often been discussed by geologists and the hypothesis of their thrusting was been presented. Indeed, the crust is thicker in the southeast of Belledonne than in the northwest zone, and a recent interpretation of experimental seismology data (MENARD 1979) proposes a model for Belledonne which the hypothesis of the thrusting is consistent with.

From magnetic studies on volcanites, some authors think that the Pelvoux has been rotated since the Trias–Lias time. However, after a severe criticism on the sampling conditions and data correction, HENRY (1978) showed that there are great doubts on the paleomagnetic direction results. A remark must be made for the Jura under which the Rhinegraben seems to extend towards southwest (MÜLLER & RYBACH 1979, RYBACH et al. 1980). If the Jura was formed essentially by subduction of its basement under the more internal zones, it is necessary to admit that the recent replaying of the rhenan structures under the Jura postdate the Jura formation. It may implicate that there is an intralithospheric shearing level in the Jura basement; this level can be the low velocity level detected by seismologists (MÜLLER et al. 1976).

The southern part of the Western Alps

The gravity and geomagnetic maps show that the principal part of the Ivrea body ends in the Cuneo region, where it twists toward the east (FROIDEVAUX & GUILLAUME 1979, Fig. 5, 8). This abrupt end must correspond to a major crustal accident, the Stura accident (GUILLAUME 1967 = *pars* of the "ligure fault" of LAUBSCHER 1975). This fault is oriented about E–W; on a map, it is a strike-slip fault with about 35 km for the horizontal component, but the vertical component is important. Indeed, the seismic models (RÖWER et al. 1977) admit that there is a mantle-like mass between the liguric Penninicum and a basement which may be the eastern extension of the Provençal basement. So, the vertical component of the Stura fault is 10–15 km and the liguric Penninicum is allochthonous. The marine extension of the penninic frontal contact corresponds to a pronounced magnetic anomaly (GALDEANO & ROSSIGNOL 1977, map). So, basic rocks are likely to be injected in this contact.

A secondary branch of the Ivrea body lies probably in the front of the liguric Briançonnais (Col de Tende region) where significant gravity anomalies exist (CORON & GUILLAUME 1966, VECCHIA 1968). The connection with the Mediterranean crust is made in the Imperia region.

The Stura accident extends toward the east, until Savone. Probably it also constitutes the southern limit of the Po plain at depth. Gravity and magnetic prospections showed that the fault is associated with probably subvolcanic masses (FROIDEVAUX & GUILLAUME 1979). Near Savone, the granite gneisses of the "liguric crystalline massive" lie above these masses, and perhaps also above the "green rocks" of the Voltri group. So, the Savone crystalline is probably thrusted. But it must be noticed that the situation of the basic rocks may be relatively recent (Pliocene?). On the other hand, the gravity data show that the Voltri rocks are not connected straight to the mantle, but lie on sialic material (BLANC et al. 1970).

The geophysical data allow to place the present limit Alps/Apennines in the Savone region. The extension of the Stura fault toward the west is not certainly known. In my opinion, it goes between the Pelvoux and the Remollon-Barles dome, where the Moho is very much deformed (Fig. 1). The southern limit of the Pelvoux-Briançonnais zone, now rising, corresponds to this extension (FOURNIGUET 1977, Fig. 2). We can think that the Stura accident is connected not only with the penninic front but also with the external massive thrust. According to this hypothesis and also taking into account the geological data (BAUDRIMONT & DUBOIS 1977), the horizontal displacement along the fault is here of 30 to 40 km. Let us recall that the virgation of the Ivrea body is about 35 km near Cuneo.

The Mercantour massive was often considered by geologists as a particular external massive. Gravity and geological data show that it is probably thrusted toward the southwest. However, some seismological models disagree with this hypothesis. The analysis of the remanent magnetization of permian schistose rocks lead some authors to consider that the Mercantour has not been rotated since the Permian. But taking into account the structural conditions in this region, the determination of the corrections to be applied to the raw data is here often relevant of the Monte Carlo methods ...

Finally it can be noticed that the crust appears rather thin in the Maritime and Liguric Alps. Moreover, according to the gravity data, it seems that it is, in mass, denser than a normal continental crust. The western limit of this crust may be a N-S fault (see high lateral gradients on the map of Fig. 1)

The northern part of the Western Alps

The Ivrea body ends, for its essential part, against the Tonale-Centovalli fault. In the same way, the penninic nappes of the Western Alps are relayed by other units toward the east.

A question concerns the eventual continuation of the Tonale fault toward the west. The inspection of the data on the Moho depth shows that a vertical discontinuity probably exists between the Valais and the Aoste valley (E-W direction; vertical component $\simeq$ 5 km). Moreover, recent seismological models admit the existence of such an accident (THOUVENOT 1976). So, it seems that the Tonale fault extends at least until the Mont Blanc. The satellite photographs show that the superficial trace of the fault is visible until the Viege meridian (GUILLAUME 1978).

Some authors (LAUBSCHER 1975, GUILLAUME 1978) admit that the Tonale fault is also a major strike-slip fault of the belt. I think that the horizontal displacement has been of about 30 km since (or during) the Neogene.

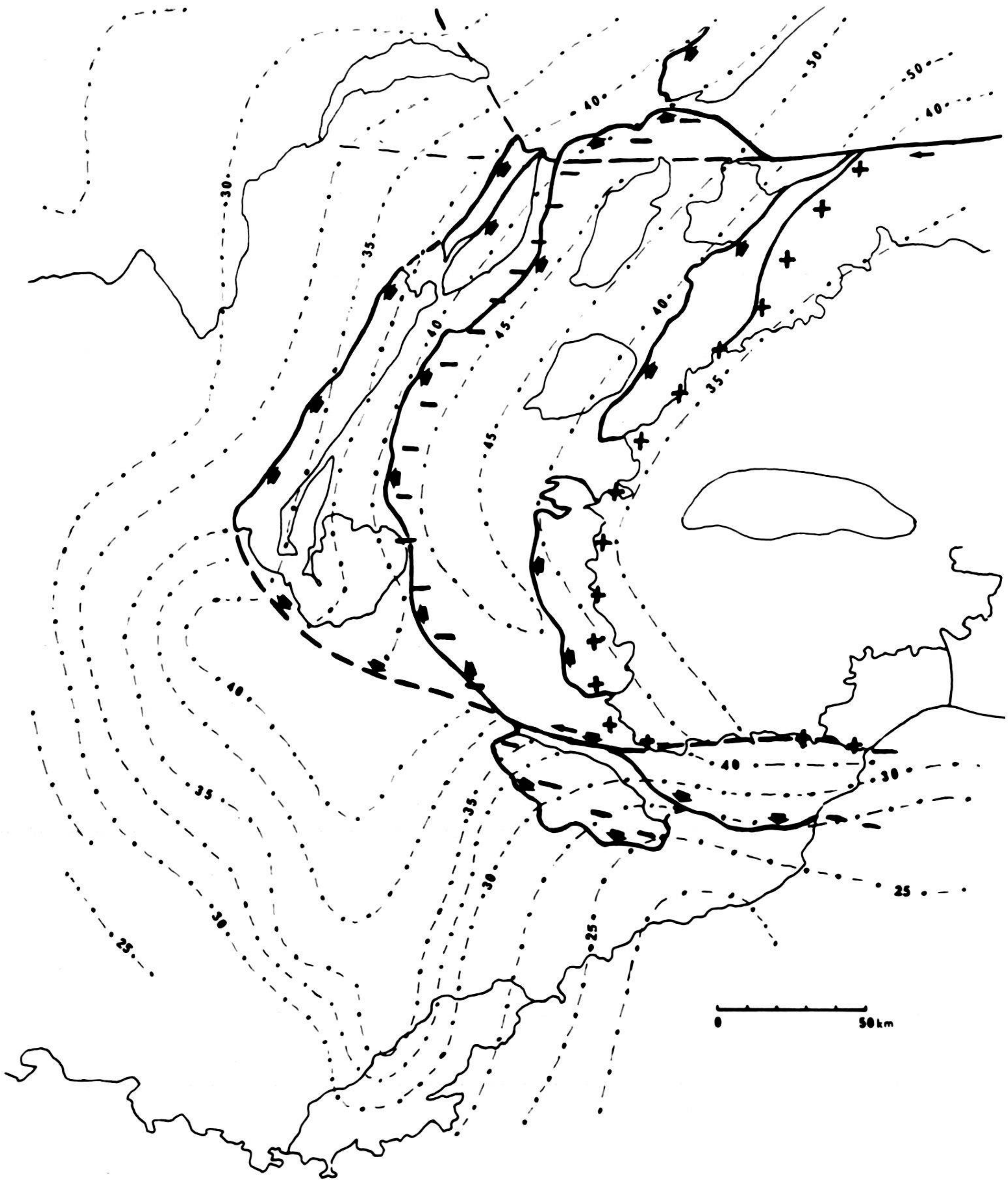

Fig. 1. Structural models of the Western Alps.
Isobaths (km) of the Moho (from works by LABROUSTE-CLOOS, BALTENBERGER, MENARD, MICHEL, PERRIER, RECQ, THOUVENOT and the Zurich group) are drawn without taking into account the Ivrea body. The places of the gravity extrema ("penninic" and Ivrea) are indicated by a chain of − and + signs.

The dynamic equilibrium of the belt

General isostatic anomaly maps (distances from 500 to 1000 km) show that the Alps and surrounding countries are globally compensated. At a scale of 10 to 100 km, the Western Alps are compensated, except the Ivrea zone which shows a strong positive anomaly (over 130 mgal); the Po plain shows also a great anomaly (under -100 mgal). The gravity influence of the Ivrea body can be substituted by the effect of a mass of the same shape and a mean continental crustal density. In the same connection, the gravity effect of the thick and light sediments of the Po plain can be corrected. The obtained map shows that it remains a high anomaly above the Po plain, with abrupt transition to the Western Alps (E–W gradient of about 3.5 mgal/km).

The shear computed (from beam theory) for the profile of Figure 1 shows a maximum between the Briançonnais and Belledonne, and another one in the western part of the Po plain. The curvature (bending moment) shows that the crust is dragged downward to the Po plain. The shearing is obviously maximum in the articulation region, that is to say (on this profile) the internal part of Dora Maria. Indeed, on this section, the Piemontese chain of seismic activity (Vecchia 1968) corresponds to this limit, which is also the external margin of the positive gravity anomaly.

Only the Po plain exists on the small scale maps of the geoid undulation. Presently, from a dynamic point of view, the subsidence of the Po plain, with increasing deviation from the isostatic equilibrium, is the primordial phenomenon.

Although the Briançonnais Alps and the more external zones are entirely compensated, the isostatic map shows local extrema in the external Briançonnais and the internal margin of the Pelvoux. These extrema are in the same structural position and have a comparable extension in the Valais (Kahle et al. 1980). As they are individually localized, their compensation levels must be rather superficial, and they could be studied to prove "crustal" movements and to define seismic risks. This zone corresponds also to the classical "arc séismique briançonnais" and the shear shows here a maximum relative value for the model of Figure 1. Still, these gravity

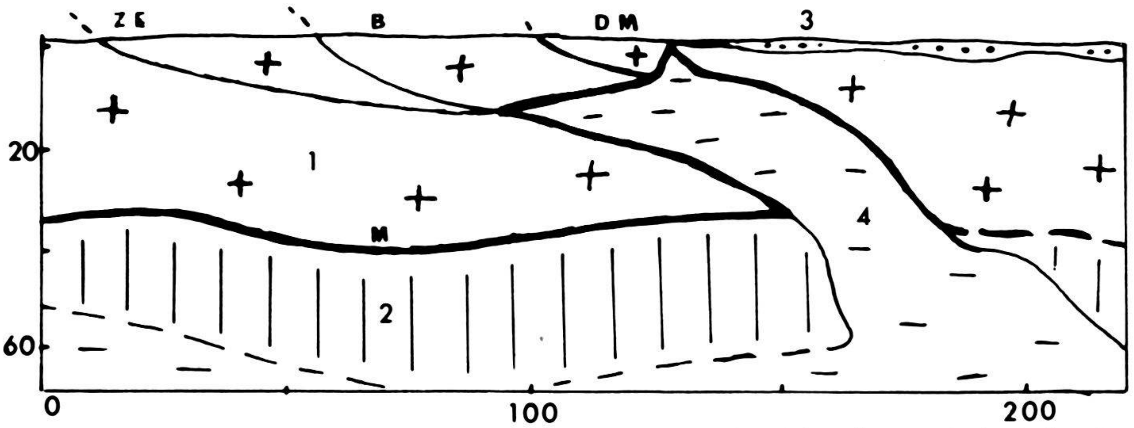

Fig. 1*a*. Interpretative and schematical cross section Grenoble–Po plain (distance in km) showing the relations between the superficial units (external zones = *ZE*; Briançonnais = *B*; Dora Maria = *DM*; Po sediments = *3*) the crust (*1*), the lower lithosphere (*2*), the asthenosphere and the Ivrea body (*4*). Moho = *M*.

minima could be due to a deeper structure, of which influence have been locally masked by superficial heterogeneities. The minima are more widespread when a correction is computed from the Moho map. It is also to be noticed that the "penninic" gravity minimum does not correspond to the maximum thickness of the crust (Fig. 1).

A structural model of the Western Alps

The map and the profile (Fig. 1) summarize the main results exposed here. The following points must be noted:

— These schemes are essentially based on geophysical models and on main geological features. But, the presented levels do not necessarily correspond to stratigraphical limits. Even if they are well selected, physical parameters of the rocks are often used by geophysicists with an extreme cylindrism; but superficial heterogeneities badly apprehended can induce important errors. Such lateral heterogeneities can exist at the top of the Ivrea body.
The part of the hypothesis is easy to do: in particular, it is admitted that the Stura and Tonale faults are connected not only with the penninic front but also with the front of the external massivs.

— The Ivrea body is a composite mass, at least near the surface: Lanzo mass and its equivalents. Oligocene andesites, subvolcanic tertiary or/and more recent masses.

— These schemes give us only a "photography" of alpine structure. Indeed, in the frame of isostasy, the Moho is now evolving, because of the uplift/subsidence (Alps, Po plain) and erosion/sedimentation processes. Only because of the erosion, the Moho has been uplifted of about 6 km (see later) since the beginning of the Pliocene time. So, there are continuous exchanges of material, and the real Moho is not the Pliocene's one, even if it gives probably a good picture of it. The cause of subsidence/uplift processes can be a little density contrast between the asthenosphere of the Po plain and of the Alps.

— The crustal elements are obliquely disposed on the main superficial units and there is no proof that the Dent Blanche–Sesia units extended far to the south. On the opposite, the estimation of the detritic rock volumes from Cretaceous to actual times shows that Argand's tectonic hemi-cylindrism must be completely left.

The recent evolution of the belt

The estimation of detritic rock volumes in the Neogene and Quaternary perialpine basins gives an idea of the mean thickness of the material which laid on the present, supposedly smoothed, surface (Guillaume & Guillaume 1979*b*). For the Western Alps, this thickness was not greater than 1.2 km at the beginning of the Pliocene, and 3.5–4 km at the beginning of the Miocene. The corresponding erosion rates are plausible: 0.17 mm/y for the Plio-Quaternary (to compare with the rate pointed out by Jäckli 1958) and 0.15 mm/y for the Miocene time.

The thickness found for the Miocene involve a rather low temperature (about 120 °C) for the presently outcropping rocks. This temperature must be compared with the indications given by the fluid inclusions of the fissural crystals of Pelvoux and Mont Blanc (POTY et al. 1974). These inclusions are about 15 my old, and seem to have been formed under relatively high temperatures (330–420 °C). If the history of the inclusions is supposed perfectly known, the two results seem not easy to be reconciled: it is difficult to admit, geologically speaking, that the Pelvoux was covered by a great thickness of rocks in the Miocene time. On the other hand, the Pelvoux zone is not exceptional concerning the fluid inclusion results. So, we can think that there was in the Alps for a short time (1 to some my) before − 15 my, a general and quasi-synchronous phenomenon, which fastly drew the rocks into depth and was followed by a fast uplift. The velocity of these processes was not necessarily very high; the values presently observed (1–1.5 km/my in the Tauern and Belledonne/Briançonnais; >1 km/my in some zones of the Po plain; some km/my in "subduction" zones) are sufficient to obtain the observed results in some my.

In my opinion, the invoked phenomenon was a generalized subduction (Miocenic phase of AMSTUTZ 1978), which happened after the Oligocene distension (andesitic volcanism of Taveyannaz and Canavese). It buried the external zones under the internal zones, with displacement of the subduction plane from east to west. Some major shearing zones were formed or/and reactivated: external massivs, Briançonnais s.l., Dora Maria fronts, N–S depression on the west of the Torino Hill. The most affected zone was certainly the Briançonnais front. Of course, if there were somewhere high heat flow values (shearing zones?) the depth of burial was lower, and the time required for the processes was shorter.

The principal mass of the Ivrea body was then injected in the contacts and the unity moved toward the west, between the Tonale and Stura faults. The process ended in the late Miocene - early Pliocene time (subalpine phase). The required time for the translation can be inferred from the horizontal component of the Stura fault. For a mean velocity of 5 to 1 cm/y, this time was from 0.7 to 3.5 my (1.7 my for a velocity of 2.3 cm/y, which is the present rate for the convergence Africa/Europe).

From the root's volume of the chain between Stura and Tonale faults, we can estimate, with some preliminary hypothesis (in particular: constant volume), that the shortening due to the penninic thrust is about 20–40 km. In this view, which supposes that no roots existed before the beginning of the process, the total crustal shortening reaches 90–100 km (about 30–40%).

In this conception, the genesis of the Po plain does not appear as independent as the Western Alps, in opposition to the classical interpretations[3]).

For the pre-Neogene history, we notice that the volume of the Ivrea body (about 200,000 km^3) corresponds to a crustal mass 200 km long (distance between Tonale

[3]) It could seem paradoxical that the Oligo-Miocene levels, which obliterate some backfolded liguric structures are not disturbed by these movements. In fact, it is easy to conceive a subduction of the Provençal-liguric bloc under the most internal units (Mercantour and liguric Penninicum). Let us also recall the existence of the Varzi-Villanervia line (TEN HAAF 1975). Only for memory we also mention here the late final situation of the Cretaceous flysch, which covered a large part of the Western Alps during the Neogene.

and Stura faults) and 100–67 km wide for 10–15 km thick. This mass can result from the mobilization of an oceanic crust, previously subducted (late Eocene-early Oligocene[?]; required time: 2 my for a velocity of 5 cm/y). It involves a transverse crustal reduction of about 40–30%. The Ivrea body can be equivalent to the probably crustal mass (rather high density and low velocities) which lies under the Tuscany continental crust.

Conclusions

To conclude this short review, some remarks have to be made:

— The numerical values mentioned above, of course, are approximative. But we see that in all cases, the processes were very fast, at the geological time scale; so, during the Miocene time (about 16 my) many phenomena may have happened. The deformations were continuous but there were probably pulsations (cf. tectonic phases) connected with the discontinuities in the global evolution.

— The alpine earthquake studies do not give us many informations on the processes located at a depth deeper than 15 km. Indeed, the observed focal mechanisms can show shallow phenomena (for instance: adjustments of sedimentary covers) without necessary connection with deeper processes. For the determination of the Neogene stress state, the statistical studies of the morphologic data can give interesting informations.

— Here, we have essentially considered the recent events checked by the belt. Most of the palinspastic reconstructions on the Western Alps are more or less implicitly based on stratigraphical and microtectonical analysis only, and refer to the Ivrea-Dent Blanche profile. But, if we take into account all the geophysical data, the problem becomes harder, particularly because of the general obliquity of the crustal elements on the superficial units. It is then obvious that these data must state to some paleogeographers more problems than solutions, but we must objectively consider them. Finally, it appears that the paleogeographic reconstitutions must be very speculative for the pre-Tertiary period and even for the Paleogene. The difficulty to do longitudinal correlations between numerous "phases" from the microtectonical data is, in this respect, very significative. About the reconstruction of the Cretaceous period, we can think that the Western Alps corresponded to a mega strike-slip fault (N–S direction) when the subduction processes acted in the Central and Eastern Alps. This accident, certainly complicated, perhaps corresponded partly to the future Ivrea zone (cf. Canavese breaking zone) along which there could be thus a quasi-permanent activity. The Briançonnais s.l. was certainly implicated by these movements[4]). It is then impossible, in these conditions, to *objectively* determinate the real position of the Cretaceous flysch basins: these basins could be "ultrapenninic" here and not there, and in a same region, their positions change with time according to their crustal neighbourings.

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[4]) For the evolution of zones of transcurrent faulting see VAN DE FLIERT et al. 1980, p. 223 (Note added during printing).

After all these considerations, the evolution of Western Alps, as we see them today, appears like a marginal process in the genesis of the orogenic belt.

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