

INTRACONTINENTAL SUBDUCTION AND MOUNTAIN UPLIFT : THE EXAMPLE OF THE WESTERN ALPS

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ABSTRACT. - Geological and geophysical data about the Western Alps show that their uplift is due : (1) to the still acting tectonic stress with a NW vergence ; (2) to the isostatic rebound linked to the progressive underthrusting of large crustal slabs in an outwards-trending process which contributes to the building of a sialic root under the inner part of the range. This double effect started at the Early Oligocene time.

RESUME. - Les données géologiques et géophysiques concernant les Alpes occidentales montrent que leur soulèvement est dû : 1) à une compression toujours active, à vergence NW - 2) à une réaction isostasique liée à la superposition de grandes lames gneissiques, lames de position de plus en plus externe avec le temps et qui contribuent à édifier une "racine" sous les parties internes de la chaîne. Ces deux mécanismes ont commencé à agir dès le début de l'Oligocène.

Mountain uplift is a difficult problem for geologists as much because of its present rate of progress as because of its geological causes. Regarding the latter, geologists mainly call upon :

- i) a tectonic bulge following the previous compression phases and still being deformed,
- ii) the effect of the isostatic rebound linked to the disturbance undergone by the crust at the site of the mountain.

The state of our knowledge about the Western Alps is such as to allow the preceding explanations to be tested and their eventual mutual interaction assessed.

I. PAST AND PRESENT RATE OF UPLIFT

Geological data from the perialpine basin conglomerates clearly show that uplift of the Western Alps started in Oligocene time, but that the present-day morphology was only outlined by the end of the Miocene when the pebbles from the External crystalline massifs arrived in the molassic basins.

In the French Alps, this uplift is supposedly continuing, at least in some areas (Fourniquet 1977). The works of this author rest upon a comparison of first-order levellings performed between 1884 and 1892 on one hand, and from 1961 to 1968 on the other hand, i.e. over a 70-80 year time-span. A mountain bulge, including the Northern External crystalline massifs (Mt Blanc, Belledonne, Pelvoux) and the allochthonous mountains to their east (Penninic zone) (Fig.1), is now rising with an average rate of 1 mm/year. Over the same time-span, the Subalpine ranges are more or less immobile.

In the Swiss Alps, a very similar conclusion arises from levelling measurements (Schaer & Jeanrichard 1974), yielding an average uplift of 1 mm/year in the Pennine area and the Aar massif. But consideration of mineralogical data (time of

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cooling of the minerals and depth of their formation, Schaer & al. 1975) shows that these results may be extended beyond the present time : the uplift may have proceeded at a similar rate (0.3 to 0.6 mm/year) since the Miocene. Guillaume (1982), after assessing the volume of material removed by erosion, reached the same conclusion for the whole Alpine arc.

Furthermore, Swiss geologists, from comparisons of two sets of levellings (1877-1919 and 1919-1970), conclude that :

1. If the average uplift is about 1 mm/year as in France, some places yield higher rates in Switzerland, e.g. 3 mm/year in the Pennine Alps immediately north of the Insubric line, at the end of the 19th century, and now 1,7 mm/year near Chur, a rate we shall discuss later.

2. The greatest rates of uplift have not always occurred in the same place. So, the various crustal blocks in the Alps have undergone different uplift histories. This is logical, since such high uplift rates running continuously from the Tertiary up to the present time would have raised the chain to heights such that the resulting erosion would have carved the material down to the deep basement. However this is possible in the Ticino area where this basement occurs alone and where metamorphism data show that 20 to 25 km thickness of terranes has been eroded away over the past 35 m.y., but the calculated average uplift is only 0.5 to 0.6 mm/y.

II. THE GEOPHYSICAL DATA

It is interesting to compare the preceding geodetic results to conclusions arising from geophysical data.

The first point concerns the present seismicity of the Alps, which is of low to medium grade intensity.

In the French Alps, the seismic centers are superficial ones, restricted to the upper 20 km of the crust (Perrier 1980). They are divided into two groups :

- (i) a Piemontese swarm, stretching from Pinerolo to the gulf of Genoa unfortunately situated in an area where levelling measurements are lacking ;
- (ii) a Grenoble-Mont Blanc belt, clearly linked with the External Crystalline massif front and extending farther in the Valais area.

The stress field (or, more accurately, the maximum compressive stress) related to these earthquakes is roughly perpendicular to the Alpine arc, from the Aar to the Argentera massif (Frechet 1978). This means that the stress trend changes from N-S in the Aar massif to E-W in the Belledonne massif reaching NE-SW in the Argentera

Seismic velocity profiles. Measurements (Perrier 1980) indicate a low-velocity channel between depths of -11 to -23 km under the Crystalline external massifs and, with a lesser accuracy, under the internal Alpine zones, i.e. precisely below the zones with highest rate of uplift (Fig.2). Thouvenot and Perrier (1980) consider this channel to be a shear zone within brittle material in the gneissic basement. This shear plane would rise from the SE to the NW, and would emerge from the basement at the western boundary of the External crystalline massifs, about 9 km in depth, at the bottom of the sedimentary cover (this cover is here thickened by folding and thrusting). For Thouvenot and Perrier, this thrust would still be active, the push acting mainly at the front of the External crystalline massifs precisely where the uplift would be maximum. Further west, below the Subalpine chains, the shear plane disappears, becoming perhaps a decollement zone along which the Subalpine cover is stripped off and displaced westwards.

In the Swiss Alps, numerous works (Giese & al. 1970, Hsü 1979, Mueller & al. 1980, Rybach & al. 1980, Mueller in Hsü 1982) strongly suggest a similar crustal structure in a stack of large slabs. The focal mechanisms of regional earthquakes show a clear component of thrust displacement at the front of the Aar massif (Ahorner et al. 1972). Further southwards, seismic data are consistent with the results arising from the French-Italian Alps : here again we find that a 200 km wide slab is probably moving northwards upon a thrust plane, from depths varying from -15-20 km to the South to -5-7 km to the North (Roeder, 1980, p. 360).

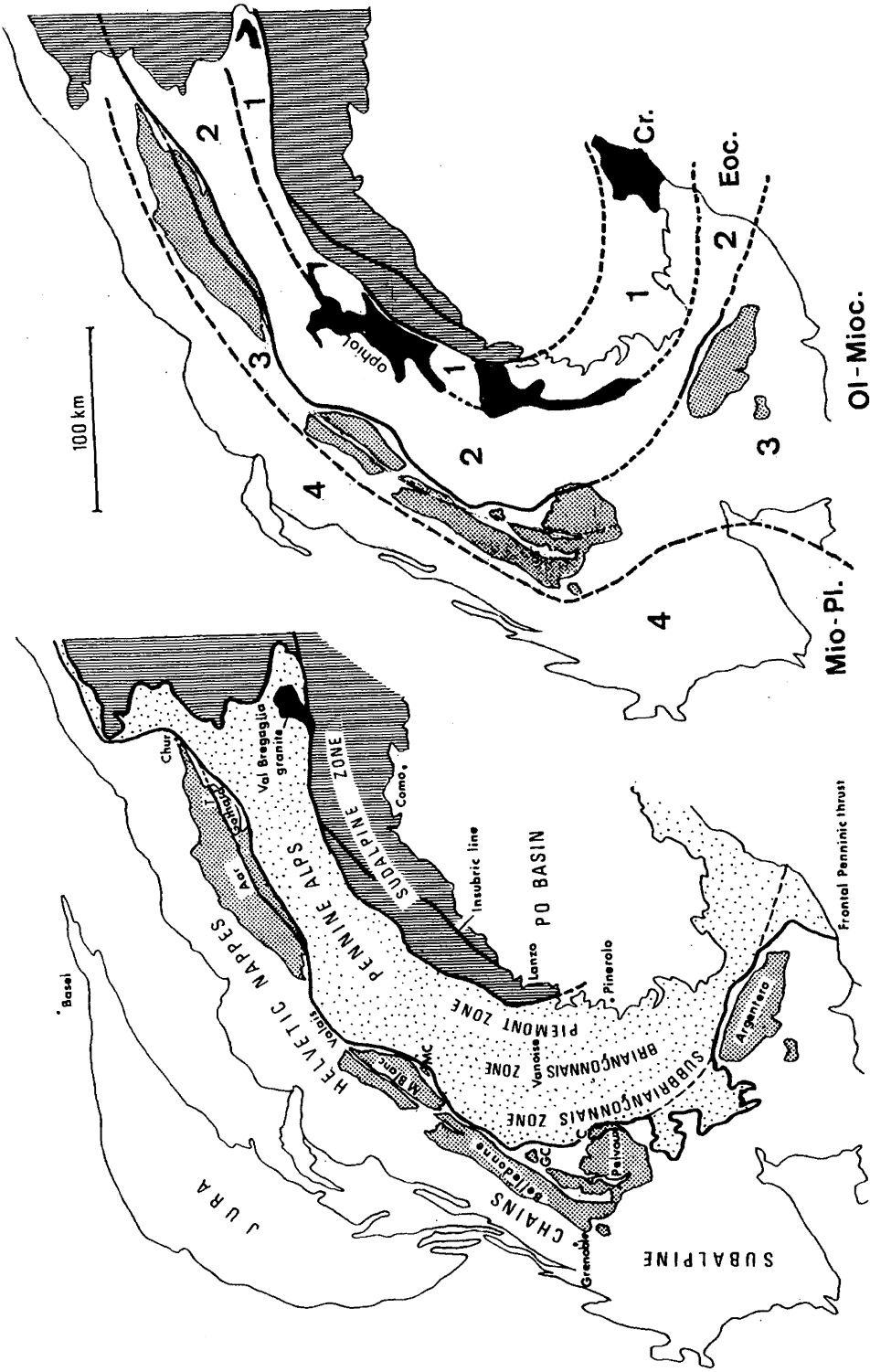


Fig.1. Simplified structural map of the Western Alps

Left : main structural units mentioned in text.

Right : successive tectonic accretionary prisms (Cr. Late Cretaceous ; Eoc. Late Eocene-Early Oligocene ; Ol. Mioc. Late Oligocene-Early Miocene ; Mio. Pl. Late Miocene-Pliocene)

C : Combeynot massif, GC. Grand Châtelard massif ; MC : Mont Chétif slice ; T : Tavetsch massif.

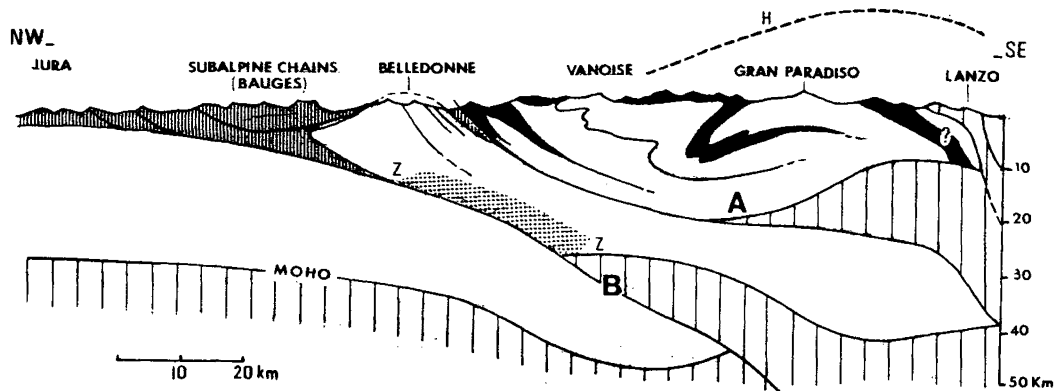


Fig. 2. E-W section through the Western Alps, North of Grenoble

White : crystalline basement

Black : Penninic sedimentary cover and ophiolites

Vertical hatching : External sedimentary cover

A. Moho Upper Miocene offset ; B. Moho present-day offset.

ZZ. Low-velocity zone of present-day seismic waves

H. Probable upper boundary of the eroded sedimentary cover

Compiled from Perrier (1980), J. Debelmas & al. (1983), Ménard & Thouvenot (1984).

III. EVOLUTION OF THE THRUSTING STRUCTURES IN THE SPACE AND TIME

After this brief mention of geodetic and geophysical data, one must return to more geologic considerations. They will suggest that the active thrusts, now observed in the front of the External crystalline massifs, are the most recent in a stack of older intracrustal thrusts, built one after another, from the Eocene, and progressively prograding outwards of the chain as Trümpy noticed as early as 1975. The idea is now in progress (Malavieille et al., 1983 ; Malavieille, 1984 ; Ménard & Thouvenot, 1984) but the published papers did not sufficiently emphasize available geological data.

1. In Cretaceous time, the crustal thickening starts from the oceanic domain and its immediate surroundings (Fig. 1) : the subduction of a part, at least, of the oceanic crust and the obduction of a large oceanic slab (or slabs) upon the European margin occurred, immediately followed by the splitting up of the Austroalpine frontal units. Such events are documented by radiometric ages of 130 My (Neocomian) to 60 (Senonian) in the Sesia gneiss, oceanic ophiolites and internal Penninic material (Trümpy, 1980 ; Desmons, 1977). But these ages are provided only by basement rocks and such an evolution is probably related to deep cleavages and splitting, while in surface, at least in some areas, the sea persisted. Fossiliferous Upper Cretaceous sediments in Piemonte and Liguro-Piemont sequences are now conspicuous : besides the classical Helminthoidic flysch, the Schistes lustrés have provided micro-paleontological Upper Cretaceous evidences (Lemoine & al., 1984 ; Marthaler & al., 1986).

This first periode is the time of the Alpine HP metamorphism. According to the 30 Kb pressure invoked by Chopin (1984) for the Dora Maira material recrystallization, we may assume that at 100 My, the splitted edge of the European margin (i.e. the Upper Penninic units) reached its maximum burial (90 km according to Chopin !).

Besides, from general considerations, it is possible to assume that this first set of movements was roughly N-S to NW-SE.

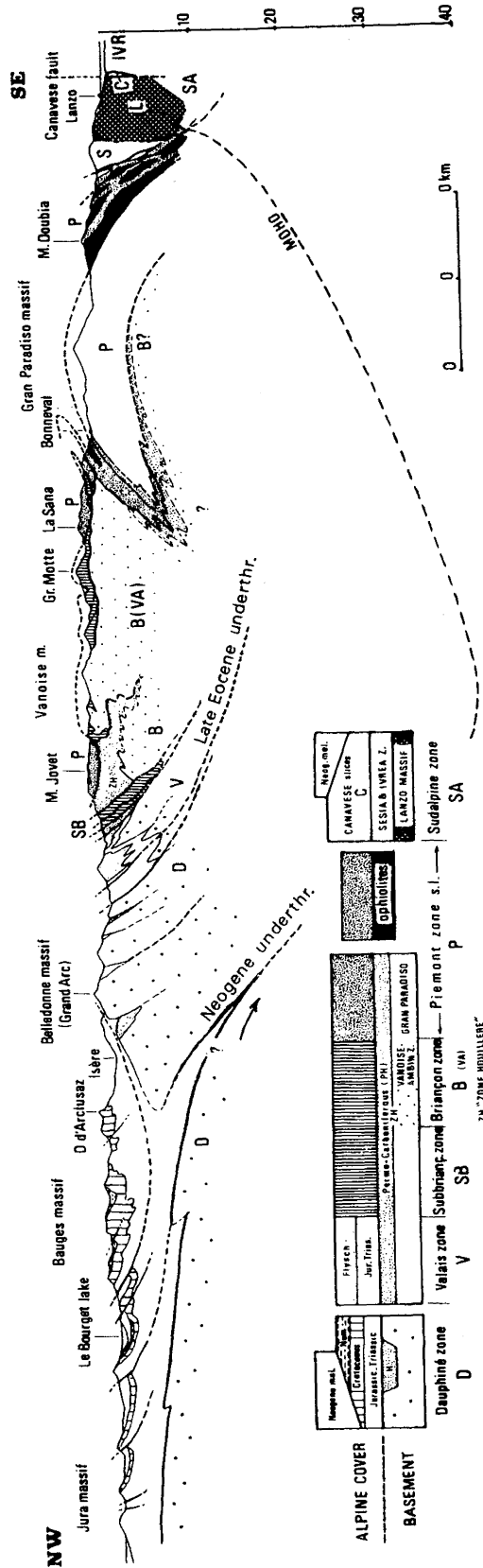


Fig. 2 bis: The Northern French-Italian Alps
Present-day Configuration

This profile, shows from west to east:

1. The External Alpine zone (or Dauphiné zone (D)), with its old basement (Belledonne massif) and its Mesozoic cover (Bauges massif).
2. The Internal Alpine zones exhibit a more complex pattern, with numerous successive structural zones. From west to east:
 - a. The Valais zone (V) is an ancient strike-slip zone, probably with a thinned crust, outlining the boundary between external and internal zones.
 - b. The sub-Briançonnais zone (SB) is reduced here to a tectonic scar, infilled with Triassic gypsum.

c. The Briançonnais zone (B) is mainly represented by its Paleozoic basement, with the following units, from west to east:

- the Carboniferous Briançonnais zone (ZH), where the Carboniferous is non-metamorphic;
- the Vanoise zone B(VA), where the Permo-Carboniferous is metamorphic, probably thinner than in the former unit and difficult to distinguish from an older polymetamorphic basement;
- the deeper substratum of the Gran Paradiso massif, which does not crop out in the profile itself.

Upon this Briançonnais Paleozoic basement lies a Mesozoic cover,

d. The Schistes lustrés zone (or Piemont zone, P) is only represented by klippes (outliers) floating upon the Briançonnais massifs (Mt. Jovet, La Sana) and by more or less narrow strips squeezed between crystalline massifs.

The ophiolite content of the Schistes lustrés increases eastwards. East of Monte Doubia, a belt of slices, the Viù-Locana zone, (VL), with Schistes lustrés, ophiolites and gneissic material, may outline the old subduction plane along which the Mesozoic oceanic realm (the so-called Internal Piemont or Liguro-Piemont realm) has disappeared downwards in the course of the Upper Cretaceous.

e. The most internal parts of the section belong to the Southern Alpine margin (SA) of the Alpine orogen. There are strips of a very old, Precambrian basement, the Sesia (S) and Ivrea (IVR) zones, inside which are pinched up a few Mesozoic slices (Canavese slices) along a great, more recent, fault (Canavese fault.)

The most original feature of the profile is the outcropping of the Southern Alpine upper mantle (Lanzo peridotites, L).

2. During the Late Eocene, the splitting of the Crustal European material prograded to the North and the West. It involved the External Penninic units (Subbriançonnais and Briançonnais units where the stratigraphical sequence ends with Lower to Middle Eocene sediments) and a part of the external Dauphinois domain (South-Eastern Subalpine and Provence chains) (Fig.1).

The age of this new set of phenomena is given :

- in the External zones, by stratigraphic records (unconformity of the Oligocene molasse upon the folded previous sediments including Eocene sediments) ;
- in the Penninic zone, by radiometric dating of the contemporaneous greenschist metamorphism minerals, i.e. 38 My (Desmons, 1977).

The conditions of this "mesoalpine" metamorphism (which is of amphibolite facies in the deepest basement slabs) implies their sinking and stacking down in an incremental process which progressively enlarged the sliced deep bulge of the Eocene Alpine chain. The origin of this new underthrusting of sialic crust slices may be the existence of a probably thinned and brittle crust below a part, at least, of the Briançonnais domain as early as the Carboniferous. Such a thinning is revealed by the thick Briançonnais Carboniferous basin and also by the importance of the pre-Permian tholeiitic material in the basement itself (Parison, 1984).

As much in the Briançonnais sedimentary cover as in the basement, the Late Eocene deformation is linked to a SE-NW stretching lineation due to thrust movements to the NW (Steck 1984, Platt & al. 1985). After more complex transitionnal deformations linked with a deep-seated dextral E-W simple shear in the Central Alps (Steck 1984), there occurs the famous "back-folding" of Alpine geologists, with an E to SE vergence in France and S vergence in Switzerland. This backfolding may represent the antithetic folds and thrusts of the Upper Eocene contractions, because the southernmost of the these backfolds are unconformably overlain by the Oligocene molasse of the South Padan basin (Debelmas 1963, p. 139), but this conclusion cannot be generalized (Tricart, 1980).

3. From the Late Oligocene or the Early Miocene, a new subduction of the crust occurred, North and West of the preceding ones, all along the line separating the External Alpine zone from the Internal ones, i.e. the so-called "chevauchement pennique frontal". The new subducted wedge includes a part at least of the External crystalline massifs, especially the slices and mylonitic zones of their eastern (France) and southern (Switzerland) side (Fig.1). This striking event of the Alpine evolution has been underestimated by most French geologists who generally did not separate it from the event of the Later Miocene-Early Pliocene. The former is dated :

- a) by radiometric data from the Crystalline external slices with 18 to 15 m.y. overprints upon ages ranging from 41 to 36 m.y. (Baggio & al. 1967 : Rb/Sr on biotites ; Leutwein & al. 1970 : K/Ar on adulaire and muscovite, Rb/Sr on muscovite ; Demeulemeester 1982 : K/Ar on phengite) ;
- b) by indirect reasoning (Tricart, 1980) : the cleavage corresponding to the discussed phase is linked to folds including Oligocene molasse of the French Subalpine ranges, but truncated by an erosion surface classically regarded as pre-Miocene.

Since the External crystalline massifs are implied in such an event, we may assume that this new splitting involves the part of the external basement which was adjacent to the Subbriançonnais zone and emplaces large granito-gneissic slices which will become the External crystalline massifs (Fig.2), whereas other ones (namely the basement of the Helvetic nappes, paleogeographically lying south of the Aar massif) disappear in depth, (except the small Tavetsch massif).

In France, the Mont-Blanc massif may also be regarded as a large slice and as the root of the Lower Helvetic nappe (Morcles nappe). More eastwards, the Italian Mont-Chétif massif, near Courmayeur (Fig.1), is also a much smaller slice, wrapped up in the Mesozoic cover, like its more southern and French counterparts, viz. the grand Châtelard and Combeynot massifs. During the splitting and the sinking down of this basement material, the cover was everywhere stripped off westwards.

This splitting is likely linked to the underthrusting of the whole external basement below the Internal zones. The resistance offered by the External crust to its sinking down probably induces the splitting up of the External crystalline massifs into large slabs thrusting upon one another. We have here to emphasize the fact that the main thrusts are not here the listric and normal faults which surrounded crustal tilted blocks in Mesozoic times : recent studies performed in the External crystalline French massifs (Lemoine 1984) demonstrate that the blocks were carried away without any notable disturbance of their Mesozoic fault-planes : the splitting plane(s) of the crust was (were) more deep-seated (Fig.3).



Fig.3. This theoretical sketch only intends to give an idea of the setting of the cleavage planes through the continental crust and their independence from the more superficial distension faults. The latter were born from the Jurassic distension of the European continental margin, the former, from the Eocene compressive stage of the margin evolution.

These events end with the Late Miocene and Pliocene p.p. with the overall folding of the Subalpine French ranges and of the Jura mountains. This folding involves the Miocene (Helvetic melange) on its outermost limit. As previously said, the Neogene events are assumed to be always connected with the subduction of the Helvetic-Dauphiné crust which is not a surprising process : compared to the warm, stretched and fragmented Penninic crust, the External crust was a cold one, with a normal thickness. It was heavier than the Penninic one and its subduction below the latter was a normal process. It was certainly capable to sink deepward and eastward. Geophysical data suggest that the eastern and deep prolongation of the main thrust plane would offset the Moho (Perrier 1980, point A of fig.2). This would explain the beak shape of the Ivrea body and would confirm that the crustal splitting extended, for the first time, to the whole width of the chain.

Exactly as for the Late Eocene contraction, this splitting, with west or north vergence, could be linked to an antithetic folding or thrusting (i.e. with an east or south vergence) involving at least the internal side of the External crystalline massifs. It is only on the internal side of the Argentera massif that the backwards structures are clearly observable in the landscapes. Elsewhere, small-scale studies only provide evidence of their existence (see namely Steck 1984, p. 72 and pl. 1).

This process is still running, since geophysical data suggest that the subduction is always acting along the shear plane deduced from the low-velocity channel between 11 and 21 km under the French-Italian Alps, but this new plane seems to be and is restricted to the Northern Alps. Ménard & Thouvenot (1984) propose that this thrusting surface would offset the Moho (point B of the fig.2), but such a hypothesis requires further confirmation.

In this scheme of the outwards progradation of the crustal splitting in the Alps, we have assumed that the stress field was approximately constant since the Eocene. That is roughly correct as recently suggested by Malavieille and al. (1983) in a study of the Alpine stretching lineations : they are always transverse to the belt, whatever the age.

To summarize the preceding evolution, the main result of all these imbrications was to insert one below another large gneissic slabs which progressively built up a "sialic root" well outlined by the deepening of the Moho which is down to 45 km beneath the Internal Alpine zones (Fig.2).

So doing, it brings about an isostatic readjustment which comes in addition to the tectonic stacking, the more so since the isostatic equilibrium is not yet completed in the Alpine realm hence negative isostatic anomalies appear, although very small one (on the average, -20 milligals in France and Switzerland, Perrier 1980, Mueller in Trümpy 1980).

The numerical calculation of the interaction rate of these two possible causes of the Alpine uplift (isostatic readjustment and tectonic stress) has been made (Neugebauer and al. 1980) on the Basel-Como geotraverse. For this purpose, a model of the crust has been built making use of the present stress-field (in situ stress-measurements) and of the gravity anomaly. The best possible agreement between the presently observed uplift and the calculated one is given by an horizontal compression less than 100 bars. This value is relatively low : here, isostasy would be the major factor.

This result is in agreement with some observations. For instance, in Switzerland near Chur, the present-day highest uplift zone (1,7 mm/year) is clearly linked with a negative isostatic anomaly of -48 mg. However this result cannot be generalized without care : for example, the Jungfrau massif is now in rapid uplift (1,5 mm/year) for a negative isotasic anomaly of -10 mg only. But we are there in the front of the External crystalline massifs and we know, from seismic data, that this front is the seat of an important tectonic activity. In this point, tectonic constraints would exceed isostasy.

If the present dynamics is roughly decipherable in the Western Valais and the Savoie Alps, it is harder to understand it south of the Pelvoux massif. We have said that the N or NW vergence of the Swiss and N-French Alps structures are linked with the N or NW displacement of a crustal slab. Its western boundary follows a Pelvoux-Argentera line along which complications occur. As already seen, field measurements indicate that the stress field turns with the range (Frechet, 1977) (Fig.4). Such a pattern may indicate a local reorientation of the European tectonic stress-field by concentric and hemicircular ramps, viz. the main thrust surfaces of the Alpine edifice (for the origin of their curved pattern, see Debelmas, 1986).

IV . UNDERTHRUSTING AND UPLIFT : RELATION AND DISCUSSION

The review of Alpine data allow us to conclude that underthrusting causes the thickening of the sialic root which in turn causes the isostatic uplift. Such a conclusion calls for three remarks :

1. Uplift ought to start as soon as the slices start on their downward emplacement, i.e. at the Late Eocene or, at least, at the Oligocene. Precisely, such uplifts occur at this time. This is shown by the incoming, in all the Oligocene molasse basins, of pebbles containing metamorphized Penninic rocks with the paragenesis of the mesoalpine event (38 m.y.) (de Graciansky & al 1971 , Trümpy 1980), i.e. rocks formed below a cover which was later very quickly removed. But the uplift rate and the height are a matter of discussion. Using data provided by the cooling rate of the Bregaglia granite (Fig.1), Jäger and al. (1984) suggested height of many thousands of meters for the Upper Oligocene. Such a height would involve, in spite of the tropical conditions of this period, low temperatures, which would be the explanation for the abnormal coolings.

Such a conclusion is probably over-estimated but we must not underestimate the Oligocene uplifts, namely in the vicinity of the Insubric fault (=Tonale line) which was acting at this time (Trümpy 1980). At the Oligocene, this fault, separated two different alpine realms : 1) a northern one, strongly uplifted and eroded, since the deepest parts of the Pennine Alps were exposed at this time and display amphibolite facies ; 2) a southern realm, with a difference in level of many thousand

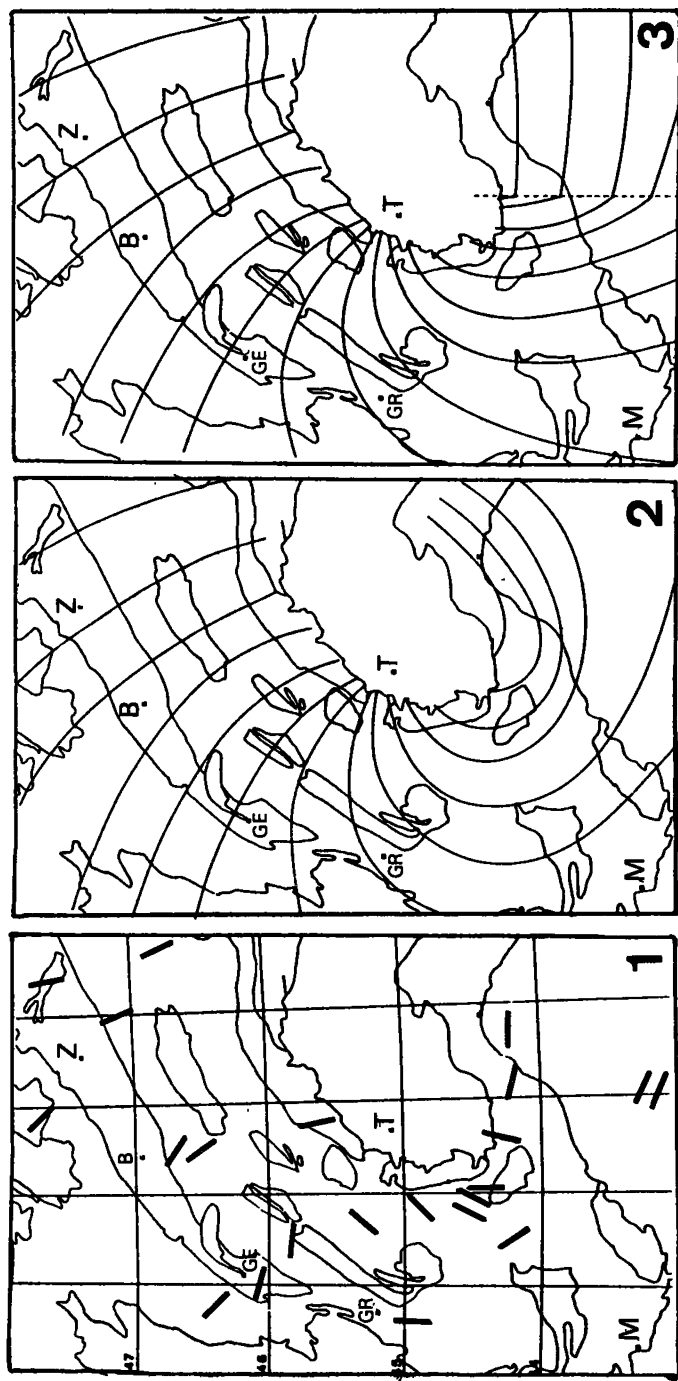


Fig.4. Present tectonic stress-field of the Western Alps (after Frechet, 1978).
 1. Focal solutions for the present seismic activity (calculated axis of the present maximum regional tectonic stress-field) - 2 & 3. Assumed present regional stress-field (two variants).

of meters (20 km according to Trümpy 1980, p. 66, and other authors, see fig.2). Of course, such a difference may have been progressively reached and it does not necessarily imply extreme heights. But contemporaneous erosion must have been very active because, in the Como area, the sediments of the Northern border of the Pô plain show that, by the Early Oligocene, a rapid uplift of the Alpine axis occurred: the Ticino mountains provided huge masses of coarse-grained conglomerates (the so-called gompholite) with crystalline pebbles. Such conglomeratic deposits last until the Miocene but it is only from the Early-Middle Miocene that the uplift overtakes the Pô border for the old gompholite levels are folded or tilted at this time and the recent ones contain calcareous pebbles of the South-Alpine provenance (Gabert 1962).

Concerning the throw of the Insubric fault, we should add that a simple calculation (20 km uplift for 20 My) yields an amount of 1 mm/year, i.e. the rate of the present uplift of the External Crystalline massifs. The Oligo-Miocene uplift is not a negligible phenomenon. It confirms that deep splitting with stacking up immediately entails uplift through the joint action of tectonic doming and of isostatic rebound.

2. A second point to discuss is the reason why that part of the range situated between Pelvoux and Argentera is no longer being uplifted, although the constraints in this area are always perpendicular to the Alpine arc, exactly as in the North.

This may be due to the amount of stress, but another geophysical explanation may be advanced: focal mechanisms of earthquakes reveal in this part of the Alps a present activity of normal faulting or dextral shears along N 140 faults which are most nearly parallel to the displacement of the N Alpine slab. Here, in other words, the present NS to NE-SW stress would induce no thrusts, but only an extension along new or old strike-slip NW-SE faults (Frechet and Pavoni 1979). The crust here not being overthick, there would not be any special isostatic rebound except that rebound linked to previous compression.

3. At least, South of the Argentera massif, the relations between compressive stress, isostasy and uplift are not clear. Moreover, the tectonic frame is disturbed by the fact that the Alpine structures were carried away northward as a whole during the Apennine Miocene orogeny. The interpretation of this area is closely linked with the problem of the increasing curvature of the Alpine arc through time, problem which is beyond of the scope of this paper.

V. CONCLUSIONS

Geological and geophysical data show that the uplift of the Western Alps is mainly due to the isostatic rebound linked to the progressive underthrusting of large gneissic slabs in an outward-trending process which contributed to the growth of a sialic root under the inner part of the range.

This double action starts at the Early Oligocene time. Since tectonic studies have shown that stretching lineations are everywhere perpendicular to the general trend of the chain, it may be concluded that the tectonic process progressed outwards all along the chain.

But by the Middle Miocene, the pattern was modified in the Ligurian Alps by the increase of the curvature of the Alps probably due to the Apennine orogeny which wrenched Alpine structures to the NE. This part of the evolution has not been developed in this paper.

Now, the tectonic activity seems to be a NW motion of a gigantic slab made of the Northern Alps. Such a motion implies a lateral shear in the Embrunais-Argentera area, more or less parallel to the overall European stress-field but the later would be here reoriented by the curvature of the chain. So, the maximum compressive stress turns and stays perpendicular to the general trend of the chain, inducing only extension all along the old shear planes.

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