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Nappe geometry in the Western Swiss Alps

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Abstract—Detailed geological mapping during the last 20 years in the Western Swiss Alps has shown clearly that most of the lower basement nappes are fold nappes possessing normal and inverted limbs. Moreover their cores are made of strongly deformed gneisses indicating that important ductile strain took place during the formation of the fold nappes. It is therefore probably wrong to imagine deep basement nappes as rigid slices as often actually claimed, especially when interpreting seismic profiles. True 'brittle type' thrust nappes involving basement rocks only occur in the internal and upper parts of the belt. Cover nappes, on the contrary, are in most parts of the Alpine belt thrust sheets following more or less the rules of thin-skinned tectonics. Many basement fold nappes lost part of their sedimentary cover during or just before their formation, by décollement along ductile horizons. The result is that many cover thrust nappes in the external part of the Alps are directly related to their original basement fold nappes.

INTRODUCTION

SINCE the early revolutionary investigations by Schardt (1907), Argand (1911, 1916), Lugeon (1914) and Heim (1919–1922), our knowledge of the Western Swiss Alps (Fig. 1) has been steadily refined and increased. The result, though fundamentally not much different from Argand's brilliant reconstruction, gives a better understanding of the exact geometry, stratigraphy and metamorphism of each Alpine unit. In a very simplified way part of these data are represented on the cross-section of Fig. 2. The NW–SE orientation of the section has been chosen to coincide with the major stretching and translation direction during the paroxysm of Tertiary deformation (*D* I phase according to the classification by Steck 1984, 1990). The exact location of the profile is shown in Fig. 1. It has been constructed by lateral projection of field information from up to 25 km off the profile. Because the folds are often non-cylindrical and vary in trend and plunge the projection paths are generally curved. The marked Alpine relief and the strong axial plunges often make it possible to reconstruct the geometry up to 10 km above and 20 km below the actual topography (Escher *et al.* 1987, Steck *et al.* 1989). Furthermore, it has been possible to correct and complete the deep structures by using the preliminary results of the Alpine seismic lines (Marchant *et al.* in press). These seismic traverses were a part of a Swiss national research program on the deep structures of the Alps (Frei *et al.* 1990, Heitzmann *et al.* 1991). In spite of all these exceptional conditions it is obvious that many parts of the profile remain largely hypothetical, especially in the deeper parts of the belt. It may in fact be that some nappes are discontinuous and that major thrust surfaces intersect different units with increasing depth.

The goal of the following pages is to discuss the geometry of the basement and cover nappes and their inter-relationship in this part of the Alpine belt. The legend for the geological profile of Fig. 2 has been chosen in such a way as to indicate the probable relation between each cover nappe and its original basement nappe for the different tectonic domains (Helvetic, Lower Penninic, Middle Penninic, Upper Penninic, South and Austro-Alpine).

BASEMENT NAPPES

The basement nappes found in the upper part of the belt mostly belong to the Southern (Adriatic) plate and to the ophiolite units. Their structure can generally be compared to that of thrust sheets and is often characterized by a basal mylonite zone. Their formation mechanism probably followed the rules of thin-skinned tectonics with ramps and flats and associated folds, as shown by Laubscher (1989) for the Lechtal and Silvretta nappes in the Austro-Alpine and Southern Alps.

By contrast, the Middle and Lower Penninic basement nappes as well as the Helvetic ones display, in most cases, the typical geometry and stratigraphy of fold nappes with a normal flank, a frontal part and an overturned limb (Fig. 2). Their internal deformational features indicate an origin by a ductile shear mechanism (Steck 1987). Exceptions to this rule are probably the Pontis and the internal Mont-Blanc nappes, whose basement cores are directly limited by narrow shear zones with the underlying units. Three examples of ductile basement fold nappes will be described in the following pages, each nappe being representative of an Alpine tectonic domain (Fig. 2).

The Mont-Blanc–Morcles nappe (Helvetic domain)

Recent detailed mapping and stratigraphic observations by Epard (1986, 1990) in the Mesozoic series southwest of Chamonix (mainly in the Col de Tricot and Arandellys regions) demonstrate the following.

(1) The stratigraphic succession of Triassic and Juras-

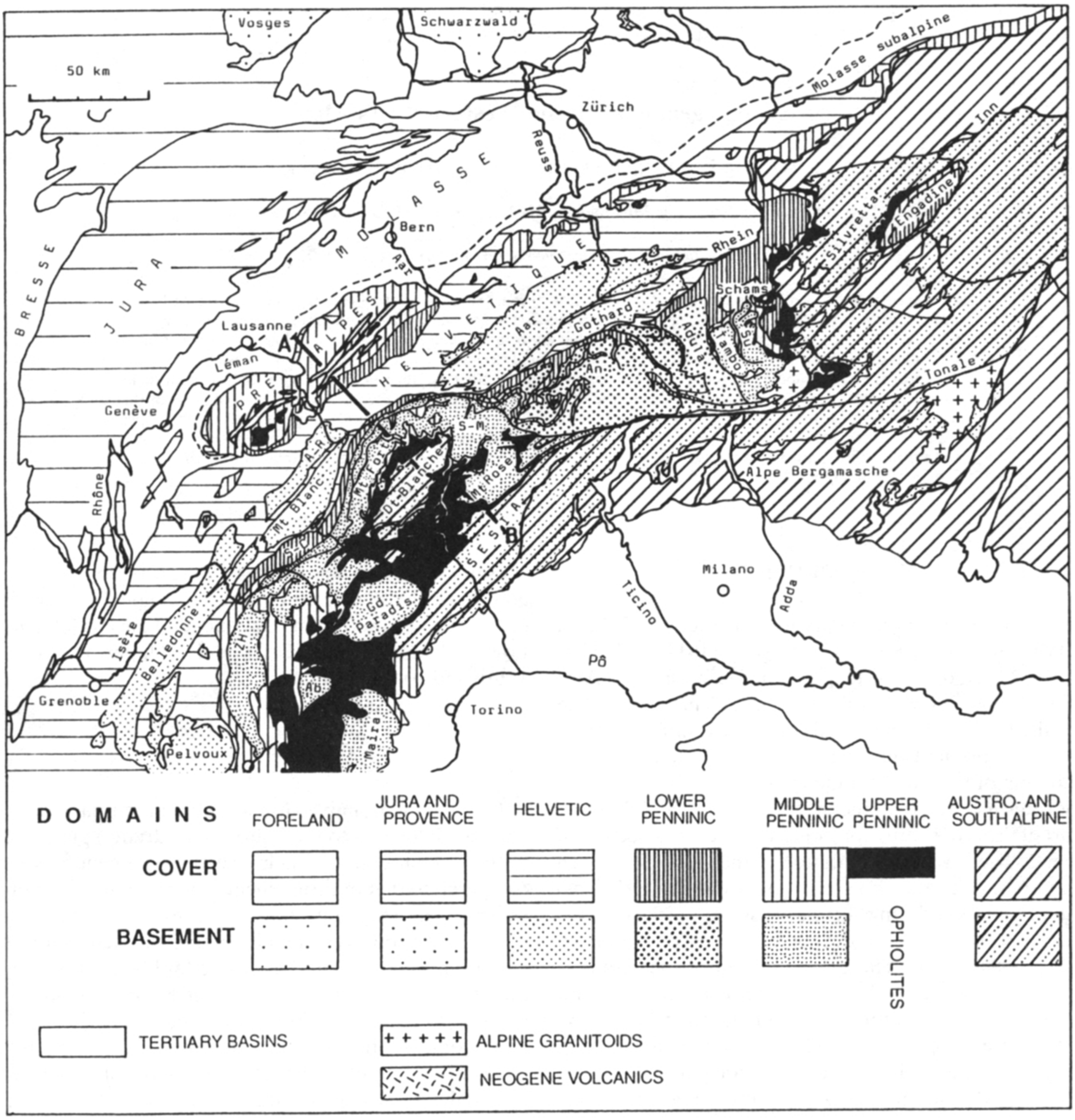

Fig. 1. Simplified structural map of the Western Alps. A–B refers to the exact location of the geological profile in Fig. 2.

sic quartzites, evaporites, dolomitic limestones, limestones, marls and shales, forms an overturned sequence in direct continuity with the basement gneisses of the external Mont-Blanc massif.

(2) The contact between crystalline basement and the Early Triassic quartzites is locally underlain by a narrow layer of green or red arkose containing dolomitic nodules and pyrite crystals. This level most likely represents a Permo-Triassic weathering surface. In places a basal conglomerate can be seen forming the transition to the quartzites.

(3) The Mont-Blanc gneisses are strongly deformed by a Tertiary Alpine schistosity which is clearly discordant to the cover–basement interface. This results in obvious small- and large-scale deformation and folding of the contact zone.

In the Northern part of the Chamonix zone, in the col de la Forclaz and col de Balme regions, Ayrton (1980) has previously reported a similar inverted stratigraphic sequence in direct continuity with the Mont-Blanc basement gneisses.

All the above observations prove beyond any doubt that the cover sediments of the internal part of the Chamonix zone are in stratigraphic continuity with the crystalline basement of the Mont-Blanc massif. Moreover they confirm the view expressed by Lugeon (1914), Trümpy (1963) and Masson *et al.* (1980) that the northern contact zone of the Mont-Blanc massif represents

Fig. 2. Simplified geological profile through the Western Swiss Alps. The section and the legend have been constructed in order to show the geometric relationship existing between basement and cover nappes inside each structural domain. Cover nappes are made of post-Permian Alpine sediments. Most basement nappes include remnants of cover rocks left behind after the partial departure of the cover units.

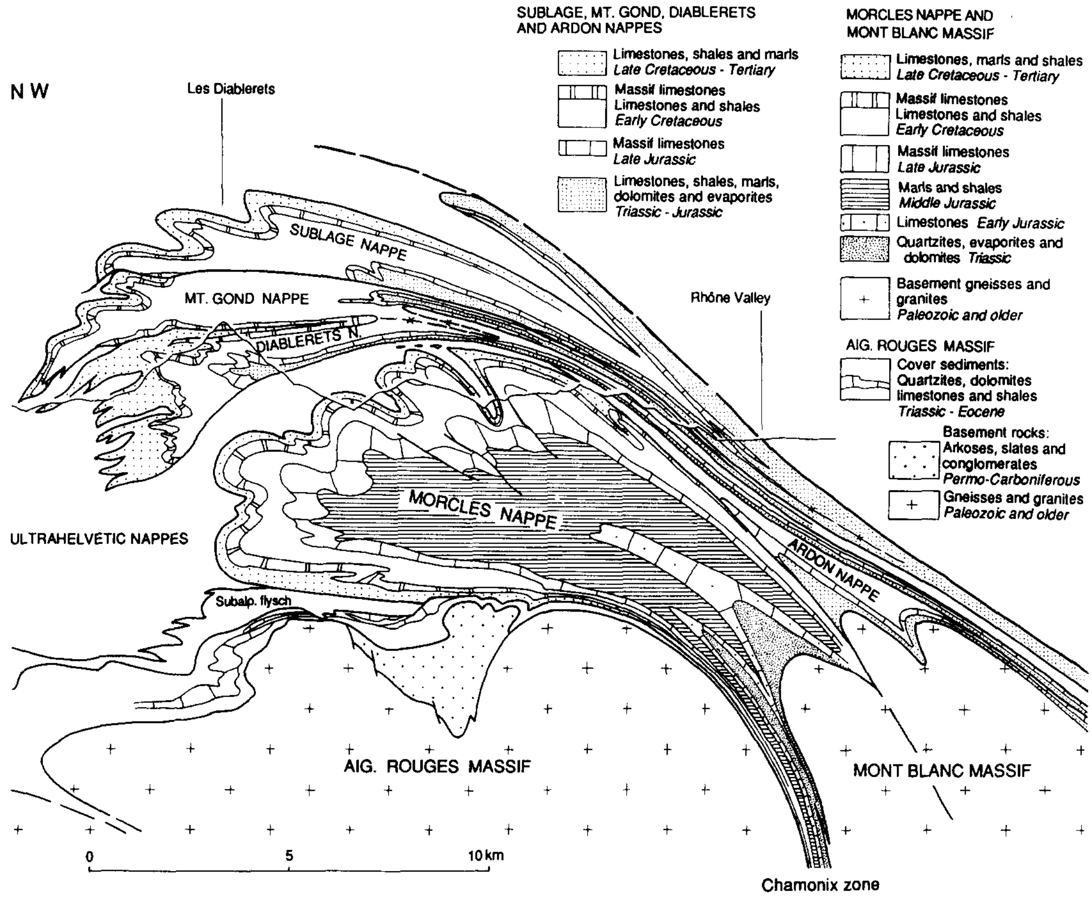

Fig. 3. Geological section through the Helvetic basement and cover nappes in the Diablerets–Morcles region. Late vertical transcurrent faults have not been represented in order not to complicate unnecessarily the general structure.

the overturned flank of a large anticlinal fold structure corresponding to the inverted part of the Morcles cover nappe (Fig. 3). Therefore the 'Mont-Blanc thrust' represented by a rigid basement slice overthrusting the northern underlying rocks (Boyer & Elliott 1982, Butler 1983, 1985) definitely does not exist. In the external part of the Chamonix zone, Ayrton (1980) clearly demonstrated the existence of an autochthonous sedimentary cover of the Aiguilles Rouges massif. The Chamonix zone is thus most likely explained as a syncline separating the southern Mont-Blanc massif from the northern Aiguilles Rouges massif. The depth of the syncline is unknown; its steepness makes it undetectable on seismic profiles.

In its frontal and upper parts (Fig. 3) the Mont-Blanc massif is affected by a thrust plane, probably reactivated during the main overthrusting of the Diablerets, Mont-Gond and Sublage cover nappes. This may have accentuated the separation of the Mont-Blanc massif and its cover into two units: the external Mont-Blanc–Morcles unit and the internal Mont-Blanc–Ardon unit.

Before this late brittle event it is most likely that both the internal and external Mont-Blanc massifs presented all the characteristics of perfect ductile basement fold nappes (Fig. 6). According to earlier workers (Lugeon 1914, Badoux 1972, Ramsay 1981) the entire Mont-Blanc massif represents the core of the Morcles nappe. The probability that it must be separated into external and internal gneiss cores, each with its own cover nappe as stated above, is based mainly on the following observations.

(1) The existence of a narrow structural unit, the Ardon nappe, separating the Morcles from the Diablerets nappe in their root zones (Masson *et al.* 1980).

(2) The stratigraphic complementarity between the rocks of the Ardon nappe (Cretaceous–Eocene) and the autochthonous cover of the internal Mont-Blanc basement (Triassic–Jurassic).

(3) The recognition in the French part of the Mont-Blanc massif (Epard 1990) of two distinct zones: (a) an external part representing the core of the SW-extension of the Morcles nappe (Mont Joly and Sangle cover units); and (b) an internal part possessing an autochthonous sedimentary cover.

The amount of cover in the Morcles nappe, which appears to be much too great to fit onto the external Mont-Blanc massif can be explained as follows: (a) the internal strain of the two limbs of the cover nappe is considerably higher than that of the basement core. It reaches extension values of 1:100 and even occasionally up to 1:400 in the inverted limb (Ramsay 1981, Dietrich 1989); and (b) the internal Mont-Blanc massif probably partly overthrusted the external Mont-Blanc gneiss, thus covering part of the basement originally corresponding to the normal flank of the Morcles nappe.

The Antigorio nappe (Lower Penninic domain)

The Antigorio nappe is part of the Lower Penninic Simplon–Ticino structural domain. It crops out east of the Simplon Pass and represents the deepest part of the Alpine belt which was uplifted during the last important phase of Alpine deformation (Gerlach 1869, Argand 1916, Steck 1984, 1990). This uplift affected the whole of the Aar–Toce culmination.

Recent detailed geological mapping (Spring *et al.* in press) revealed the following observations (Fig. 4).

(1) The Antigorio nappe displays the geometry of a large recumbent anticlinal fold with an amplitude of more than 12 km and a wavelength of about 2 km. Its frontal part has a hemi-cylindrical shape.

(2) The core of the Antigorio nappe is made of Paleozoic granites and gneisses, which were strongly deformed and metamorphosed to amphibolite facies during the early Tertiary phases of nappe emplacement and deformation. Two early penetrative schistosities associated with SE–NW stretching lineations can be distinguished (Steck 1984, 1990).

(3) A sedimentary cover can be observed from the central flank via the frontal part to the overturned limb (Fig. 4). Its stratigraphy consists of basal Late Paleozoic metagreywackes of the Baceno unit. These are overlain by Triassic quartzites, dolomites and shales. The sequence is completed at the top with thick Teggiolo marbles, calc-schists and breccias of probable Jurassic age.

(4) At the frontal part of the nappe, the Baceno schists and the Triassic quartzites and dolomites have been eroded during the early Jurassic. They are replaced by the Teggiolo marbles and calc-schists which locally display a basal conglomerate containing Antigorio gneiss pebbles, in direct contact with the basement gneisses.

(5) There is a stratigraphic continuity between the basement rocks and cover sediments all along the inverted limb of the nappe. This continuity also exists on the top of the Verampio gneiss, where it forms a normal succession.

The above observations all clearly indicate that the Antigorio nappe displays the characteristics of a true ductile fold nappe with a basement core. Nowhere can traces be seen of an early basal structural discontinuity. The link between the Antigorio and the underlying Verampio nappe is represented by a perfect recumbent syncline of Baceno and Teggiolo metasediments (Fig. 4).

It is possible to imagine that the metasedimentary cover of both nappes is incomplete and that originally an upper sequence of Cretaceous and Tertiary rocks existed. This very ductile part of cover rocks may have been displaced towards the northwest, to the Prealps. A possible equivalent may be found in the Infra-Niesen nappe (Fig. 2).

The Siviez-Mischabel nappe (Middle Penninic domain)

South of the Rhône Valley in Valais, the Siviez–Mischabel nappe forms a huge nappe structure belonging to the Middle Penninic tectonic domain. It represents the central unit of the Grand Saint-Bernard super-nappe (Escher 1988). During the past 15 years this unit has been mapped and investigated in detail from the Zermatt region to the Val de Bagnes (Burri 1983, Marthaler 1984, Sartori 1987, 1988, Thélin 1987). The result of these investigations can be summarized as follows.

(1) The Siviez–Mischabel nappe has the geometry of a very large recumbent fold with an amplitude of more than 35 km and a wavelength of between 3 and 10 km. After its formation and emplacement it was backfolded in its internal part (Fig. 2). This resulted in the spectacu-

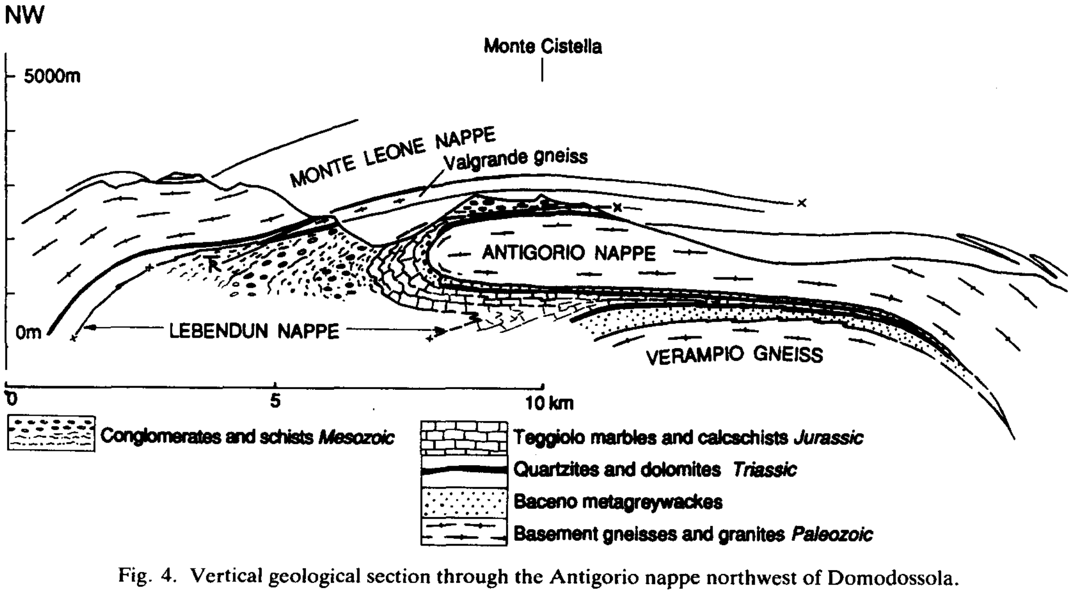

Fig. 4. Vertical geological section through the Antigorio nappe northwest of Domodossola.

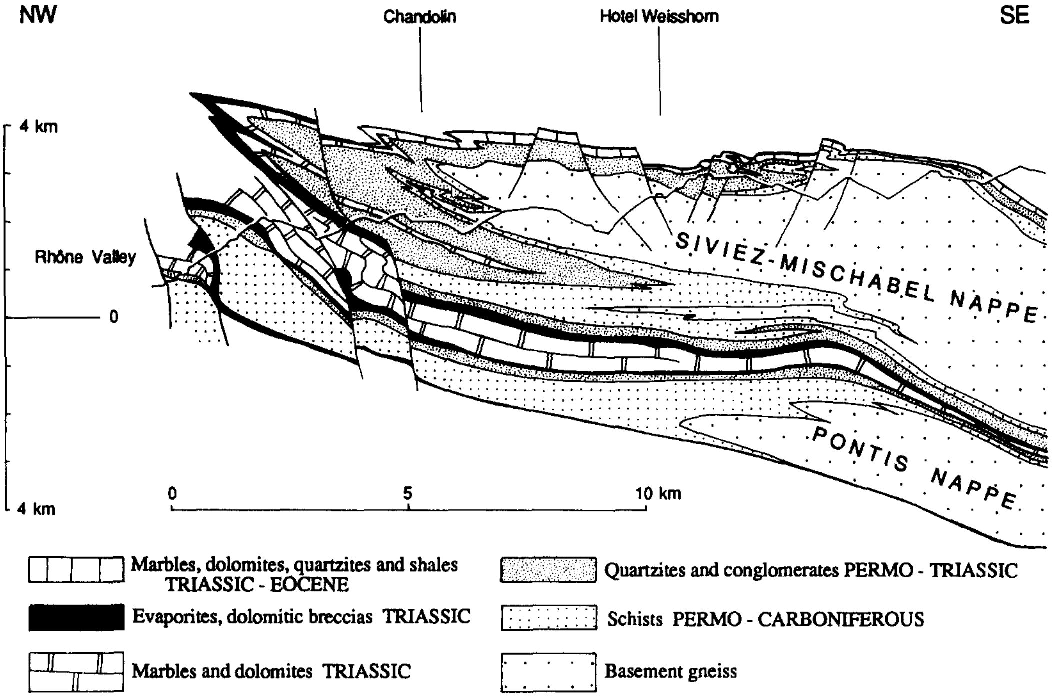

Fig. 5. Vertical geological section through the frontal part of the Siviez–Mischabel and Pontis nappes in the Val D'Anniviers region.

lar Mischabel backfold, studied in detail by Milnes *et al.* (1981) and Müller (1983).

(2) The core of the nappe is composed of gneisses and amphibolites of pre-Late Carboniferous age. They display an early penetrative axial-surface schistosity formed under upper greenschist facies conditions during the nappe formation. Finite strain measurements in augen gneisses give X/Z ratios between 3/1 and 10/1. The intensity of strain clearly increases in the lower, overturned part of the nappe. A SE–NW early stretching lineation can be observed in many places.

(3) Completely surrounding this basement core, a metasedimentary cover can be followed from the normal flank throughout the front of the nappe to its inverted limb (Fig. 5). This cover displays the following stratigraphic sequence from base to top: (a) Permo-Carboniferous schists, especially well represented in the overturned limb; (b) Permo-Triassic quartzites and conglomerates; (c) Triassic evaporites and dolomitic breccias (cornieule); and (d) Middle Triassic to Eocene dolomitic limestones, marbles and flysch on the normal flank of the nappe and in its eastern part.

(4) A perfect stratigraphic continuity between basement and cover rocks is preserved in most places, while nowhere can any trace of early thrust planes be found. The only brittle deformation is represented by frontal dextral transcurrent faults (*D* IV transpressional phase according to Steck 1990), and late normal faults (Fig. 5).

The obvious conclusion from all these observations is that the Siviez–Mischabel nappe was mainly formed by ductile deformation resulting in strong internal strain of the basement core, especially its lower part. Simultaneously an inverted flank of cover rocks must have been formed. The missing part of the cover rocks (Middle Triassic to Eocene) in the frontal part and in the inverted limb were probably stripped from their basement at the same time and tectonically translated towards the Préalpes Médianes Rigides nappe (Figs. 2 and 6) (Baud & Septfontaine 1980, Sartori 1988).

The recumbent synclinal zone separating the Siviez–Mischabel nappe from the underlying Pontis nappe displays an asymmetrical stratigraphy: in the overturned flank the youngest rocks are Lower Triassic quartzites while in the normal limb they are represented by Middle Triassic dolomites and marbles (Fig. 5). This anomaly may have been caused by the original absence or presence of evaporites above the Middle Triassic marbles, which could be used as selective detachment horizons. It could also have been caused by a more fundamental, not yet understood mechanism during the basement nappe formation and the simultaneous departure of its cover nappe.

COVER NAPPES

In contrast to basement nappes, most cover nappes in the Western Swiss Alps display a normal stratigraphic sequence indicating a probable origin by detachment along narrow basal shear zones. A frontal anticlinal complex fold, truncated by a basal thrust is present in many cases. These thrust nappes are internally much less deformed and their metamorphic grade is much weaker than that of the corresponding basement nappes. Most cover thrust nappes used ductile layers like Triassic evaporites and cornieules or Jurassic and Cretaceous shales as detachment horizons. An exception to these rules is the Morcles nappe which possesses all the features of a true fold nappe (Figs. 2 and 3). Internal deformation and metamorphism increase generally from the external part of the cover nappes towards their root zones.

A special case is the intermediate type of nappe made of Late Carboniferous, Permian and early Triassic rocks. These nappes were disconnected from their older basement along shear surfaces inside the ductile Carboniferous schists. Their mainly post-Triassic cover travelled even farther to the northwest, forming an independent external unit. The Mont Fort nappe (Fig. 2) is a typical example of such an intermediate type nappe: its original basement probably corresponds to the internal Siviez–Mischabel or the Monte Rosa nappe, while its younger cover rocks are found in the Prealpine nappes.

RELATION BETWEEN BASEMENT AND COVER NAPPES

From the preceding pages and from Figs. 2 and 6, it is clear that a very definite relationship exists between deeper basement fold nappes and cover thrust nappes in the Western Swiss Alpine belt. Most cover nappes have been translated towards the northwest for distances of 10–100 km from their 'home land'. They can generally be related directly or indirectly to their original basement nappes (Fig. 6). Even if there is not yet enough field information concerning the area of connection between cover and basement nappes, it is possible to imagine that the link corresponds to a progressive transition between a wide and ductile basement shear zone and a relatively brittle cover thrust. The dip of the axial surfaces of the basement nappes is between 10° and 30° steeper than that of the thrusts of the external cover nappes.

The departure and transport of most cover nappes must have taken place before or at the beginning of the building of the basement nappes (Steck 1987, Sartori 1988). The former have generally escaped the relatively high Alpine metamorphism of the basement rocks (between lower greenschist to higher amphibolite facies). In some cases it is possible that the original cover was replaced by another cover sequence translated from a region farther to the southeast before the formation of the basement nappe. This 'remplacement de couverture' took place for instance when the Tsate and Cimes Blanches nappes replaced parts of the original sedimentary cover of the Mont Fort basement. Anyway this does not change the basic problem of simultaneously building an external cover thrust nappe and an internal basement fold nappe.

CONCLUSIONS

Deeper parts of the Alps show clear evidence for the predominance of basement fold nappes, probably formed by heterogeneous ductile shear strain during the NW-directed overthrusting of the upper part of the Alps. This Tertiary (Late Eocene–Early Oligocene) deformation took place under relatively high temperature (above 300°C) conditions (Steck 1987, Merle *et al.* 1989). The strain distribution inside most basement nappes suggests strong deformation, mainly by simple shear resulting in an early dominant NW–SE stretching

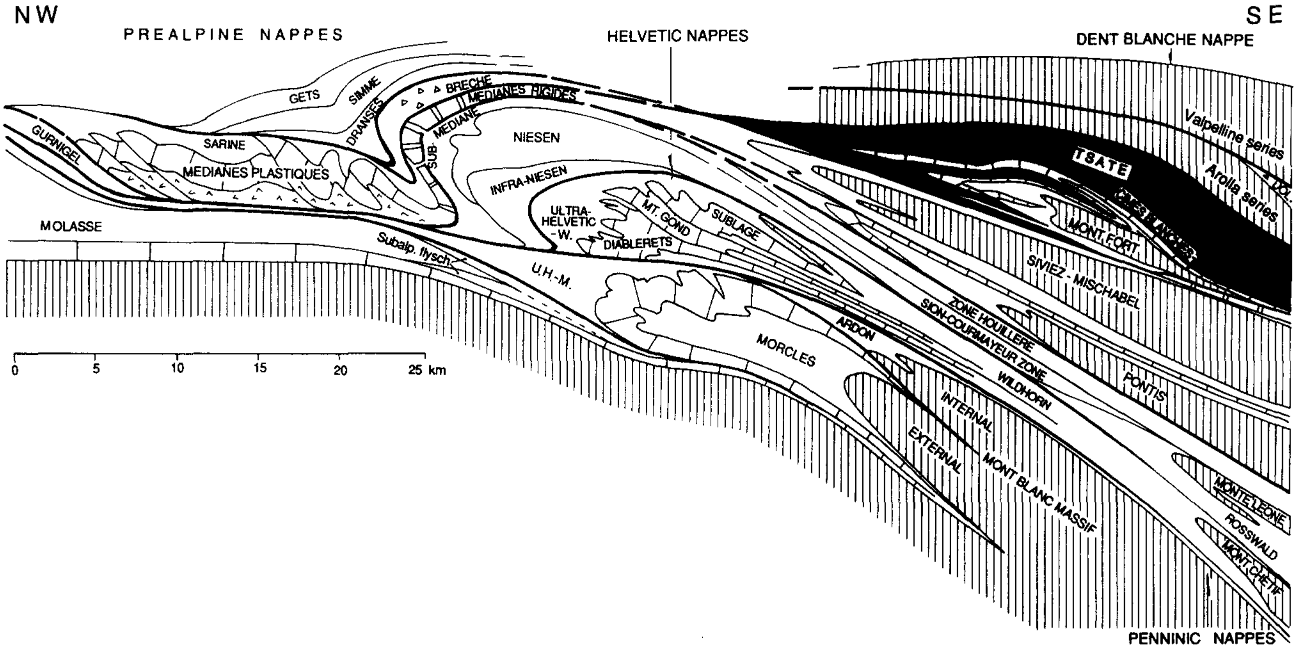

Fig. 6. Structural profile showing the simplified geometric relations between cover and basement nappes in the more external part of the Western Swiss Alps. In order to clarify this relationship, the effects of late backfolding, back thrusting and uplift have been subtracted (compare with Fig. 2). Thick lines correspond to narrow shear zones or thrusts, pre Permo-Triassic basement rocks are shaded. The Zone Houllière, though largely of Carboniferous age, has been considered as cover because of the dominance of shales. It is interesting to note that several important early thrust surfaces have been refolded during later movements.

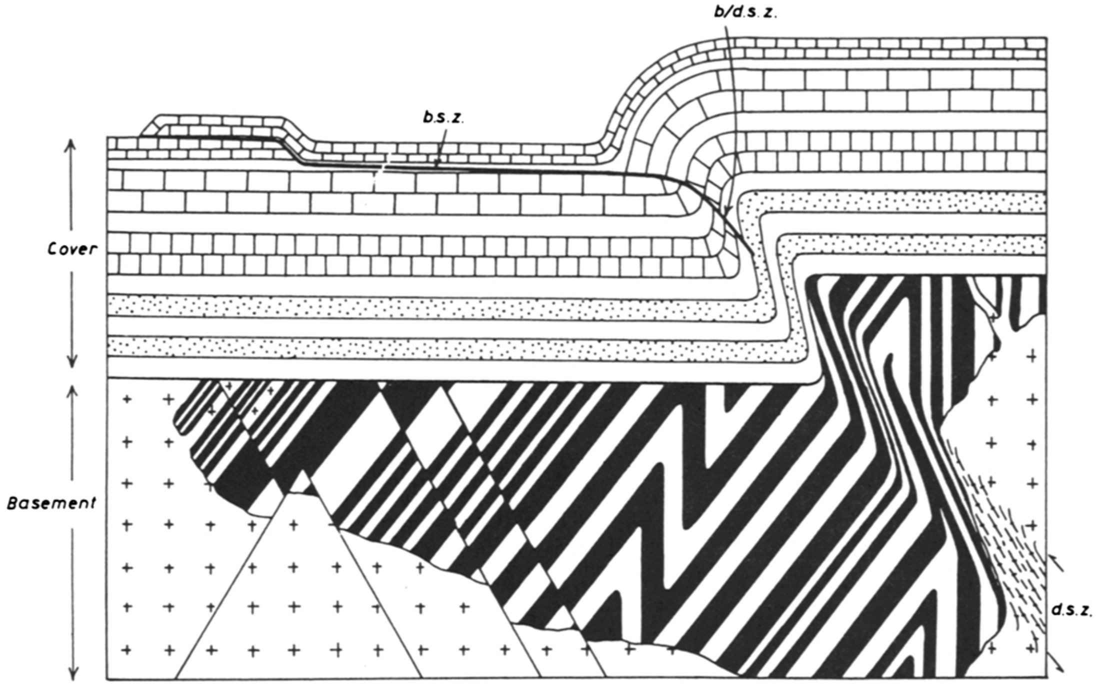

Fig. 7. The possible interrelations between high-level and low-level shear zones in the crust in a region of crustal compression (brittle shear zone = b.s.z., ductile shear zone = d.s.z.). After Ramsay (1980).

lineation, transverse to the Alpine belt. The base of each nappe is always considerably more deformed than its upper part, which explains the existence of inverted limbs. The importance of this mechanism for the formation of basement fold nappes in the Alps was first recognized by Heim (1919–1922) and was later analysed by Voll in Nabholz & Voll (1963). Recent work by Steck (1984, 1987, 1990) confirms this view and makes it possible to distinguish several wide ductile shear zones in the Central Alps. Post-nappe pure shear deformation, and simple shear following mainly longitudinal NE–SW directions, was superimposed on the original nappes, creating locally intense ductile refolding (Milnes 1974, Burkhard 1986, Steck 1990).

It is therefore wrong to always imagine deep basement nappes as rigid slices, as often claimed, especially when interpreting seismic profiles in mountain belts. Schmid *et al.* (1990) came to similar conclusions when describing the geology of the Schams nappes in the Eastern Swiss Alps.

In contrast to the basement nappes, cover nappes of lower metamorphic grade generally show features of thrust nappes. They may follow the tectonic rules of brittle type ramps and flats as in the external part of some Prealpine or Helvetic nappes (Pfiffner 1985, Mosar 1991). Mostly however they display internal ductile strain which increases considerably together with the metamorphic grade from their fronts towards the root zone (Dietrich 1989, Groshong *et al.* 1984). Moreover their fold geometry suggests that the nappes were formed mainly by selective simple shear deformation, controlled by the presence of ductile beds like the Middle Jurassic and Early Cretaceous shales. As shown by Dietrich & Casey (1989), the observed thinning of the Helvetic nappes towards the root zone can be explained by the superimposition of pure shear deformation on simple shear. The amount of the pure shear component increases towards the internal part of the nappes. Whatever the complexities of the internal deformation of the Prealpine and Helvetic cover nappes, their main characteristic is, with the exception of the Morcles nappe, that they have been translated over considerable distances along basal shear zones or thrusts.

There is a definite link between ductile basement fold nappes and cover thrust nappes. It is therefore necessary to imagine one or more mechanisms explaining the more or less simultaneous formation of both types of nappes. One possibility is the one proposed by Ramsay in 1980 (Fig. 7) in which ductile deformation of basement rocks along a wide zone of simple shear is correlated with brittle deformation of the corresponding cover along a narrow subhorizontal shear zone or thrust. Dietrich & Casey (1989) present a very plausible model showing how the transition may take place from a wide and ductile shear zone to a brittle thrust. Though this concept was used to explain similar relations in the Helvetic nappes it could easily be extended to the deeper part of the Alps. It very nicely demonstrates how a ductile shear zone gradually dies out and is replaced by a thrust while the displacement along the thrust increases. This fits very well with many of the observations in the transition zone. Much work however remains to be done, mainly by detailed geological mapping in the field, to find a totally satisfactory model explaining this particular basement nappe–cover nappe relation.

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