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Post-Nappe Folding in the Western Lepontine Alps

By ALAN G. MILNES[1])

ABSTRACT

The Lower Pennine nappe complex of the western Lepontine Alps (Italy and Switzerland) consists of a series of pre-Triassic basement sheets and irregular masses embedded in a matrix of calcareous Mesozoic cover rocks. These nappes suffered complex large-scale folding subsequent to their emplacement which cannot be described as a succession of clearly defined "fold phases". Instead, major folds with associated parasitic minor structures, or systems of obviously related major folds, are described on the basis of type localities and followed outwards from there until they "die out" (become progressively more open until they can no longer be distinguished) or "disappear" (become progressively tighter until the combination of isoclinal form and penetrative axial plane foliation obliterates the hinges). Eleven such groups of post-nappe folds are distinguished, none of which can be proved coeval, and their relative ages are deduced as far as possible using the principles of superposition – a kind of major fold "stratigraphy". They can be sub-divided into *main Alpine* folds, which developed before or during the rise in temperature which marked the onset of amphibolite facies metamorphism (in lower Oligocene times), and which affected a "multilayer", competent (basement)–incompetent (cover) complex, and *late Alpine* folds, which developed during the period of high temperature (middle Oligocene to upper Miocene) in an essentially homogeneous, but mechanically anisotropic mass consisting of equally recrystallized basement and cover penetrated by a common main Alpine foliation. Except at the earliest stages, when two distinct phases of basement nappe formation can be distinguished, the regional picture can be thought of as the result of a continuous process.

1. Introduction

Superimposed folding is a typical feature of the world's orogenic belts, and the geometrical and mechanical problems associated with it have been studied in detail in many areas (see, for instance, WHITTEN 1966, RAMSAY 1967). In this respect, the Central Alps have remained somewhat in the background: the numerous tectonic maps of the region (STAUB 1924, KÜNDIG 1936, AMSTUTZ 1971, SPICHER 1972, and many others) show only the outlines of the various nappe structures and because of the strong relief give little idea of the importance, distribution or complexity of later folding. In many areas, however, the tectonic picture changes considerably once the significance of the post-nappe deformations is understood. The purpose of this paper

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is to describe the post-nappe folding over an area of some 900 square kilometers of the western Lepontine Alps (see Fig. 1) and to attempt a new tectonic interpretation of this region. Originally, my work was aimed at obtaining a clearer idea of the earlier nappe-forming movements and possibly also the pre-orogenic stratigraphy and basement geology. The unexpected intensity and complexity of the later movements, however, showed that earlier attempts in this direction (for instance, BURCKHARDT 1942, JOOS 1967, MILNES 1968) were premature. Even now many problems remain, and many conclusions reached in the following must be regarded as tentative working hypotheses, to be modified or rejected in the light of future studies.

2. Structural correlation – problems and methods

It has long been known that the rocks of the Central Alps have been subjected to several phases of deformation during the Alpine orogeny. In most outcrops, the evidence for this can be seen in the folded and/or boudinaged folds, lineations and cleavages, and local deformation histories can be worked out. The difficulty, here as in other mountain belts, is to relate these local features and sequences to the large-scale structure and to the overall history of the belt. For many years, correlations both of scale and time were mainly based on orientational criteria, sometimes solely on comparisons of trend and plunge of fold axes (see, for example, WUNDERLICH 1963). In general, however, correlations are now being carried out using a whole range of criteria – fold axis and axial plane orientation, style, class, relation to metamorphic mineral growth, cleavage, boudinage, lineation and bulk strain (see RAMSAY 1967) – in which orientation does not necessarily play a decisive role. Even this procedure has been criticized recently (PARK 1969) and has occasionally led to correlation mistakes (for instance, NABHOLZ & VOLL 1963, see TRÜMPY 1973, and CHATTERJEE 1961, see MILNES 1968, p. 73). An analogy can be drawn between structural geology and stratigraphy in unfossiliferous rocks at this point. Only in extreme cases, say, in the correlation of bore-hole data, does the stratigrapher correlate the rocks from two localities on lithology and sedimentary structure alone. He knows that facies changes can be extremely rapid, and that, failing diagnostic fossils, he must show that the two localities do in fact represent the same stratigraphic level by tracing the horizon continuously from one to the other. In the present study, I have tried to extend the accepted procedures of minor structural analysis by introducing a kind of major fold "stratigraphy" – an attempt to trace each major fold as a separate "horizon" by mapping its axial surface. Minor structural relations were used more as a field mapping tool (equivalent to lithologic criteria in stratigraphic studies) than as objects of study in themselves. Careful watch was kept for changes in "facies" – changes in the overall style and geometry of the major folds possibly related to changing conditions (lithology, relative time of recrystallization, type and intensity of strain). I am not convinced that structural or strain "facies" can be set up and interpreted in the same way as is done in stratigraphy and metamorphic petrology, as has been recently suggested (E. HANSEN 1971), but I believe the concept is an important tool in building up a picture of the structure and history of a deformed zone.

The following account, then, is based on detailed field work in a relatively small area (see MILNES 1964, 1968, 1973), followed by the tracing of the major structures

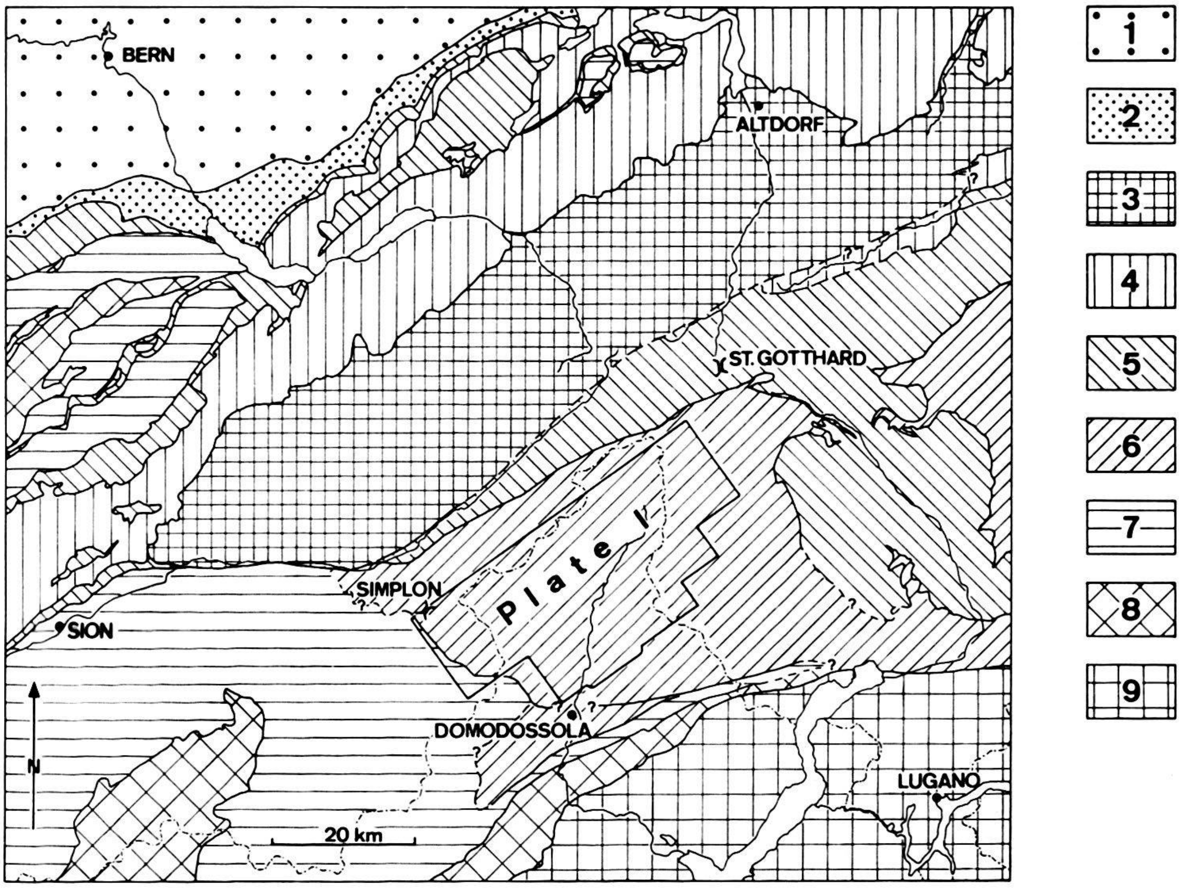

Fig. 1. The main tectonic units of part of the Central Alps (modified after SPICHER 1972) showing the location of the described area (Pl. I).
Key: 1 Molasse of the Swiss plain, *2* Subalpine molasse, *3* Autochthon and parautochthon of the Helvetic zone, *4* Helvetic cover nappe complex, *5* Ultrahelvetic cover nappes and the "sub-Pennine" basement complex from which they were stripped, *6* Lower Pennine nappe complex, *7* Upper Pennine nappe complex and Prealpine strip sheets derived from it, *8* Sesia zone, Dent Blanche nappe and Prealpine strip sheets derived from it, *9* Autochthon of the Southern Alps.

discovered through a much wider region. Towards the end of the investigation, emphasis was placed on understanding the major structure at the expense of a rigorous and systematic study of the minor structures. It had by this time become clear that the strong lithological contrasts (basement–cover) and the large-scale irregularity of the units being folded made "statistical" orientation analysis in the classical sense (SANDER 1948–50 [1970], TURNER & WEISS 1963) pointless. From this study of major post-nappe folds, some of which are almost isoclinal and extend well outside the map boundaries (see Pl. I, II), I have tried to build up a picture of the pre-folding relationships, incomplete and uncertain as it may be, which may represent a small advance on previous ideas. Some of these will now be summarized, before the folds themselves are described in more detail.

3. Some aspects of general geology

Detailed systematic remapping of most of the region under consideration has been carried out in the last decade, and the results have appeared in a series of

Ph.D. theses, mainly concerned with petrographical and geochemical aspects of the metamorphic rocks (RAGNI 1960, HIGGINS 1964, MILNES 1964, HUNZIKER 1966, WIELAND 1966, JOOS 1969, HALL 1972, J.W. HANSEN 1972, KEUSEN 1972). Unfortunately, this great accumulation of data has never been compiled, and it lies outside the scope of this paper to attempt a synthesis. For structural purposes, two main petrographic complexes can be distinguished more or less clearly as follows:

1. Grey-weathering quartzo-felspathic gneisses, schistose gneisses and schists.
2. Brown-weathering calcareous schists and impure marbles (generally referred to as "Bündnerschiefer" or "calcescisti"), with thin but locally important associations of dolomitic, gypsum-bearing and quartzitic rocks (often referred to as "Trias").

Although the picture has been obscured by repeated deformation and high-grade Alpine metamorphism, these complexes are thought to represent the "basement" (pre-Triassic crystalline rocks, granites and high-grade metamorphites) and the "cover" (a Triassic–Jurassic sedimentary sequence deposited in the "Valais" trough, see TRÜMPY 1960), respectively. At an early stage in the Alpine orogeny, basement and cover rocks became interleaved, and the larger basement sheets and irregular masses have long been called "nappes" and named according to type localities (SCHMIDT & PREISWERK 1908). On Plate I, I have retained as far as possible the original nomenclature although it became clear that it was not everywhere equally satisfactory.

In general, the basement–cover contact delineating these nappes is clearly defined but in two situations this is not the case. Firstly, the Lebendun nappe shows a thick "transitional" sequence of psephites, psammites and brown-weathering non-calcareous schists ("scisti bruni") between basement and cover, thought to be in original stratigraphic association (? Permo-Carboniferous, see FRIZ 1963, JOOS 1969, p. 286–289). All contacts in this transitional sequence are gradational, in particular the margins of the "scisti bruni", which cannot be fixed with any certainty (see Pl. I).

Secondly, the relatively homogeneous granitic gneisses of the Monte Leone and Antigorio nappes are not everywhere separated by a continuous well-defined wedge of cover. This is particularly true to the southeast of the Antigorio valley where the two units are separated by an extremely heterogeneous zone containing streaks of cover-like marble and calcareous schist at various levels. The zone contains gneisses and schists of almost any composition and texture, as well as amphibolites and ultramafic pods and lenses, and seems to be the deformed and metamorphosed equivalent of a tectonic mélange. Detailed descriptions of this zone appear in WIELAND 1966 ("Isorno series" and "Forno zone") and in GRÜTTER 1929 ("Bosco series", see also HUNZIKER 1966, HALL 1972). The same "mélange" appears also northwest of the Antigorio valley, there however definitely part of the Monte Leone nappe (the zone containing the Geisspfad ultramafic body and the Ofenhorn complex, see MILNES 1968, KEUSEN 1972), so the mélange-like units to the southeast are also included in it. The significance of the "Monte Leone mélange" will be discussed further after the post-"mélange" and post-nappe, deformational history has been described.

4. Late Alpine folds

For the purposes of description, the post-nappe folds of the western Lepontine Alps have been sub-divided into two groups: *main Alpine* folds, which in general show a strong penetrative axial plane foliation and often a marked elongation lineation parallel to the fold hinges, and *late Alpine* folds, which affect an already developed penetrative foliation and, when present, lineation, and which show little or no axial planar structure. As we shall see, only a very rough time sequence is implied by this terminology (compare MILNES 1969), and the impression of two distinct phases which inevitably arises must be eradicated from the beginning. The major folds or fold systems, and their parasitic minor structures, are named after type localities, and no longer numbered according to "age". As has also been realized recently in the Scottish Caledonides (TOBISCH and others 1970), the numbering system is a useful shorthand for local sequences but is too inflexible and cumbersome for fold correlation over wider regions and gives a false impression of orogen-wide "fold phases".

The late Alpine folds affect an already well-developed penetrative foliation and are generally the last fold event in any one area. On the micro-scale the folds are seen to be reflected mimetically by the micas, indicating development after the phase of orientated mica growth but before the time when the temperature dropped below that necessary for mica recrystallization. For these reasons, they generally show much more regular geometries than the earlier structures. The irregularities of the early nappe structures had less effect on the fold development at this stage – recrystallization of the cover rocks was complete by this time, reducing the competence difference between basement and cover, and the new foliation, planar or nearly so over wide areas, became the active element in the folding process. Being unaffected by later major folding, the axial planes of any one group generally have a constant orientation (see Pl. I).

Four groups of late Alpine folds have been recognized, the Devero, Rebbio, Cervandone, and Basodino fold systems. They are arranged along the northwest edge of the mapped area and probably become more important outside it, along the southern margin of the autochthonous block of the Helvetic zone (see Fig. 1). These fold systems will now be described and their relative ages discussed.

a) Devero folds (D)[2]

Major and minor folds of the Devero system are widespread in the cover and transitional rocks below the Monte Leone nappe around Lago di Devero. They are mainly concentrated in a monoclinal zone extending from Pianboglio southwards along the steep southeast bank of the lake (Pl. I, II/3). The minor fold axes trend SW–NE and the axial planes dip gently ESE. A related crenulation lineation is sporadically developed parallel to the fold axes but only rarely is any sort of axial planar cleavage to be seen. The individual minor folds die out rapidly, both parallel and perpendicular to the hinge line (Fig. 2). They are parasitic to meso-scale folds, which are in turn parasitic to larger folds, all with rapidly changing fold shapes. The whole monoclinal zone shows the same relationship – it dies out before reaching Alpe Sangiatto, where only isolated *d*-folds affect a generally unfolded foliation.

[2]) In the interests of brevity, the initial letter of the type locality will often be used in referring to the folds of a particular system, whereby a capital letter indicates major structures (e.g. *D* – major Devero folds, see Pl. I, II) and a small letter related minor structures (e.g. *d* – minor Devero folds, see Pl. I).

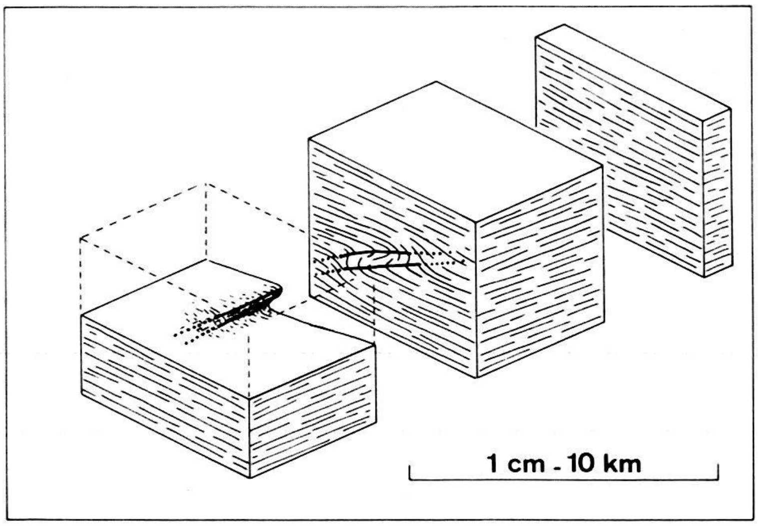

Fig. 2. Block diagram of an isolated antiform/synform fold pair "dying out" in all directions, a relationship typical of the Devero folds and probably of the late Alpine folds in general. The unfolded rock surrounding the folded volume probably deformed homogeneously during the formation of the folds (see text).

North of Pianboglio, where the major axial traces enter the Monte Leone basement, relations become less clear because the folds affect an already complexly refolded series without the single penetrative foliation found in the cover below. Their effect can be discerned for a short distance by the folding of an earlier major fold axial plane (*F* on Pl. II/3, see later).

b) Rebbio folds (R)

Folds of the Rebbio system are best exposed on the southeast ridge of Rebbio (Bortelhorn) above Alpe Veglia and possibly increase in importance to the west of the present area. Like the Devero group, the major structure is that of a monocline (Pl. II/5): in contrast, however, it affects an already strongly folded complex of mainly basement rocks. At least two phases of earlier folding can be distinguished (*W* and *V*, see later), neither of which resulted in the development of a penetrative foliation in this area. However, in one of these phases (probably *W*), a strong elongation lineation or rodding developed. The Rebbio fold axes generally coaxial to this, trending E–W, although in some places the early lineation is folded obliquely across the *r*-fold hinges. The axial planes dip 15–30° N at the surface although there is some indication that they must steepen downwards (see Milnes 1973, Fig. 2). The Rebbio folds never show an axial planar structure, but often a "mica lineation" – a crenulation and/or elongation of mica platelets – parallel to the fold hinges. Again, the minor folds die out rapidly in all directions, imitated by the dying out of the whole zone in the cirque east of Rebbio (see Pl. I).

c) Cervandone folds (C)

On Cervandone, a large synformal structure of late Alpine type is developed and folds the Geisspfad ultramafic body (Pl. II/4, and Keusen 1972, Fig. 18 and Pl. I). Again, the fold seems to die out to the northeast and possibly increases in importance to the west, outside the present area (see, for instance, Schmidt & Preiswerk 1908, Pl. III/10). Related minor folds are widespread only at the type locality, and typically show a steep N-dipping axial plane orientation. A similar major fold on the south flank of the Ofenhorn, not studied in detail, could be a related structure (see Pl. I).

d) Basodino folds (B)

The foliation in the Lebendun nappe of the Basodino area is affected by a whole series of major folds of late Alpine type (see Pl. II/1). The axial planes of major and minor structures vary systematically from subvertical in the south to moderately N-dipping in the north (Pl. I)[3]). Once more, the rapidity with which these folds die out both parallel and perpendicular to the hinge lines is impressive.

e) Time relations

The time relations are obscure amongst the above groups of folds. Because of the rapid lateral dying out, direct superposition of one major structure on another cannot be demonstrated conclusively. The only possible example is the superposition of *C* and *D* folds in the Pianboglio/Albrun Pass area (Pl. II/3), but here the *C* synform has become so weak that it is nearly impossible to decide which was the later of the two. Systematic variation in the attitude of the *d* fold axial planes, which would have been expected if they were pre-*C* structures, was not observed. Another line of evidence, however, suggests that it is unlikely that the late Alpine folds developed simultaneously. Microstructural relations (see, for instance, BISCHKE 1968, HIGGINS 1964) indicate that they developed *after* the growth of the main porphyroblasts (garnet, kyanite, staurolite) but *before* the rocks had cooled below the recrystallization temperature of micas. The results of radiometric age dating show that this represents a time span of 15–25 m.y. (lower Oligocene to upper Miocene, see HUNZIKER 1970, Fig. 7), sufficient for the successive development of numerous major fold systems (see CHEENEY 1972). A possible overall picture is that these folds developed at various times in the lithologically heterogeneous core of the asymetric regional synformal zone along the south margin of the Helvetic autochthonous block. The corresponding regional antiform would be the broad domal structure known as the Toce culmination, which makes up much of the present map area (see Pl. III).

5. Main Alpine folds

Folds included in this group generally show a well developed axial planar foliation and often a marked elongation lineation parallel to the fold axes. Some fold hinges can be followed until they die out, but in general they "disappear" – i.e. they become isoclinal, with compositional banding parallel to the axial planar foliation and no obvious fold closures. This disappearance of folds because of foliation transposition poses grave mapping problems which can only be solved under rather favourable conditions. Hence many folds of this category remain problematic and can only be imperfectly described. Also, in contrast to the late Alpine folds, these did not fold a

[3]) After a restudy of the critical outcrops, I have somewhat reinterpreted the data of HIGGINS (1964) for the Basodino region in that I correlate his "F_4" minor folds (according to him, not related to any major structure) with the *B* folds, of which only the northernmost was described by him (his major "F_3" synform). I also believe that his "F_3" antiform on Pizzo Pecora is in fact a rather open synformal structure on the flank of the main *B* antiform (see Pl. I).

rather regular planar structure, but mainly lithological discontinuities dominated by the irregular basement–cover contacts of the original nappes. Hence they do not even approximate cylindrical shapes and axial trends are often very variable (see Pl. III).

a) Wandfluhhorn folds (W)

The main Wandfluhhorn fold (see Pl. III) is probably the most important post-nappe structure in the area. The relations at the type locality (northwest of Bosco-Gurin) have been described recently in considerable detail (HUNZIKER 1966, HALL 1972). Here, the spectacular fold hinge, with granite gneisses of the Antigorio nappe on the outside and Monte Leone mélange and cover streaks in the core, plunges gently ESE and the fold is perfectly isoclinal (HALL 1972, Fig. 9, 23). The fold affects an already well developed foliation in this area and the abundant related minor folds are of crenulation or chevron type with axial planes dipping SE at gentle angles. Major post-nappe folds related to the development of this pre-*W* foliation (the "F_2" phase of HALL 1972) have also been distinguished (see Pl. I/1). The main *W* axial trace can be followed southwestwards into upper Valle dell'Isorno, although the only other well exposed closure is that at Alpe Bosa (WIELAND 1966, p. 286–289, see Pl. I). Here it leaves the mélange zone and enters the Monte Leone gneiss and, by extrapolating parallel to the now well developed axial plane foliation, it can be followed further as far as Crevola (see MILNES 1973, Fig. 2). East of the Wandfluhhorn, the course of the axial trace becomes problematic and leaves the present map area. HALL (1972, p. 60–62) suggests that it runs into upper Val Peccia and through the Maggia crystalline complex to the head of Lago Sambuco and beyond. Its exact location and significance is perhaps the main structural problem remaining in the Lepontine Alps.

The same axial trace has been identified in the more northerly outcrops of the Monte Leone unit (see Pl. II/4, and MILNES 1973, the "M" fold). Here, however, no really convincing fold hinges have been found – the axial plane runs through the whole of the area mapped inside the Monte Leone gneiss parallel to the penetrative foliation. On the southeast ridge of the Albrunhorn, a hinge may be discerned, under conditions of exposure unlikely to convince sceptics, and has been correlated with that at Alpe Bosa (Pl. III, closure 2, see also MILNES 1968, Fig. 2, "the edge of the Monte Leone granite gneiss"). On Monte Leone itself, the main *W* fold is accompanied by several related major structures (MILNES 1973, folds "m_1, m_2, m_3"). On both sides of the Toce culmination, the Monte Leone gneisses show a well developed elongation lineation (the "L_1" lineation of MILNES 1968) which is parallel to the Wandfluhhorn fold hinges where these can be identified with certainty. Probably a major part of the penetrative deformation suffered by these basement rocks took place during this folding and not, as earlier postulated (MILNES 1968), during the nappe-forming movements.

An attempt has been made to reconstruct the main *W* axial surface from all these observations (Pl. III). The fold is seen to be a recumbent northeast- or east-closing structure with extremely curved hinge lines. It affected an already emplaced nappe complex and it is clear that the nappe pile on one side of the axial surface is the inverted equivalent of that on the other. The Antigorio nappe is structurally equivalent to the Boccareccio gneiss (traditionally regarded as the upper part of the Monte

Leone nappe, see Pl. I) and the Verampio–Baceno complex to the Berisal nappe. These correlations are based on the assumption that the original basement nappes were continuous sheets of regional extent. A more realistic assumption is perhaps that we are dealing with a jumble of irregular and partly detached basement masses which attained their apparently sheet-like form only during the subsequent phase of isoclinal folding (the *W* folding). The fact that the sequence on one side of the *W* axial surface is structurally inverted, however, remains, and there is disagreement as to which is the normal limb. There are two possibilities:

1. The Wandfluhhorn fold is a synform, facing southwest, with the lower limb normal and the original nappe sequence on the upper limb being: Monte Leone over Boccareccio over Berisal (see MILNES 1973, p. 273).
2. The Wandfluhhorn fold is an antiform, facing northeast, with a normal upper limb and the original nappe sequence on the lower limb being: Verampio–Baceno over Antigorio over Monte Leone (HALL 1972, p. 209–211).

A decision can only be reached when the Wandfluhhorn fold and related structures have been much more completely mapped than at present.

b) *Lebendun folds* (*L*)

The Lebendun nappe has been omitted from the above nappe sequences because it shows a much more complicated structure and history than the other units. The whole nappe is dominated by intense and complex folding, the Lebendun folding. Only one detailed description of this folding exists (HIGGINS 1964, his "phase 2") although its complexity can be discerned in some other published cross-sections (FRIZ 1964, Pl. I; JOOS 1969, Pl. II/1). The following generalities give only a rough impression of the mental somersaults necessary to understand some of these structures.

The *L* folding is typified by the development of a strong axial planar foliation, commonly marked also by strong flattening of the conglomerate pebbles in the psephites. Major hinges are discernible only where the axial planes traverse clear lithological boundaries – the nappe margins, in places, and marble horizons within the nappe. These boundaries were strongly irregular before folding took place, so the folds are very far from cylindrical.

The Lebendun folding can best be studied in the Basodino area, unfortunately also an area where the relations are further complicated by post-*L* deformation (the *B* folds, see above). On the west of the mountain, around Lago Castel, a large recumbent fold structure affecting the whole of the nappe has long been recognized, but not explicitly described (see, for instance, SCHMIDT & PREISWERK 1908, Pl. II/2). The complicated hinge zone of this fold is well exposed southeast of the lake, in the lithologically heterogeneous rocks separating the cover, in the core, from the large mass of psammitic and psephitic gneisses which make up the main part of the nappe in this area. If we are dealing here with a stratigraphic succession, as other workers have postulated (FRIZ 1963, JOOS 1969), we can call this the main *L* syncline, with the Lebendun of the Basodino range representing its inverted, upper limb (see Pl. III). In the complicated hinge zone, the upper limb seems to have been partly sheared off, since *l*-folds there have only lower limb vergence. Inside the gneisses, the axial trace runs parallel to the main foliation until the other margin of the nappe – the basal thrust plane – is reached, where another hinge can be discerned (west of the Tamia Pass). Here the complications increase – the basal Lebendun thrust seems to have been strongly imbricated in places; the whole is affected by a prominent *B* synform (Pl. II/1); the lower limb of the syncline contains a mass of medium-grained granite with swarms of xenoliths (seen in the cliffs around Canza and in the famous Toce "waterfall") which, although irregular sheared, acted more as a rigid block during the *L* folding. And then, east of the Tamia Pass, all that remains of the lower limb of the syncline are a few shreds of gneiss interleaved with cover (Pl. III). The axial trace seems to run further through undifferentiated cover rocks into the zone separating the Antigorio and Maggia nappes (see Pl. I).

The intense folding of the marble horizons in the inverted limb of the *L* syncline has been described in detail by Higgins (1964, p. 124–132). On his cross-section (op. cit., Fig. 68), a regional antiform can be distinguished which may be the counterpart of the syncline described above. This affects Maggia and Lebendun nappes alike, which, together with certain lithological similarities (for instance, the presence of conglomeratic rocks), seems to indicate that they have undergone similar orogenic histories.

Southwest of the Basodino area, the Lebendun of the inverted limb of the syncline has been completely removed by erosion for a distance of some 30 kilometers (see Pl. III). It is exposed once more, in a much reduced form in the Simplon area (compare Milnes 1973, Fig. 2, and Pl. II/5). Under favourable lighting, the whole syncline can be seen on the east face of Pizzo Valgrande, with brown-weathering "scisti bruni" occupying the core. Here, however, its fold nature can hardly be recognized, partly because it is much more strongly compressed, partly because of the lack of strong lithological contrasts. From this exposure, the axial trace runs southwards into the zone separating the Antigorio and Monte Leone basement units, but the closure expected in the base of the Lebendun (corresponding to that west of the Tamia Pass mentioned above) has not yet been identified. The Lebendun gneisses seem to get streaked out in this zone and become juxtaposed with similar gneisses from the other basement units (the problematic ??? zone, Pl. I). It must certainly exist, however, in the inaccessible and little known outcrops along the south wall of the Gondo gorge, since when the same zone descends once more to the valley at Crevola, the Lebendun unit is completely missing (Milnes 1973).

The axial trace of the main *L* syncline could not be established with certainty between these two areas. Its postulated course has been plotted through the complex imbricate zone in the Lebendun/cover boundary on Monte Cazzola (Bischke 1968, Fig. 16) and the tectonic line of unknown significance mapped by Joos (1969) in the cover around Lago Vannino (Pl. I). In the south, it is assumed to run along the Antigorio/Monte Leone separation (Pl. III).

c) *Problematic folds of unknown regional significance*

Throughout the area there are a number of major structures which do not seem to be related to any fold systems hitherto described. In all cases, the folds are at least partly accompanied by a strong axial planar foliation and are sometimes seen to be refolded by late Alpine structures, so they are included under this heading. Some aspects of these problematic structures are briefly noted below.

Antabbia folds (*A*)

The Antabbia antiform (Pl. II/1) is beautifully exposed on the east of the Tamia Pass, towards Val Antabbia, and it is hard to understand how this huge structure is missing from earlier profiles (see, for instance, Burckhardt 1942, Pl. V). It is delineated by an unusual quartzitic facies of the cover rocks and folds the cover/basement contact of the Antigorio nappe. The gneiss in its core is foliated parallel to the axial plane. The *A* axial plane steepens upwards from a moderate S-dip in lower Val Antabbia to vertical south of the Tamia Pass, and is affected by later mesoscopic folds with gentle ENE-dipping axial planes, possibly related to the *W* folding. An infold of marble into the Antigorio gneiss in Val Antabbia probably represents the corresponding synform, and numerous such interleaved cover and gneiss sheets around the Antigorio nappe (see Pl. I) may be related structures.

Forno antiform (*F*)

The Forno antiform, or antiformal zone, is best exposed in the cirque north of Alpe Forno, where marbles are infolded into the base of the Monte Leone nappe (Pl. II/3). Here, the coarse-grained augen gneisses show the complete spectrum of conditions from an intensely folded earlier foliation, through partial development of a new foliation, to complete transposition and obliteration of the earlier structure. A fold structure possibly related to the pre-*F* foliation has been described by Heim (1972, see also Pl. II/3), completing the catalogue of four superimposed phases of major folding which make the Albrun Pass area so fascinating. The main *F* axial plane becomes concordant to the main foliation in the gneisses east of the type locality and disappears.

Nefelgiù antiform (*N*)

Perhaps the most spectacular of these problematic structures is the Nefelgiù fold, best exposed on the south flanks of Corni di Nefelgiù and in the valley below Lago Vannino (formerly known as the Lebendun valley, type area for the Lebendun nappe). In the recent detailed description of this area (Joos 1969), this fold is not mentioned, and its axial trace (Pl. I) has been plotted after only a cursory field study. At the type locality, erosion has cut through the huge arch of Lebendun gneisses to expose cover rocks in the core, strongly foliated parallel to the axial plane. South of here, the fold rapidly dies out (compare Pl. II, sections 2 and 3), whereas northwards it seems to become progressively tighter and is last seen as an isoclinal fold core with strong axial planar foliation (folded by *b*-folds), in the cliffs below Lago Castel (Pl. I). In the type area, the *N* fold affects earlier isoclinal structures (see Joos 1969, Pl. II/1) and probably the main *L* syncline (Pl. II/2): it may also refold the main *W* fold, in which case the large structure cursorily mentioned by Hansen (1972, p. 115) northwest of Alpe Nefelgiù is to be interpreted as a Wandfluhhorn fold hinge (see Pl. II/2).

Sangiatto folds (*S*)

Near Alpe Sangiatto, above Lago di Agaro, on Monte Giove, and northeast of Alpe Ciamporino, the Lebendun of the *L* syncline's lower limb is thrown into a series of major folds of lesser importance, in antiform/synform pairs, collectively called the Sangiatto folds (see particularly Pl. II/4). These fold pairs all show the same vergence, a sense of overturning opposite to that expected if they were parasitic to the *L* syncline. The only ones mapped in detail were those of the type locality. As with the Nefelgiù fold, these structures die out in one direction along the axial trace and disappear parallel to a well developed axial planar foliation in the other. North-east of Alpe Sangiatto, interference between earlier Sangiatto and later Devero minor folds is well seen.

Veglia folds (*V*)

North of Alpe Veglia, a single antiform/synform fold pair has been mapped in the base of the Berisal unit. The folds are very tight, with sporadically developed axial planar foliation, and their vergence excludes the possibility that they are related to the huge south-closing *W* fold in this area. They probably represent a pre-*W* phase of deformation. The axial traces seem to run into the zone separating the Boccareccio gneiss from the rest of the Monte Leone unit (compare Pl. II/5 with Milnes 1968, Fig. 3/XY).

d) Time relations

The tracing of the *L* axial planes into the zone separating the Antigorio and Monte Leone nappes and the draping of the Lebendun around the "front" of the Antigorio nappe (Milnes 1973) suggests that the *L* folding can be correlated with the main nappe-forming movements and is therefore a pre-*W* event. Hence the *L* folds are only "post-nappe" with respect to the Lebendun and Maggia complexes, and two phases of nappe formation must be distinguished. Where the other fold systems fit into this *L–W* sequence and their relation to eachother is unclear. The Nefelgiù fold is the only one which probably post-dates both *L* and *W*, and the "F_2" phase of Hall (1972) certainly occurred between the two, but the relative timing of *A*, *V*, *F* and *S* can only be guessed at. Higgins found some evidence for a pre-*L* phase of ductile deformation, for instance, already flattened conglomerate pebbles folded by *l*-folds (op. cit., Fig. 69), in the Basodino area.

The results of this major fold "stratigraphy" can be summarized as follows:

- late Alpine folds
- Nefelgiù fold
- Wandfluhhorn fold
- ? Antabbia, Forno, Sangiatto, Veglia folds and Hall's "F_2" phase (not necessarily coeval)
- Lebendun folds (= Higgins' "phase 2") and Antigorio–Monte Leone–Berisal–Boccareccio–Verampio nappes (probably coeval)
- Lebendun–Maggia nappes

Although a fairly clear sequence of events can be recognized, there is no evidence or necessity for introducing "interkinematic" or "static" phases of regional significance into this deformation history.

6. Lower Pennine orogenic history: a discussion

The structural and general orogenic history of the western Lepontine Alps, probably representative for the Lower Pennine nappe complex as a whole (see Fig. 1), can be summarized as follows:

a) Early overthrusting

The first recognizable event was the overthrusting of the Lebendun–Maggia basement complex, together with its "transitional" sequence (? Permo-Carboniferous) and Mesozoic cover. In this phase, the thrust mass became sliced up in places and discontinuous marble horizons now mark the internal thrust planes. At a later stage in the movements, the rocks became locally more ductile, resulting in the sporadic development of the earliest penetrative foliation. The overthrust masses had very irregular shapes, and parts became completely detached, including the whole of the Lebendun unit.

It is tempting to place the formation of the "Monte Leone mélange" also in this bracket. It appears to be an integral part of the Monte Leone nappe, i.e. a pre-nappe feature, yet it contains abundant streaks of cover rocks implying that it represents a zone of strong late Mesozoic movement. Similar relationships have been recently described in the Upper Pennine Monte Rosa nappe (WETZEL 1972), where, however, the typical mélange structure has been much better preserved due to a lower degree of post-mélange deformation and metamorphism.

b) Main nappe emplacement

This already complicated edifice was then thrown into a series of nappes, of which the Monte Leone, the Antigorio–Boccareccio and the Berisal-Verampio–Baceno complexes form the basement cores in the area described. The mechanical state of the basement at this time is difficult to envisage, but the obvious ductile reaction of the Lebendun–Maggia rocks at this time (the *L* folding) and the presumed pressure increase suggest widespread ductile faulting, "shearing" and mylonitization, probably concentrated in the zones of interleaved cover rocks which would later be used to separate the nappe structures. Again, with progressive shortening and thickening of the nappe pile, the rocks became progressively more generally ductile, and by the end of this phase the basement rocks generally showed a new Alpine foliation and the first major refolding of the nappe boundaries took place (HALL's "F_2" phase and fold systems *A*, *F*, *S*, *V* in the present area). Even so, small pockets of undeformed basement remained (MILNES 1964, p. 53–56; WIELAND 1966, p. 209–211; HALL 1972, p. 139–152) which acted as rigid pods throughout all succeeding deformations and provide peep-holes into pre-Alpine basement relationships.

c) Regional isoclinal folding

At the time of maximum ductility of all rocks, major isoclinal refolding of the whole nappe complex took place, in this area called the Wandfluhhorn folding. Over large areas, this resulted in the transposition of the newly formed foliation into the axial planes of the folds and in strong elongation parallel to the fold axes. The high basement ductility indicates a unique combination of high temperature and high pressure conditions. Amphibolite facies temperatures were probably first reached in lower Oligocene times (see, for instance, HUNZIKER 1970) and lasted into the early Miocene. During this period, highest pressures pertained at the beginning, since in the lower Oligocene general uplift of the whole belt set in (TRÜMPY 1960, MILNES 1969). Hence, the lower Oligocene seems the most likely time for the isoclinal folding of the nappes[4]).

During this phase, the mechanical differences between basement and cover have become much less important owing to the complete recrystallization of all rocks, and there is a transition from a multilayer competent/incompetent complex to a more mechanically homogeneous but anisotropic mass (COBBOLD and others 1971) in which the penetrative foliation becomes the dominant control in the structural development.

d) Late stage deformations

Temperatures remained high now for a very long period – only towards the end of the Miocene, 10–15 m.y. ago, did biotite become once more a closed system (JÄGER and others 1967) – and this mass of recrystallizing rock continued to deform, producing the late Alpine fold systems.

Again, the mechanical condition of the zone as a whole is open to question in this period. The late Alpine folds on all scales die out rapidly in all directions (Fig. 2). Did the rocks which remained unfolded throughout this phase suffer any internal deformation (i.e. deform homogeneously) or not? The relations in the region where the Rebbio folds die out seem to suggest that they did. As noted previously (MILNES 1968, p. 70), in this area, the Monte Leone gneisses commonly show the pre-*R* elongation lineation strongly curved on planar or slightly undulating foliation surfaces. This indicates that in other areas, where the lineation is perhaps lacking or differently orientated, lack of late Alpine folding in no way implies lack of late Alpine deformation. This is particularly important for the interpretation of microstructural relations (see the recent controversy concerning "force of crystallization", MISCH 1971, SPRY 1972, and others). Indeed, this, together with the possibility of porphyroblasts growing both before and after the *W* folding makes the dating of fold phases on the basis of their relation to porphyroblast growth (CHATTERJEE 1961) a rather hazardous procedure. At least it seems that the Pennine zone was by no means "consolidated" during this period, as recently suggested by TRÜMPY (1973).

After temperatures dropped below those necessary for recrystallization, weak deformation continued into the Pleistocene, producing complex fault and joint patterns (STRECKEISEN 1965, STECK 1968, GÜNTHERT 1971).

The sequence of phases distinguished above is merely a descriptive tool for an essentially continuous process, except possibly for the early overthrusting, which can be imagined as clearly separated from the rest. The local episodic character of

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[4]) HALL (1972) shows that in the Bosco area the *W* folding took place *after* the growth of garnet, staurolite, kyanite and plagioclase porphyroblasts during the Alpine metamorphism. Regionally, however, the metamorphic isograds show little sign of being isoclinally folded (see WENK 1962, NIGGLI 1970, and many others). The isotherms were presumably strongly disturbed immediately after the folding but the succeeding long period of high heat flow was sufficient for them to readjust to their simple domal shape (presumably with the growth of post-*W* porphyroblasts in rocks where this readjustment involved temperature increase). The slight but significant inversion of the metamorphic zoning in the Varzo area (WENK 1962; MILNES 1964, p. 50–51) may indicate that the readjustment did not everywhere go to completion.

deformation can in no way be taken as evidence for regional pulses separated by "static" intervals (see also KRAUSKOPF 1968, GILLULY 1973, for similar conclusions in other fields). This must be discarded as a basic premise for structural correlations.

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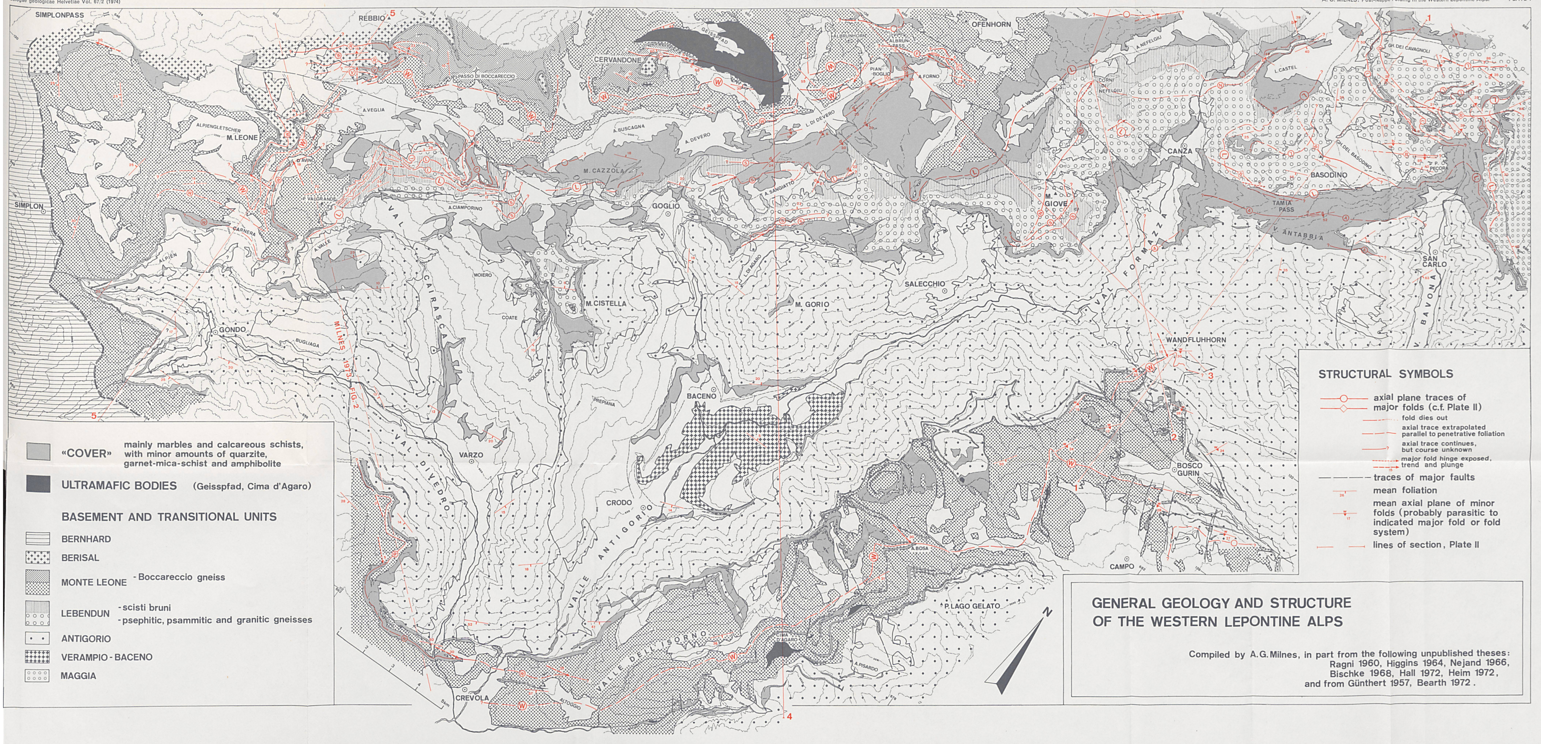
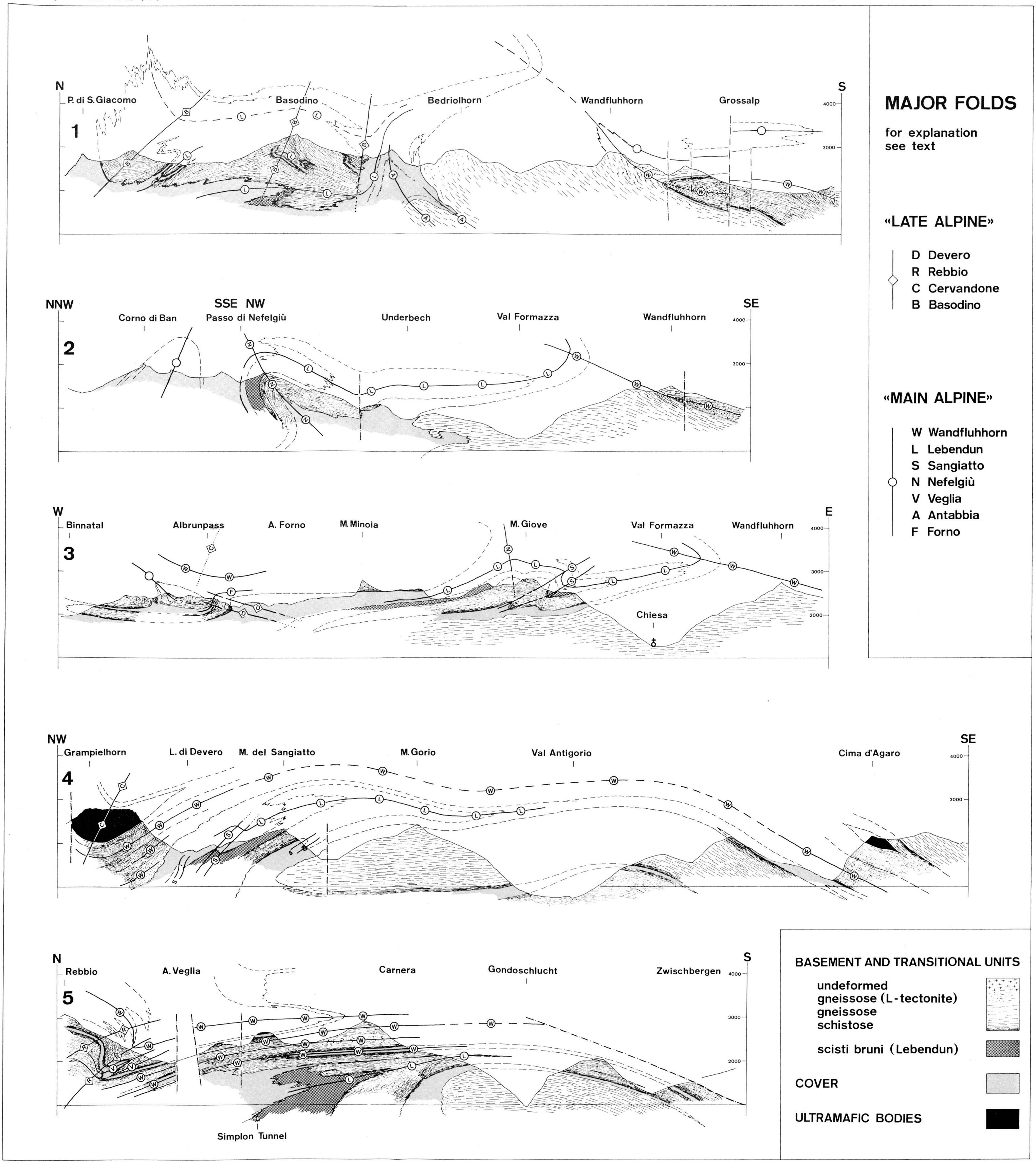
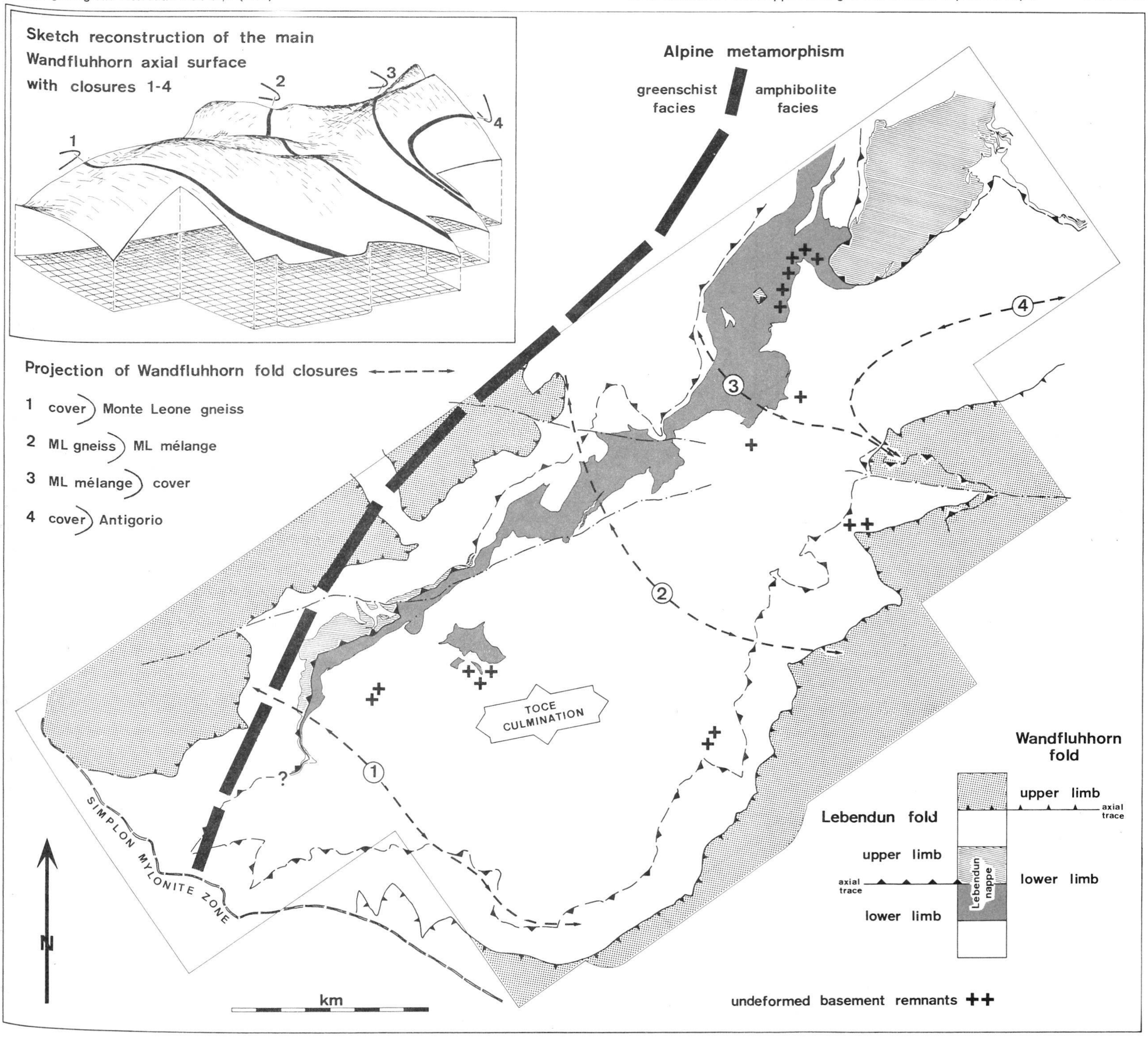

SIMPLONPASS
REBBIO
OFENHORN
CERVANDONE
M. LEONE
SIMPLON
GONDO
GOGLIO
M. CISTELLA
M. GORIO
SALECCHIO
CANZA
BASODINO
M. GIOVE
SAN CARLO
WANDFLUHHORN
BACENO
VARZO
CRODO
BOSCO GURIN
CAMPO
P. LAGO GELATO
CREVOLA
VAL CAIRASCA
VAL DIVEDRO
VALLE ANTIGORIO
VALLE DELL'ISORNO
VAL FORMAZZA
V. ANTABBIA
V. BAVONA
TAMIA PASS
N
«COVER» mainly marbles and calcareous schists, with minor amounts of quarzite, garnet-mica-schist and amphibolite
ULTRAMAFIC BODIES (Geisspfad, Cima d'Agaro)
BASEMENT AND TRANSITIONAL UNITS
BERNHARD
BERISAL
MONTE LEONE - Boccareccio gneiss
LEBENDUN - scisti bruni - psephitic, psammitic and granitic gneisses
ANTIGORIO
VERAMPIO - BACENO
MAGGIA
STRUCTURAL SYMBOLS
axial plane traces of major folds (c.f. Plate II)
fold dies out
axial trace extrapolated parallel to penetrative foliation
axial trace continues, but course unknown
major fold hinge exposed, trend and plunge
traces of major faults
mean foliation
mean axial plane of minor folds (probably parasitic to indicated major fold or fold system)
lines of section, Plate II
GENERAL GEOLOGY AND STRUCTURE OF THE WESTERN LEPONTINE ALPS
Compiled by A. G. Milnes, in part from the following unpublished theses: Ragni 1960, Higgins 1964, Nejand 1966, Bischke 1968, Hall 1972, Heim 1972, and from Günthert 1957, Bearth 1972.



Simplified structural cross-sections of the western Lepontine Alps

(for lines of section, see Plate I)



Synopsis of Wandfluhhorn and Lebendun fold relationships

(for explanation, see text)