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Sequence and style of major post-nappe structures, Simplon–Pennine Alps

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Abstract—In the Upper Pennine nappe complex of the Simplon–Pennine Alps (Switzerland and Italy), at least three phases of major post-nappe folding (in places associated with thrusting) can be distinguished. These are superimposed on an earlier-formed, partly chaotic, complex of tectonic units, including the Bernhard and Monte Rosa continental flakes and the Zermatt–Saas and Antrona ophiolite complexes. The earliest post-nappe folds were essentially isoclinal throughout the whole region and were accompanied by a strong schistosity which is the main foliation in most areas. Later, two successive phases of back-folding led to the present overall structure. Both phases typically show rapid variations in style from open folds lacking axial planar schistosity to very tight structures with complete foliation transposition. This has been demonstrated by systematically mapping the major axial traces over the whole region. Successively removing the major structures in reverse order shows that the ophiolite complexes were originally part of a continuous unit marking an important suture between the Bernhard and Monte Rosa nappes.

INTRODUCTION

THIS paper presents a provisional and rather tentative description of the large-scale structure of the Upper Pennine nappe complex in the western Central Alps, the area of Argand's famous synthesis (Argand 1911). Argand's composite profiles and later attempts to represent the structures of the region in cross-section have been reproduced in so many subsequent books, journals and field guides that the Simplon–Pennine Alps can surely claim the largest audience of any orogenic segment in the World. In spite of this, published material is not very enlightening about the precise structural relations, nor is the sequence of deformational events which led to the present edifice very clear (e.g. Bearth 1952 (Fig. 1)). If it were possible to understand these, particularly in the critical region where the base of the complex is accessible, it should also be possible to pass judgement on the widely-accepted palaeogeographic reconstruction of the Pennine realm (e.g. Trümpy 1960, 1980). At the moment, this reconstruction must be considered as only one of several possibilities, rather than as the most probable solution, because of the extremely shaky tectonic premises on which it is founded (Milnes 1974a, Homewood *et al.* 1980). These considerations formed the starting point of the present project and led to the preliminary results presented here.

Our structural studies had the advantage of being able to build on an exceptionally extensive data base. The whole of the Swiss part of the region is covered by a series of 1 : 25,000-scale geologic maps of high quality (Geologischer Atlas der Schweiz, sheets 29, 30, 31, 43, 61 and 71) with accompanying descriptive memoirs (Bearth 1953, 1957a, 1964, 1973). In addition, a number of detailed structural analyses of small parts of the region became available during the course of the work (Laduron 1976, Klein 1978, Wilson 1978, Gosso *et al.* 1979, Steck *et al.* 1979). Using this material, our aim was to study the regional deformation patterns, utilizing the major post-nappe fold structures as guides (see Milnes 1974b, Milnes & Schmutz 1978). This method contrasts with the more usual but time consuming method of regional synthesis, that of the piecing together of fully-covered structural mapping areas. The end result of our work is to be compared with an open network rather than the more usual solid mosaic. We concentrated mainly on the threads of the network — the traces of the major folds and thrusts. Once these were identified, and could be defined and followed, the spaces between were paid only passing attention. Many details thus remain to be studied and interpreted, and some major traces are far from being satisfactorily located, but the main outlines of the picture are beginning to emerge. The aim of this paper is to present a first sketch.

MAIN TECTONIC UNITS

We take 'tectonic unit' in this context to mean a rock mass within the present orogenic edifice which before Alpine orogenesis represented a coherent crustal segment. An individual tectonic unit or 'nappe' may include both basement and cover, or either alone. Although this concept is fairly clear in theory, it is difficult to put into practice for two main reasons. First, in complexly deformed areas, practically every lithological boundary is affected by deformational events which occurred later than the formation of the unit itself. In the Pennine zone, nappe formation (formation of tectonic units) was typically followed by several phases of intense post-nappe deformation. This makes it difficult or impossible to distinguish between originally stratigraphic or intrusive and originally tectonic contacts within the earlier-formed nappe complex. Secondly, in the Pennine zone, dismem-

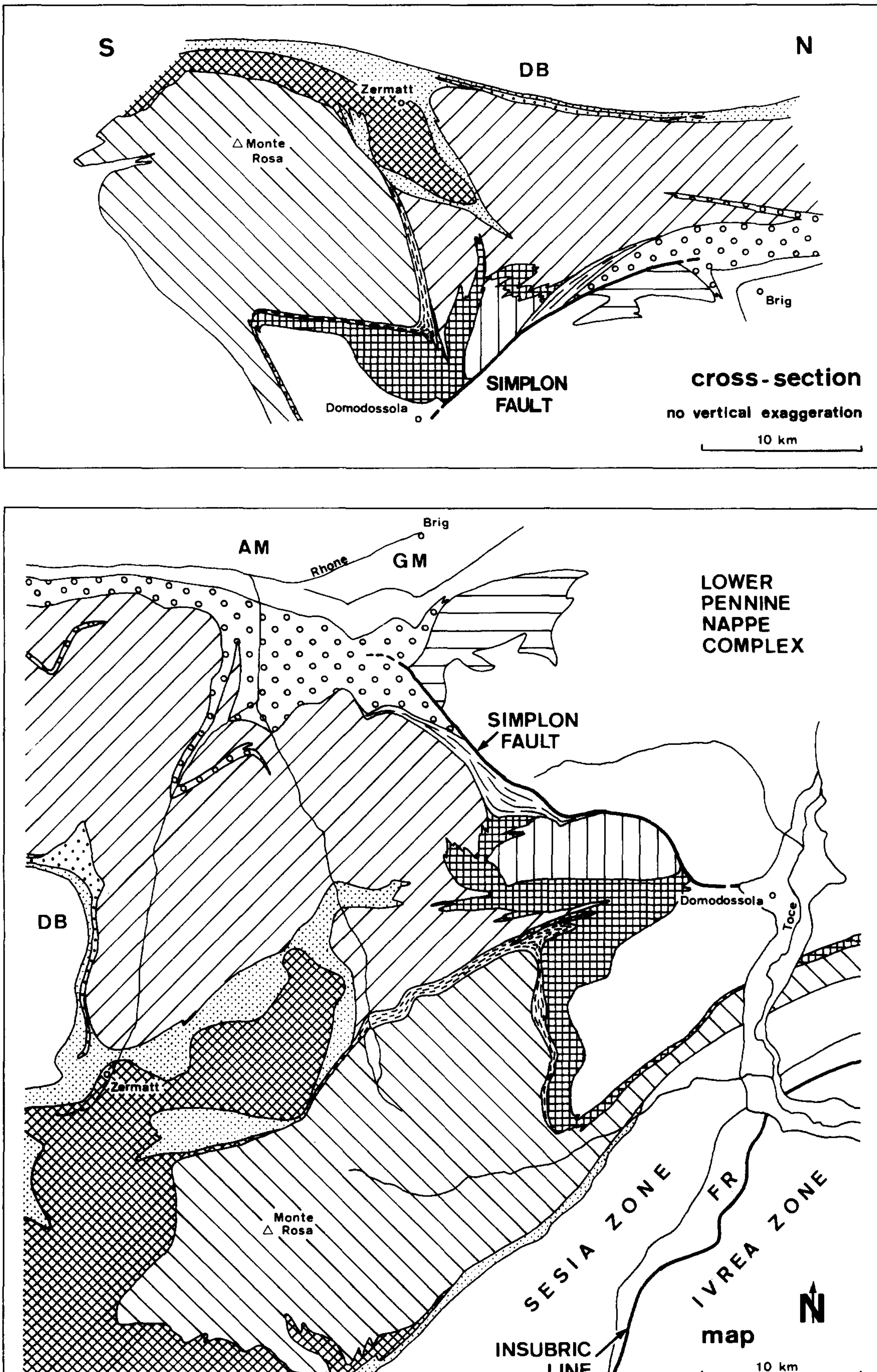


Fig. 1. Composite cross-section and map of the Simplon–Pennine Alps showing the main tectonic units (see Table 1). Abbreviations: DB, Dent Blanche nappe; FR, Fobello–Rimella zone; GM, Gotthard massif; AM, Aar massif. The cross-section has been constructed approximately perpendicular to major fold axes on the basis of all available structural data. Locations are inserted only at the correct structural position and give no indication of relative elevation.

Table 1. Notes on the contents of the tectonic units in the Upper Pennine nappe complex, Simplon–Pennine Alps (see Fig. 1)

Tectonic unit (degree of dismembering)	Signature on Fig.1	Basement (incl. pre-Triassic sediments)	Sedimentary cover (Mesozoic-Tertiary)	Main references
Combin (strong), incl. upper Zermatt Schuppenzone and Theodul-Rothorn zone		small basement flakes normally included in Bernhard or Monte Rosa units: Saas Fee augengneiss, Stockhorn crystallines	(Permo-?)Trias very continuous, Lias(?) breccias, Schistes Lustrés with intercalated greenstones (volcanics)	Güller 1947 Bearth 1976 Wilson 1978 Caby *et al.* 1978
Barrhorn (slight)		----------	Briançonnais facies: Trias?, Dogger? (or thrust zone), Malm, u.Cret., Flysch	Ellenberger 1952 Bearth 1964
Zermatt - Saas (moderate)		ophiolite complex, prob. Jurassic (high P metm. ca. 90 my ago)	thin but continuous: metacherts and Schistes Lustrés (u.Jur. - l.Cret.?), ophiolitic mélange in places (Riffelberg zone)	Bearth 1967 Dal Piaz & Ernst 1978
Bernhard, also known as Grand St. Bernhard (slight), incl. Portjengrat		mainly polymetm. paragneiss, intruded by late Hercynian granite (Randa gneiss); Permo-Carboniferous sedimentary cover	locally (Permo-?)Trias	Bearth 1963 Bearth 1964 Bearth 1973
Verosso (strong)		paragneiss, some granitic remnants	locally Trias and Schistes Lustrés	Amstutz 1954 Blumenthal 1952
Berisal (slight)		paragneiss, some granitic remnants	locally Trias and Schistes Lustrés	Bearth 1973 Milnes 1974 b
Monte Rosa (slight)		mainly late Hercynian granites and assoc. minor intrusives, remnants of high-grade pre-granitic basement	------------ (Stockhorn crystallines and cover normally assigned to Monte Rosa, here incl. in Combin zone)	Bearth 1952 Reinhardt 1966 Frei & Hunziker 1976
Furgg (mélange)		matrix of mélange mainly Permo-Carboniferous cover of Monte Rosa basement, remnants of ophiolite complex (ultramafic and mafic lenses)	streaks and lenses of Trias and Schistes Lustrés	Wetzel 1972 Frei & Hunziker 1976
Antrona (strong)		ophiolite complex, prob. Jurassic	streaks and masses of Schistes Lustrés, ophiolitic mélange (cf. Riffelberg zone) in places	Blumenthal 1952 Müller 1976 Laduron 1976
Laggin (mélange)		sheared remnants	sheared remnants of ophiolites and ?Trias	Bearth 1973 (not treated there as separate unit)
Stalden - Visperterminen, incl. St.Niklaus syncline and part of Gebidem digitation (moderate)		Permo-Carboniferous sediments	Trias, Cretaceous Flysch formations	Bearth 1973 Burri 1979 Matthes 1980

bering commonly occurs on many different scales, so the units distinguished depend also on the scale of mapping. Larger units are typically made up of a complex of smaller units and so on, down to the scale of individual outcrops or even parts of outcrops. Also, the degree of dismembering varies from unit to unit, in some cases being almost absent (large basement nappes), in others amounting to a complete mixing of all the original rock types (i.e. tectonic mélange).

In spite of these difficulties, we have attempted to draw a tectonic unit map (Fig. 1) as a basis for the discussion of the post-nappe structures. In order to emphasize the original coherence of the units, lithological boundaries within the units have been omitted, this is in contrast to most tectonic maps of the Alps, in which basement and cover are distinguished whether in tectonic contact or not (see SGK 1980). Otherwise, Fig. 1 shows only minor deviations from previous interpretations. The Upper Pennine zone of the Central Alps (Milnes 1974a) still called 'Middle Pennine' by some authors (e.g. Trümpy 1980), includes units with basement of either old continental (Hercynian and older) or oceanic (Mesozoic) type and with Mesozoic cover sequences belonging to one of two main facies realms, Schistes Lustrés or Briançonnais. Table 1 summarizes the contents and supposed ages of the various units.

It is now generally recognized that the unit boundaries have suffered large-scale folding subsequent to formation. Some of these post-nappe folds have long been known and described at specific localities, such as the Mischabel back-fold ('pli en retour Mischabel', Argand 1911, see Güller 1947) and the Vanzone antiform ('voûte de Vanzone', Argand 1911, see Bearth 1957b). The rest of this paper is concerned with the regional significance of these and the many lesser-known major post-nappe structures in the area.

REGIONAL STRUCTURAL HISTORY

When the local structural histories recognized in outcrops and small areas are correlated across the whole region using the axial traces of the major folds as guides, a regional structural history with at least 4 phases of deformation emerges. As in other parts of the Pennine zone (e.g. Milnes 1974b, Milnes & Schmutz 1978), a typical feature of all phases is the rapid change in style and intensity from place to place. This makes local structural sequences a poor representation of the overall situation. Large, open fold structures without axial planar schistosity develop laterally into isoclinal folds with completely transposed foliation. The deformation associated with, say, regional phase 4 may be absent in some areas and so intense in others that earlier structures are hardly discernible. Earlier phases often leave completely undeformed relics, so that the superposition of a later deformation locally results in first-phase structures. A further complication is the presence of pre-Alpine polyphase deformation in the old continental basement, remnants of which are so well preserved in places that they tend to be integrated into the local structural sequence. The regional history below is thus an attempt to see past all these local complications.

(1) Zermatt phase (nappe formation, main development of tectonic units).

(2) Ragno–Randa phase (early isoclinal folding).

(3) Mischabel phase (early back-folding).

(4) Vanzone phase (late back-folding).

Some aspects of the major structures belonging to these phases will now be described in reverse order. The two back-folding phases are now fairly well understood and will be treated in some detail. Our treatment of the earlier phases is more speculative, depending on the correct reconstruction of pre-back-folding relationships. The axial traces of all the post-nappe folds are shown in Fig. 2.

LATE BACK-FOLDING (VANZONE PHASE)

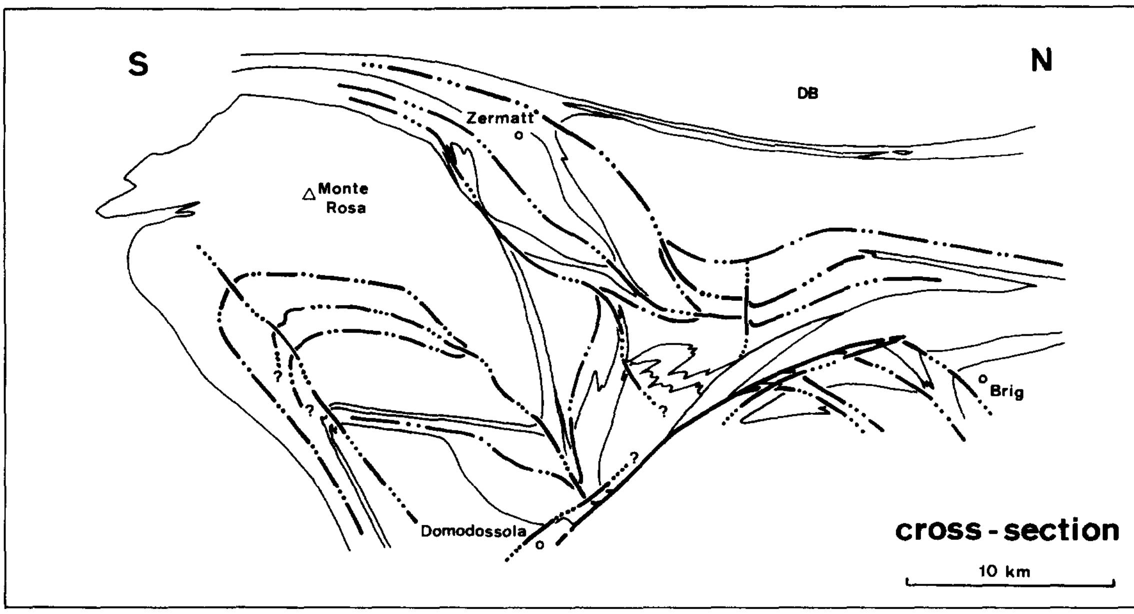
The major folds associated with this phase are: the Vanzone antiform, the Böshorn synform, the Masera synform and the Tochuhorn antiform (Fig. 3). The latter two seem to be closely associated with an important low-angle fault, the Simplon fault, which also shows a component of 'backward' movement (upper block displaced southwards). The contemporaneity of the Vanzone and Böshorn folds with the Masera/Simplon/Tochuhorn association can be questioned, but all these structures are clearly later than those of the Mischabel phase. Although microstructural analyses have been carried out only in a few areas (Laduron 1976, Matthes 1980, Greller in prep.), all the observations point to a low temperature post-metamorphic environment for the Vanzone phase, in particular, the folded and displaced metamorphic isograds (SGK 1980).

Vanzone antiform

The sudden turn-down of all tectonic units into the southern steep zone (root zone) is one of the most striking features of the Central Alps. In the west, the huge antiform is named after a village in Valle d'Anzasca, where the Antrona ophiolites sweep round a spectacular, southwest-plunging fold hinge (locality C, Fig. 3, see Bearth 1957b). Here, the base of the Monte Rosa unit, the Antrona ophiolites and the underlying lithologies in the Lower Pennine complex, together with the main schistosity (S_r, Ragno–Randa phase), are all affected by the major fold (segment CD, Fig. 3, see Laduron 1976, Baumann 1979). No axial plane schistosity is developed and even parasitic minor folds are rarely seen.

Away from this type locality, the Vanzone antiform rapidly changes shape and style. Towards the southwest (BC, Fig. 3), the well-defined hinge broadens and splits into a series of smaller hinge zones as the axial trace passes through the Monte Rosa complex. Typical of these zones is a crenulation-type minor folding, with a sporadically developed. Vanzone-phase cleavage, S_v, parallel to the northwest-dipping axial planes (Greller in prep.). Further southwest (AB, Fig. 3), the broad back of the Monte Rosa nappe and all higher units are affected by similarly orientated but even more sporadic and open structures (the late post-nappe folds of Gosso *et al.* 1979).

Passing northeastwards from Vanzone along the axial trace reveals style changes of quite a different kind (Milnes, in Steck *et al.* 1979). From the sharp, angular hinge an isoclinal fold core develops which may be a large-scale example of the geometric accommodation features sometimes observed in the cores of chevron folds (Ramsay 1974, fig. 9). In Val Antrona (DE, Fig. 3) a strong asymmetry in the structural relations appears (Laduron & Merlyn 1974). In the hinge zone and particularly on the steep southeast limb, compositional banding and earlier schistosities become completely transposed into parallelism with the major axial plane. The strong foliation on the southeast limb thus seems to be a composite schistosity ($S_{v/r}$) and it is rarely possible to assign the widespread minor isoclinal folds to one or the other of the superimposed deformations. Further northeast (EF, Fig. 3, and see Greller 1976), the fold becomes truly isoclinal (axial plane and both limbs parallel) and the core is marked by a granitic gneiss in which the axial plane



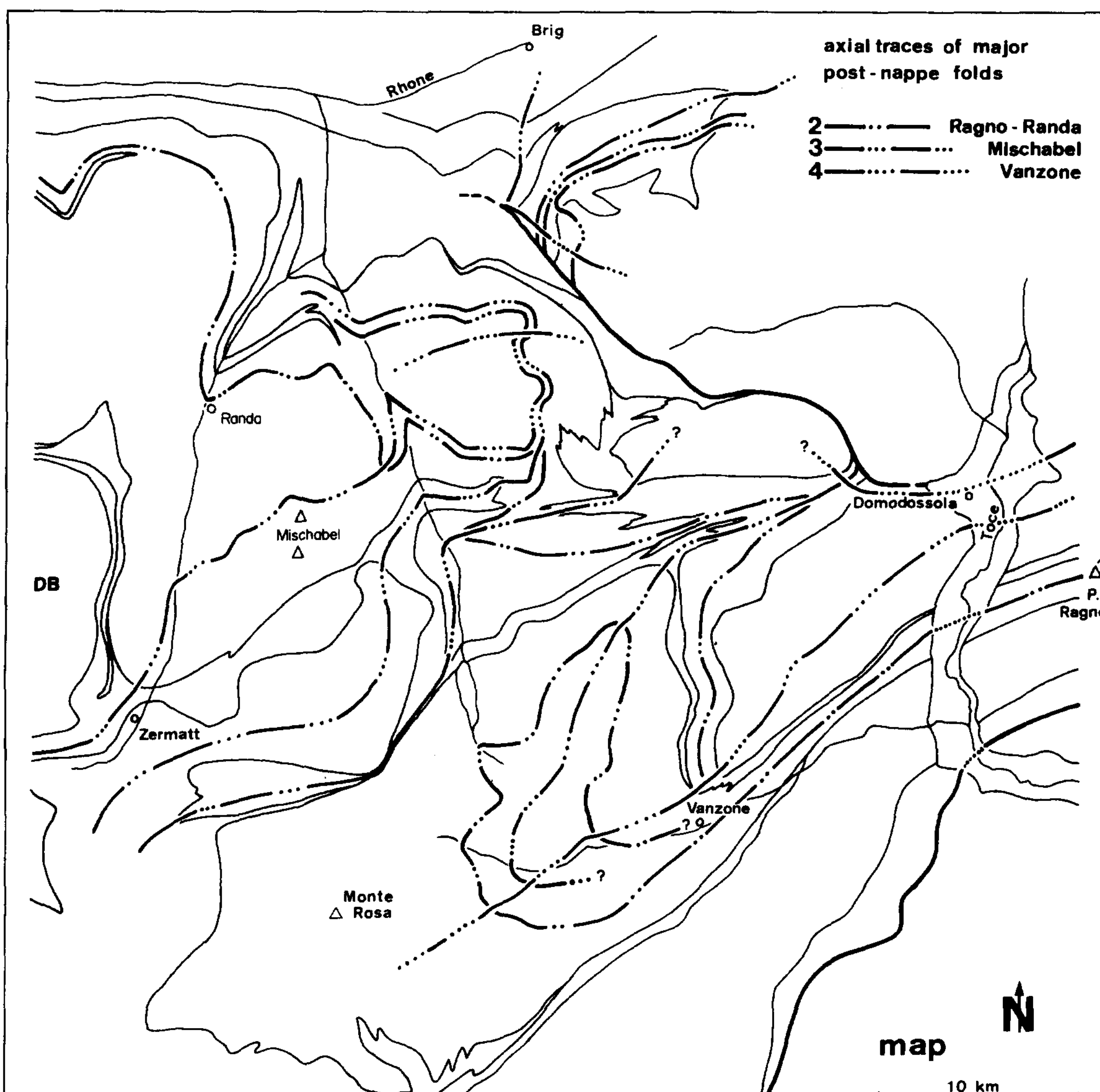


Fig. 2. Composite cross-section and map showing the axial traces of the major post-nappe folds (tectonic boundaries as in Fig. 1), symbols for axial traces are identical in the map and section.

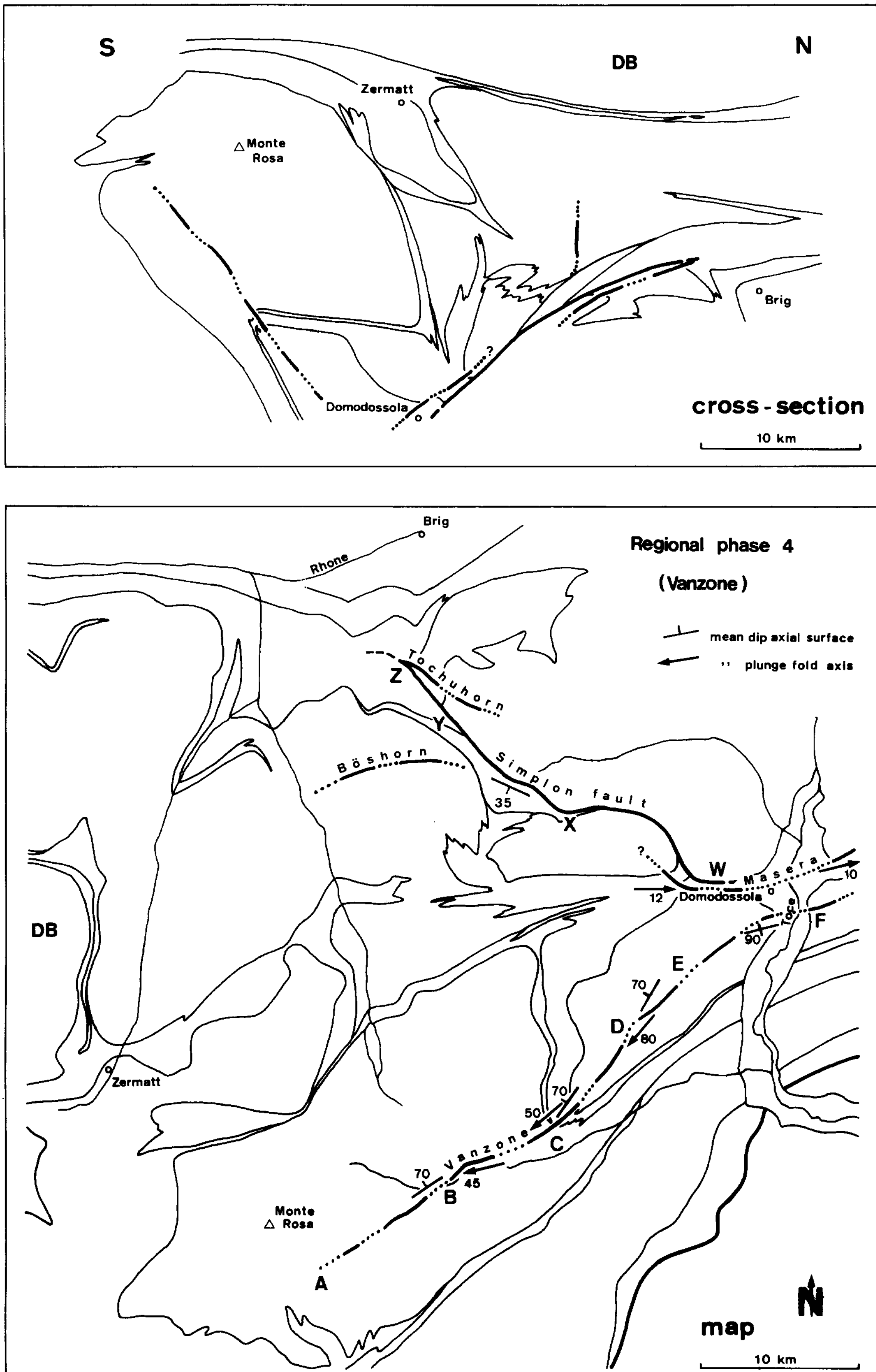


Fig. 3. Composite cross-section and map showing details of the Vanzone-phase structures (regional phase 4, see text), axial trace symbol as in Fig. 2.

schistosity, S_v, overprints the earlier foliation, S_r. These relations — clear overprinting in the hinge zone, composite schistosity on the limbs — are typical of fold development in other fold phases (see below) and are a major cause of uncertainty in regional correlation. The isoclinal character of the Vanzone antiform in the Ossola valley (locality F, Fig. 3) contrasts sharply with the style of the adjacent and supposedly related Masera synform (see below) and probably indicates that the whole structure opens again far below the present exposure level.

Simplon fault and related structures

The eastern outcrop margin (base) of the Upper Pennine nappe complex is marked along much of its length by the late-stage Simplon fault (Bearth 1956a, b). The main displacement along the line is certainly post-metamorphic (Hunziker 1970, Bearth 1973) and some component of the movement was such that the upper block was displaced southwards (Milnes, in Steck *et al.* 1979, SGK 1980). The relations along the fault line show a remarkably symmetrical distribution. Along the central part of its outcrop, between Zwischbergen and Engiloch (segment XY, Fig. 3), the line is marked by mylonites and cataclasites in an ill-defined zone which follows the Upper Pennine/Lower Pennine contact and is parallel to the schistosity and compositional banding in the strongly laminated elements on either side. Northwest of Engiloch (YZ, Fig. 3) the fault zone becomes discordant to all elements below it. Before being truncated, these elements, including the axial planes of major folds presumed to belong to the Mischabel phase, are rotated into closer parallelism with the fault, producing a major 'drag' fold, the Tochuhorn antiform (Fig. 3). East of Zwischbergen (WX, Fig. 3), the same relations appear, but in reversed position — discordance and drag fold (Masera synform) above the fault, continued concordance below. The Masera synform develops eastwards into a really major structure and in the same direction the Simplon fault dies out, leading to the hypothesis that the displacement along it in its central section is being successively transformed into the ductile deformation represented by the Masera/Vanzone fold pair (Milnes, in Steck *et al.* 1979). However, this is only part of an obviously more complicated story — other evidence indicates a movement history with changing displacement directions on the fault (Hunziker 1970, Matthes 1980), and some post-Mischabel folds are difficult to fit into this simple picture (e.g. the Böshorn synform, Fig. 3). Northwest of the Simplon pass (Z, Fig. 3), the fault again becomes concordant and probably splits into a number of smaller faults, a situation which has led to various interpretations of its position within the poorly-exposed Stalden–Visperterminen unit (Bearth 1956b, Burri 1979, Steck *et al.* 1979).

EARLY BACK-FOLDING (MISCHABEL PHASE)

In the Mischabel phase of back-folding, the following major structures developed: the Mischabel antiform, the Mittaghorn synform, the Balmahorn antiform and the Gabbio synform. These, and a number of smaller but still large-scale parasitic structures, delineate an intensely folded monoclinal zone through the centre of the region (Fig. 4). In contrast to the late back-folds, the structures of this phase are typically very tight to isoclinal and are only locally marked by well-developed fold hinges. As an example of the style changes observed, the Mischabel antiform will be described in detail; afterwards, the other structures will be dealt with more briefly.

Mischabel antiform

The Mischabel antiform is the classic back-fold of the Alpine literature, but up to now it has only been described from the one spectacular locality between Täsch and Zermatt, where the contact between the pre-Triassic rocks of the Bernhard nappe and the Mesozoic sediments of the Combin zone outlines a huge, rounded fold hinge (locality B, Fig. 4). Within the Bernhard unit the main schistosity is pre-Mischabel in age (S_r or older). It trends parallel to the contact but is only sporadically affected by minor Mischabel-phase folds, generally open undulations without any sign of an accompanying axial planar foliation. Along the axial trace as a whole, these relations are quite exceptional and indicate that the Bernhard basement in this area (segment BC, Fig. 4) behaved as an exceptionally competent mass during the folding. North and south of this locality, the fold rapidly becomes isoclinal with the main schistosity parallel to its axial plane.

To the south, the axial trace enters the Schistes Lustres of the Combin zone and, after passing through extremely complicated relations in the 'shadow' area of the main hinge (where two phases of earlier isoclinal folding can be distinguished, Müller in prep.), trends subparallel to the base of the overlying Dent Blanche nappe (see also Argand 1911). In this region (AB, Fig. 4), the whole thickness of the Schistes Lustrés has not yet been mapped in detail. The lower limb has been described by Wilson (1978) and it seems likely that the Mischabel phase here is represented by the 'F_2 folds' as he suggests.

From the main hinge northwards and eastwards, now completely within the Bernhard basement, the Mischabel antiform again becomes isoclinal, through a succession of intermediate styles. In the Mischabel massif itself (C, Fig. 4), the hinge zone is still a broad open structure, but it follows a curious course which can best be explained by postulating a major discordance or major pre-Mischabel (Alpine or pre-Alpine?) structures within the Bernhard basement (Müller in prep.). These uncertainties exist because of the lack of good marker horizons in this complex of schistose paragneisses. Where the axial traces descend into the Saas valley, the fold shows a new feature: the base of the hinge zone becomes sharply defined as the lower limb becomes a strongly laminated zone in which all earlier structures are transposed into a composite schis-

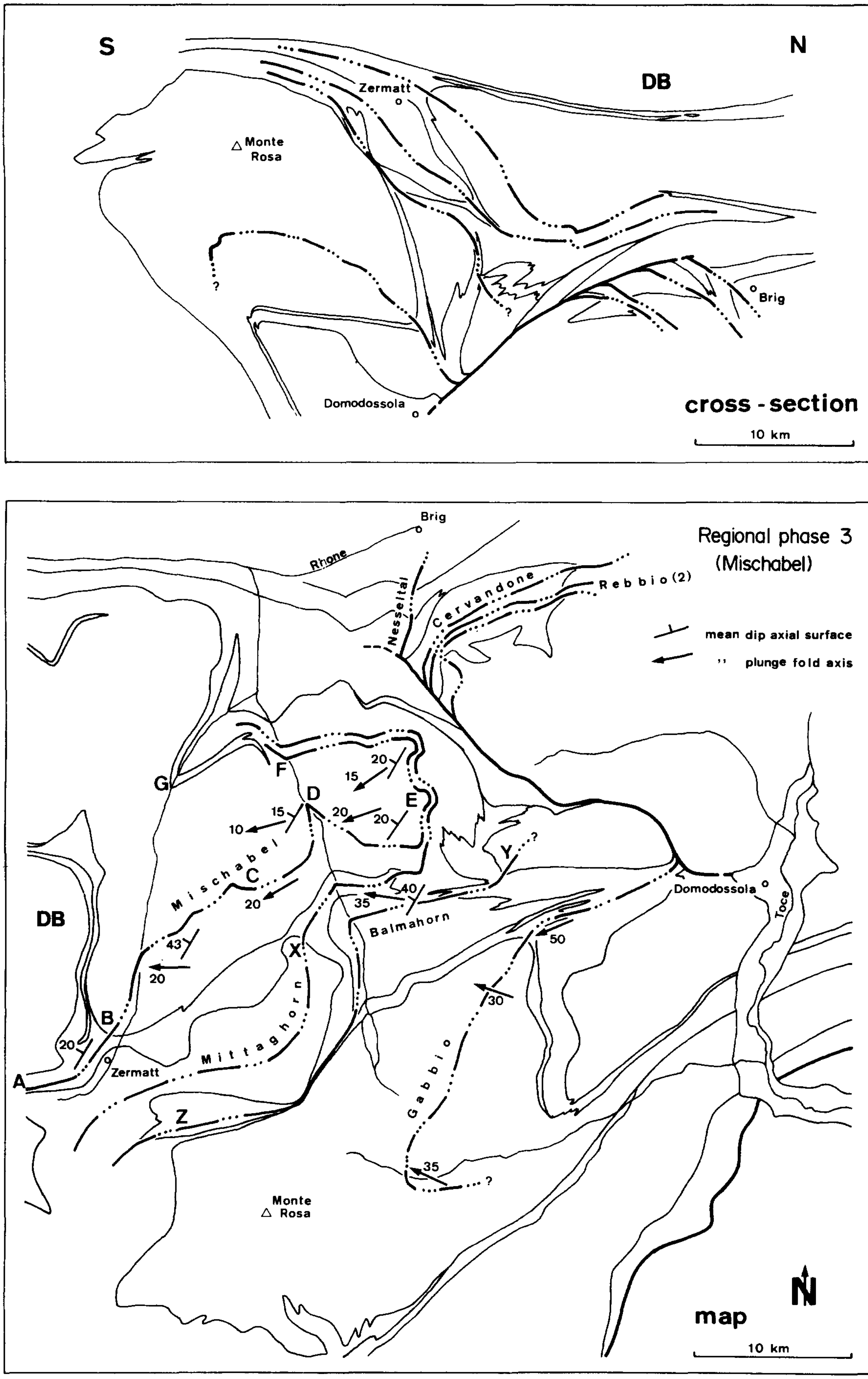


Fig. 4. Composite cross-section and map showing details of the Mischabel-phase structures (regional phase 3, see text), axial trace symbol as in Fig. 2.

tosity, $S_{m/r}$, subparallel to the major axial surface (CDEF, Fig. 4). Although the further course of the Mischabel axial trace did not form part of this study, its strongly laminated lower limb is contiguous with the schistose sequence underlying the zone of infolded Permo-Carboniferous and Triassic rocks near St. Niklaus (G, Fig. 4). Thus it seems likely that the Mischabel trace runs into this isoclinal fold core.

Other Mischabel-phase structures

The zone underlying the Mischabel antiform axial surface is one of very intense and heterogeneous deformation, with tight to isoclinal folding on all scales (the 'F_2' fold zone of Klein 1978). Typical for much of the zone is the widespread transposition of earlier foliations and compositional banding into a composite foliation, $S_{m/r}$, parallel to a penetrative axial plane foliation, S_m, in the fold hinges (Fig. 4). However, this overprinting is not complete and some fold hinges are preserved in which the dominant structure is the folded pre-Mischabel anisotropy. Examples of the latter are the large hinge zone above Saas-Fee (locality X, Fig. 4), where the Zermatt–Sass ophiolites are folded into the core of the Mittaghorn synform, and the complex antiformal fold zone of the Balmahorn (locality Y, Fig. 4). The Balmahorn antiform can be followed through a series of tight fold cores until it also affects the base of the Zermatt–Saas ophiolites in the Gornergrat area (locality Z, Fig. 4). The base of the whole Mischabel-phase fold zone is marked by the axial surface of the Gabbio synform (Fig. 4), along which approximately the reverse relationships to the Mischabel antiform can be observed, that is a strongly laminated upper limb and a lower limb with little sign of Mischabel phase deformation. The Gabbio synform is the structure which determines the external shape of the Monte Rosa nappe (Argand 1911, 'pli de Latelhorn' and 'cuillère de Bognanco').

This description of the structural relations in the zone between the axial surfaces of the Mischabel and Gabbio folds by no means does justice to the complications actually present. A more detailed picture is given by Klein (1978), although we do not agree with his tracing of some of the major axial planes. Finally it remains to be mentioned that some structures below the Simplon fault probably belong to this zone of back-folding (the Rebbio and Cervandone folds of Milnes 1974b, whose axial planes are designated 'S_4^p' in Steck *et al.* 1979).

PRE-MISCHABEL RELATIONSHIPS: DISCUSSION

The primary aim of this work was to test an earlier working hypothesis of Pennine structure (Milnes 1974a) and to attempt to use large-scale structural evidence to place controls on palaeogeographic reconstructions (Milnes & Schmutz 1978, Homewood *et al.* 1980). This involves successively removing the regional deformations to approach the original relative positions of the tectonic units after their primary formation. In the Simplon–Pennine Alps, removing the back-folding (Vanzone and Mischabel phases) reveals an edifice which still shows strong penetrative deformation of basement rocks throughout much of its volume. Associated with this reconstructed complex are major and minor isoclinal folds which clearly affect the nappe boundaries in some areas. Two major fold structures have been identified; the Ragno fold (Blumenthal 1952, Reinhardt 1966) and the Randa fold (Müller in prep.), in the cores of the Monte Rosa and Bernhard units respectively. Their locations in areas distant from the type localities (Fig. 2) are largely speculative. In spite of these uncertainties, the discovery that the ophiolitic rocks constitute a more or less continuous horizon which can be followed through the whole structure (Fig. 5) makes some generalizations about pre-Mischabel relationships possible.

Partially unfolding the Mischabel-phase folds after the Vanzone structures have been removed shows that the following ophiolite-bearing zones are remnants of a once continuous nappe structure: the Upper Zermatt Schuppenzone (part of the Combin zone immediately below the Dent Blanche nappe), the Zermatt–Saas ophiolite complex, the Furgg zone, the Antrona ophiolite complex, and elements in the Laggin zone (Fig. 5). This dismembered ophiolite nappe separates the Bernhard unit from the Monte Rosa and Verosso units, respectively above and

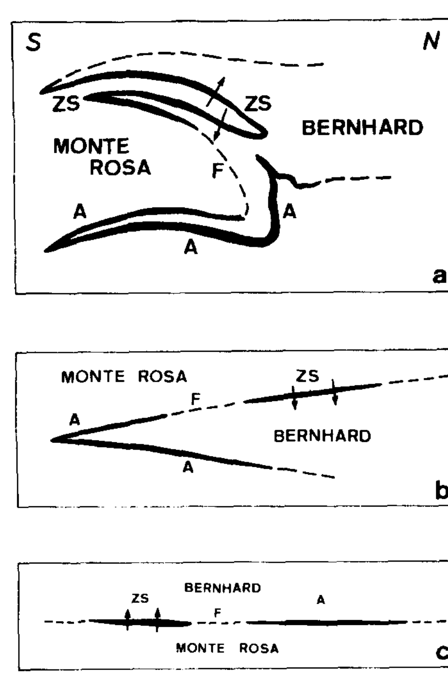


Fig. 5. Schematic reconstruction of pre-Mischabel relationships. (a) Continuous ophiolite-bearing zone after removal of Vanzone-phase structures. (b) Reconstruction of the Randa fold by removing the Mischabel-phase structures. (c) Original relative position of the main tectonic units before the formation of the Randa fold. Abbreviations: ZS, Zermatt–Saas ophiolite complex; F, Furgg zone; A, Antrona ophiolites. Arrows indicate stratigraphic younging directions (Bearth 1976). The three cartoons are at decreasing scale to accommodate the increasing width due to unfolding (schematically indicated by decreasing size of lettering).

below the Randa isoclinal fold core when this is restored to its pre-Mischabel state (Fig. 5b). Because there is good control on the stratigraphy of the Zermatt–Saas ophiolites in the Mittaghorn synform (Bearth 1976, Bearth & Schwander 1981), we know that they are inverted on the upper limb of this reconstructed isocline, and hence original relative positions of the main units can be determined (Fig. 5c). Although this is only a preliminary attempt at making palaeogeographic deductions from structural data, this conclusion puts a question mark against most previous ideas (e.g. Dal Piaz *et al.* 1972, Trümpy 1960, 1980, Dal Piaz & Ernst 1978, Homewood *et al.* 1980). A major suture, with remnants of a consumed ocean floor (including both the Zermatt–Saas and Antrona ophiolites), seems to separate the Monte Rosa from the Bernhard continental basement, implying that these units were originally separated by some kind of ocean basin. The evidence is as yet too weak to maintain that this is the most probable reconstruction. It is, however, strong enough to serve as a warning to keep the options open.

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