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The Simplon Line: a major displacement zone in the western Lepontine Alps

By NEIL MANCKTELOW[1])

ABSTRACT

Mylonites and cataclasites developed along a marked structural discontinuity (the Simplon Line) are the most obvious manifestation of a broader zone of deformation (the Simplon Phase) within the western Lepontine Alps of southwestern Switzerland and northern Italy. Structures associated with this deformation overprint earlier features for several kilometers into the footwall block northeast of the Line. In contrast, the trends of earlier structures in the hangingwall block are often sharply truncated by the Simplon Line, and there is little discernable imprint of the Simplon Phase of deformation. Sense of shear indicators within the mylonites (shear bands, asymmetric quartz textures, etc.) reflect a downthrow of the hangingwall block along much of the zone, with excellent internal consistency. Interpretation of the presently available isotopic evidence suggests a relative displacement of around 12 km.

ZUSAMMENFASSUNG

Mylonite und Kataklasite, die entlang einer markanten strukturellen Diskontinuität (Simplon-Linie) aufgeschlossen sind, stellen die ausgeprägten Merkmale einer breiteren Deformationszone (Simplon-Phase) in den westlichen Lepontinischen Alpen der Südwestschweiz und Norditaliens dar. Strukturen dieser Deformationsphase überlagern frühere Elemente um einige Kilometer im Liegenden nordöstlich der Linie. Die Spuren der früheren Strukturen des Hangenden sind jedoch oft durch die Simplon-Linie scharf abgeschnitten, und dieser Block ist sehr wenig von der Simplon-Phase überprägt. Schersinn-Indikatoren innerhalb der Mylonite (Scherbänder, asymmetrische Quarztexturen, usw.) weisen sehr systematisch auf eine Abscherung des Hangenden entlang des Hauptteils der kartierten Simplon-Linie. Die Auswertung der veröffentlichten Isotopendaten von beiden Seiten der Linie deutet auf eine relative Bewegung von etwa 12 km.

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Introduction

The extensive zone of mylonites and cataclasites which occurs between the Simplonpass in southwestern Switzerland and the Bognanco Valley in Italy (Fig. 1) was first recognized and mapped by Bearth and Amstutz in the 1950's (Bearth 1956a, 1956b, 1973, Amstutz 1954). The continuation and/or termination of this structural discontinuity (which will be referred to as the "Simplon Line"), and its tectonic significance, have been a matter of some conjecture. It has been generally accepted that the Simplon Line continues to the southeast and east as a brittle, distributed fault zone (the Centovalli Fault, e.g. the Tectonic Map of Switzerland SGK 1980, Fig. 1). This was questioned by Milnes (in Steck et al. 1979), who noted that such a continuation is

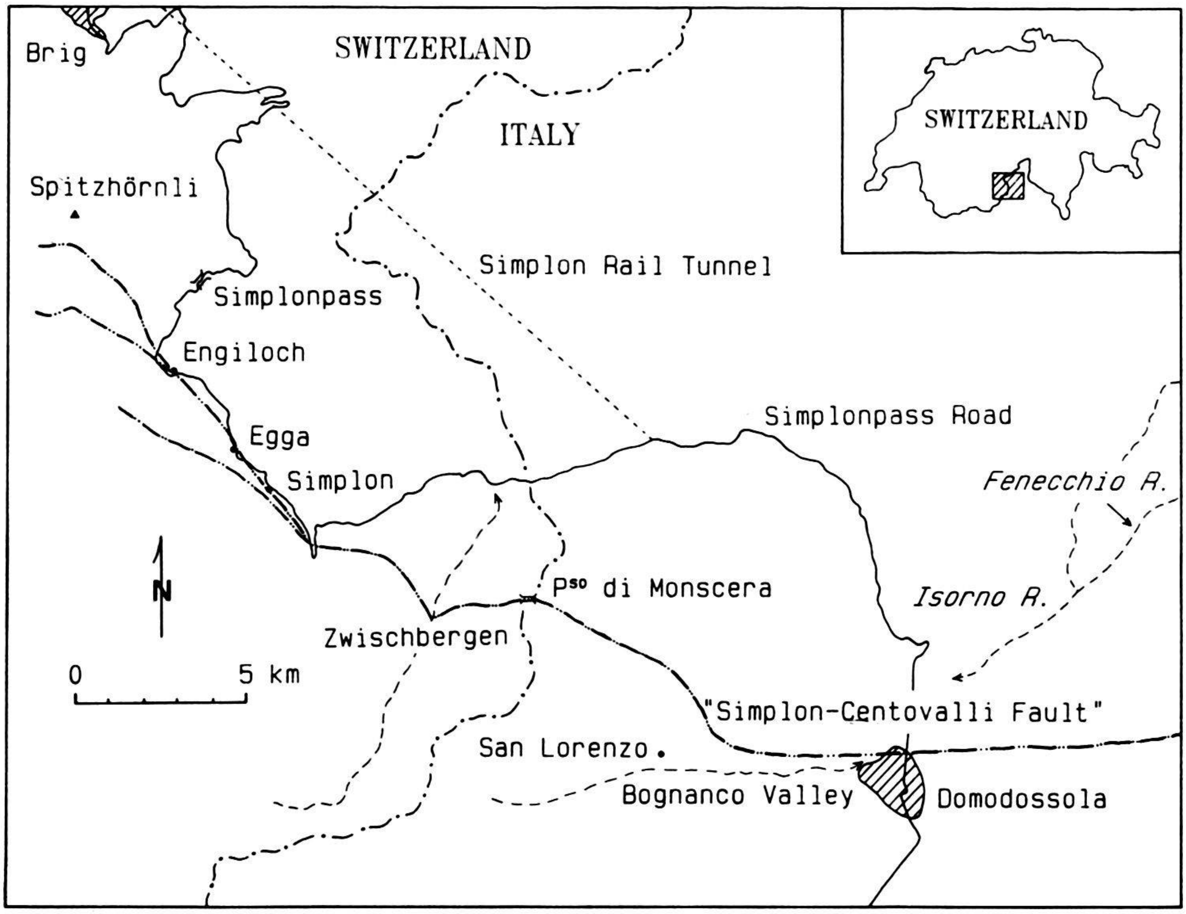


Fig. 1. Location map for the Simplon region. The "Simplon–Centovalli Fault", as portrayed on the Tectonic Map of Switzerland (Schweiz. Geol. Kommission 1980), is shown for reference.

difficult to reconcile with the actual field geology. The continuation to the north, in the region of the Simplonpass itself, has been even more doubtful. On most maps, it is shown either continuing to the northwest, south of Spitzhörnli, or rapidly dying-out in this general direction (Fig. 1, BEARTH 1956b, BURRI 1979, STECK et al. 1979, GEHRING 1981).

The Simplon Line is commonly described as a rather narrow, late, semi-brittle fault, cross-cutting and offsetting all the major structures (including the metamorphic isograds and mineral ages) and having little effect on the blocks it separates (e.g. SGK 1980). However, if the strike of the dominant tectonic foliation, irrespective of its structural relationship, is plotted and trend lines constructed (Fig. 2), the impression gained is quite different. In the central segment, where the Simplon Line was first recognized, the strike of the dominant foliation in the northeastern (footwall) block is concordant with that of the structural break itself, while the foliation in the southwestern (hangingwall) block is obviously truncated. These relationships are equally clear in profile view. Indeed, the present work demonstrates that a phase of predominantly ductile deformation (the "Simplon Phase") overprints earlier structures in the footwall block for a considerable distance away from the Line itself. The hangingwall block is,

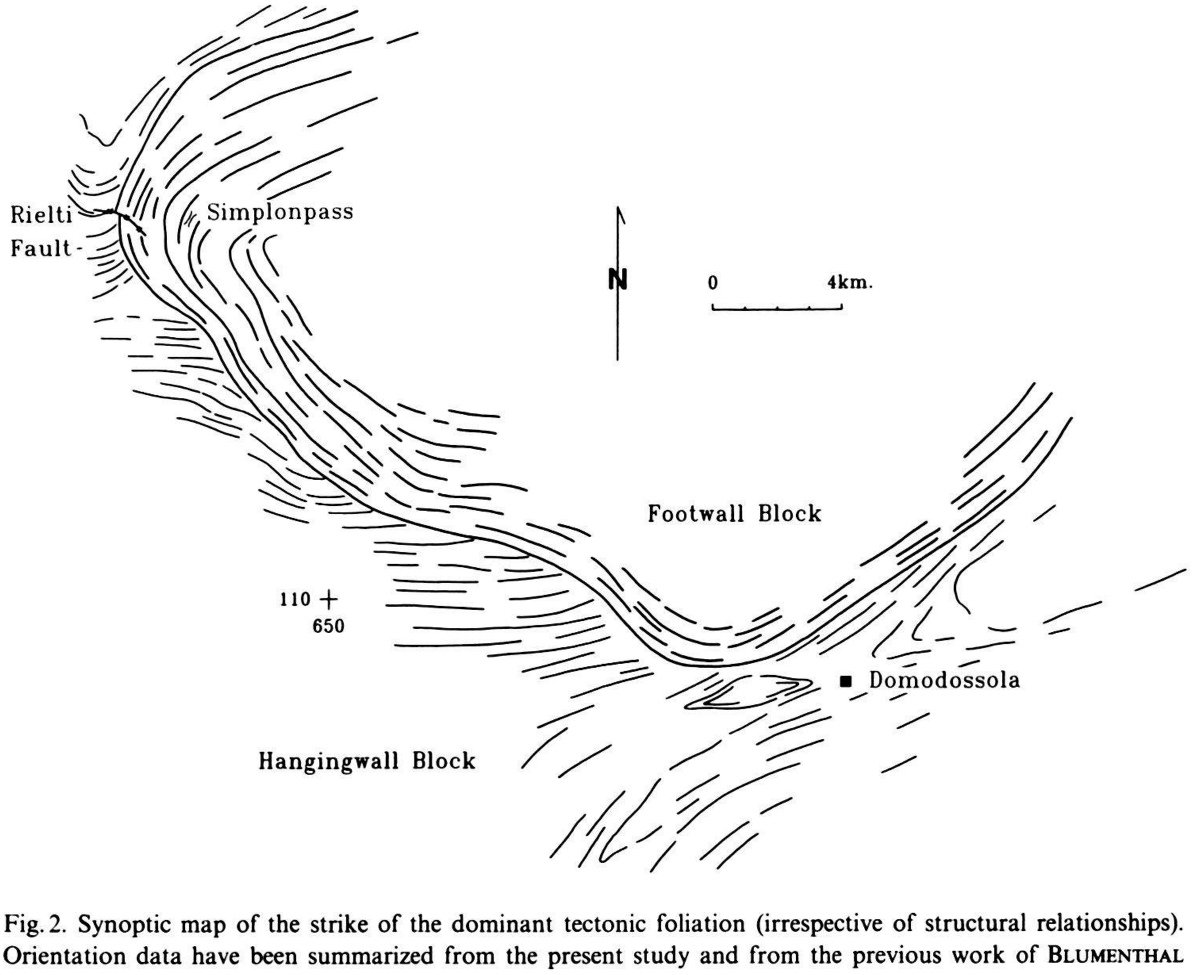


Fig. 2. Synoptic map of the strike of the dominant tectonic foliation (irrespective of structural relationships). Orientation data have been summarized from the present study and from the previous work of BLUMENTHAL (1952), BEARTH (1956a, 1956b, 1972), MATTHES (1980), GEHRING (1981), WIELAND (1966), WENK & TROMMSDORF (1965), and MILNES (1974). The Rielti Fault is a minor late stage structure which offsets the Simplon Line.

in contrast, little affected; earlier structures are abruptly truncated by the Simplon Line. Recognition of these relationships is critical to the study of this important phase of heterogeneous deformation.

Structural elements

1. Introduction

The Simplon Phase of deformation is represented by two dominant structural elements: a foliation S_m and a variably developed lineation L_m. The general relationships can be readily seen in the stylized cross section of Figure 3, which shows the salient features of the zone in the central region between Engiloch and Zwischbergen. As noted above, the hangingwall block, although multiply deformed from earlier events, is not significantly affected by the Simplon Phase. Local, fairly narrow zones of strongly foliated and lineated tectonites do occur hard up against the structural discontinuity (e.g. near Egga, Fig. 1), but in general the earlier structures are clearly truncated by the Simplon Line (Fig. 2). The Line itself is usually marked by a zone of fault breccia or fine-grained cataclasites, which includes randomly oriented blocks of poorly lineated mylonite, and occasionally also includes lenses up to several hundred meters in length of brecciated, buff-coloured marble (e.g. southeast of Passo di Monscera and near Zwischbergen). This narrow zone is underlain by several tens of meters of dark grey-green, fine to very fine-grained, micaceous mylonite. This unit is very well foliated, but poorly lineated. The foliation is often rather irregular in orientation, forming open basins and domes with a wavelength of 1–2 m. These rocks grade in turn into lighter coloured, strongly foliated and lineated, fine to medium grained, quartzo-feldspathic mylonitic gneisses and micaceous schists. The darkening in colour with decreasing

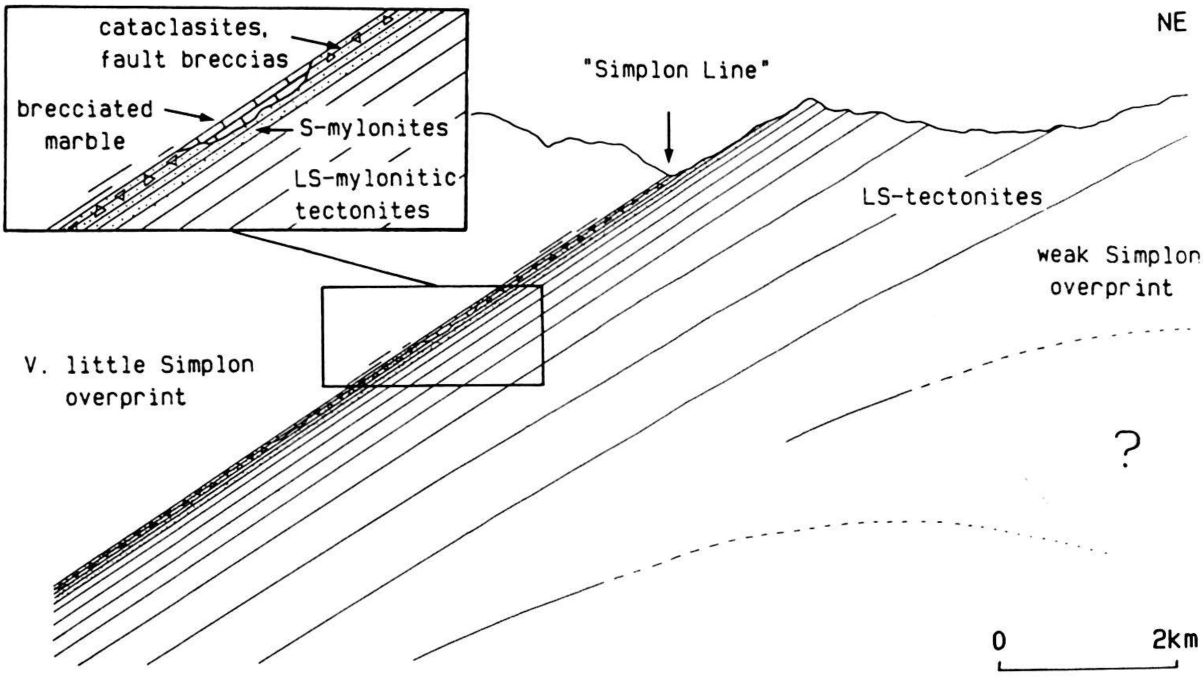


Fig. 3. A synoptic, simplified cross section through the central portion of the Simplon Line.

grainsize is due to the breakdown of the originally rather coarse-grained, separated porphyroblasts of biotite (and white mica) into fine-grained cleavage platelets scattered throughout the rock. In general, the degree of foliation decreases and the grainsize increases in a gradual manner with distance from the Simplon Line, although in detail there is considerable variability in both parameters. The average dip of the foliation also appears to decrease gradually with distance (cf. BEARTH 1973, Tf. 1).

2. *Foliation*

The units affected by the Simplon Phase generally possessed a prior tectonic foliation. Consequently, where the overprinting Simplon deformation is only weakly developed, it is seen as a moderately open to tight folding of the earlier foliation, usually with the development of an incipient axial plane crenulation cleavage (e.g. in the hillside outcrops around Balma, 2–3 km northeast of Egga, Fig. 1). With increased strain, this new foliation, S_m, rapidly obliterates the earlier foliation to produce a lineated, generally well-foliated tectonite. As is obvious from Plate 1, the S_m foliation discordantly overprints the large scale nappe structures, and the Simplon Phase must postdate the main period of nappe emplacement (cf. MILNES 1974, MILNES et al. 1981).

3. *Lineation*

The strength of the lineation L_m in the weakly to moderately deformed areas depends on position within the folds. Hinge regions, where the two foliations are at a high angle, are more highly lineated than limb areas, where the two foliations are more nearly parallel. Such varying texture is a function of two complementary effects: the purely geometric effect of the intersection of two planar structures, and the cumulative strain resulting from the addition of two finite strain increments at differing angles (Fig. 4). The geometry outlined in Figure 4 does present some initial problems in considering the strain increment associated with the Simplon Phase alone. For regions only weakly affected by this later deformation, the finite elongation and/or intersection lineation within the multiply deformed gneisses need not bear any readily determinable relationship to the incremental elongation lineation associated with the Simplon Phase. However, with increasing strain, the measurable lineation should approach the orientation of the Simplon Phase elongation lineation as a combined result of two factors:

a) The intersection lineation, like any other material line, will gradually rotate towards the Simplon Phase elongation direction (with one unlikely exception: a line which remains strictly parallel to the intermediate finite strain axis, cf. SANDERSON 1973, ESCHER & WATTERSON 1974).

b) The later strain increment will eventually dominate the previous increments to such an extent that the finite elongation lineation is effectively, though never strictly, parallel to the Simplon Phase elongation.

More direct information on the strain associated with the Simplon Phase can be obtained from units which were introduced after the earlier deformation phases but before the Simplon events. This criteria appears to be met by some (but not all) quartz veins in the region under study.

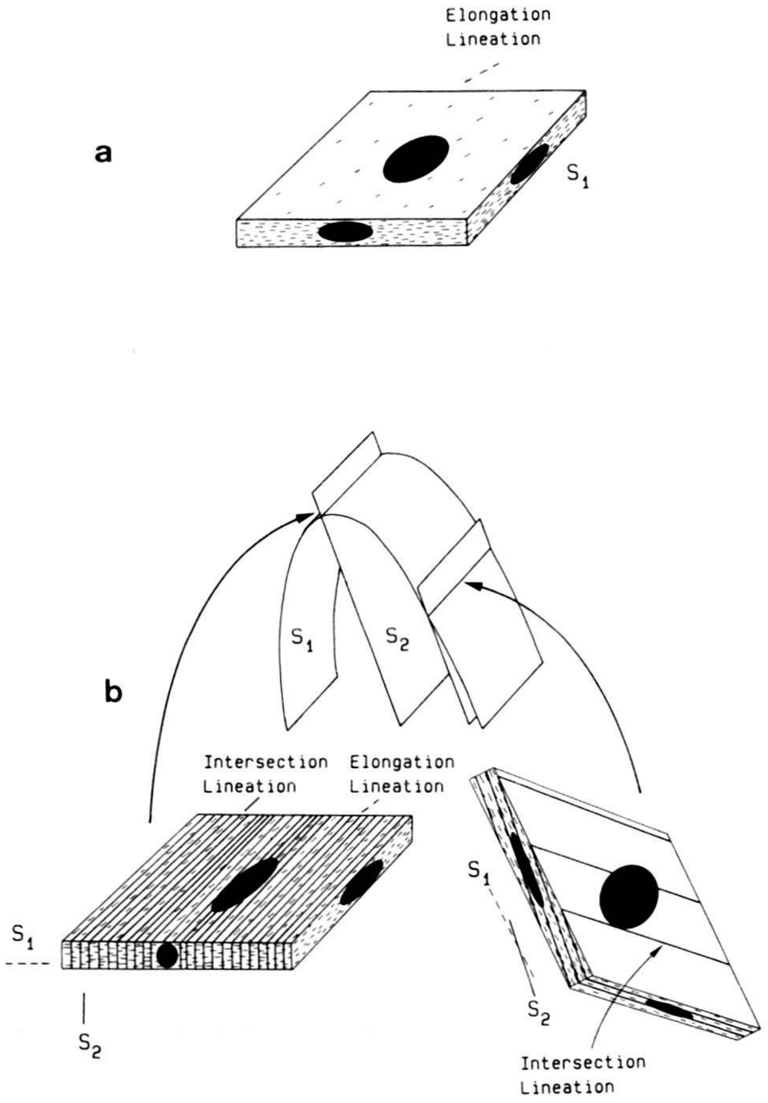


Fig. 4. The relationship between fabric style and position within a fold in an earlier foliation. a) the earlier tectonic foliation, S_1, and its associated finite strain prior to folding. b) the folded foliation, S_1, with a newly developed axial plane foliation, S_2. The resultant tectonic has a linear fabric in the hinge region and a more planar fabric on the limbs.

The discussion above leads us to expect that in areas apparently only weakly affected by the Simplon Phase of deformation, the intersection, finite elongation and incremental elongation (Simplon Phase only) lineations should have distinct, nonparallel orientations, but should become indistinguishable in the highest strain zone(s). Rather suprisingly, the region under study consistently displays a single lineation, L_m, with characteristics of all three, irrespective of the apparent intensity of the Simplon Phase. In the micaceous schists and gneisses, the lineation can often be shown to be a crenulation intersection lineation parallel to the elongation direction of the component minerals. This lineation is in turn parallel to the mineral elongation lineation in adjacent quartz veins, which were either initially crystallized (or strongly annealed) immediately prior to the Simplon Phase (i.e. they appear to retain little memory of earlier deformation events).

Such a consistent L–S fabric does provide a simple specimen reference framework for the study of the microstructure and crystallographic texture of these rocks. The principal finite strain axes provide the only rectilinear coordinate system which will remain rectilinear for variable amounts of finite strain. It follows that the remarkable internal consistency of the measured quartz textures when referred to the L–S specimen coordinate framework (e.g. Pl. 2), for specimens which represent a wide spectrum of finite strain, provides circumstantial support for the assumption that the kinematic axes can be directly related to the fabric elements in these rocks (foliation taken as XY, lineation as X).

4. Shear bands

In the most strongly foliated zones, the S_m foliation is itself often overprinted by a "shear band" foliation (Fig. 5, cf. GAPAIS & WHITE 1982, WHITE 1979). The intersection trace of this new S_s foliation on the S_m plane is invariably at a high angle to L_m, though seldom strictly perpendicular. The angle between S_s and S_m is usually around 30°, often with the development of a conjugate pair of shear band foliations approximately symmetric about S_m (e.g. S_{s1} und S_{s2} in Fig. 5, cf. fig. 2 in WHITE 1979). One of the pair is always more strongly developed than the other; this is consistently the one which is designated S_{s1} in Figure 5, and which has the same sense of shear across it as that inferred for the zone as a whole (see the discussion on kinematics below). Occasionally, the development of shear bands is so pervasive as to form the dominant foliation. In one such example, 2 km WSW of Simplonpass (the Rielti Fault of Fig. 2

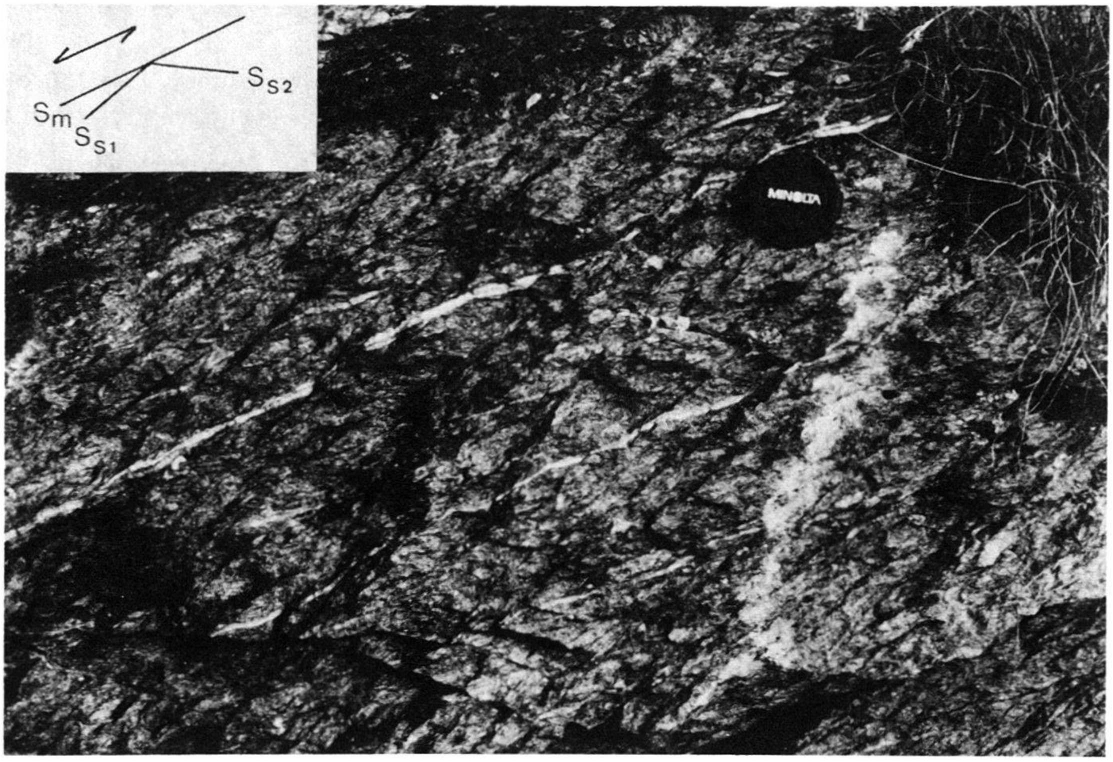


Fig. 5. Mylonitic foliation S_m and the less penetrative, spaced, shear-band foliations S_{s1} and S_{s2}. Note that the foliation is more strongly developed, indicating a sinistral shear movement. Location coord. 644.300/119.800, road cutting, main Simplonpass road, opposite Nideralp.

and Pl. 1), the shear band zone grades into similarly oriented cataclasites, and the Simplon Line itself is offset across the zone. The generation of the shear bands must have been a late-stage event in the progressive deformation history of the Simplon Phase. They probably reflect the development of internal mechanical instabilities during the continued deformation of an already highly foliated, anisotropic rock (cf. COBBOLD et al. 1971, WHITE et al. 1980).

5. Late structures

In several localities (e.g. SSE of Engiloch) the S_m foliation is quite strongly refolded with an angular, kinklike style. The fold axes closely parallel the earlier L_m lineation, and their orientation was probably controlled by this pre-existing linear anisotropy (cf. COBBOLD & WATKINSON 1981). The axial plane is variable in orientation, but generally steeply dipping. A fine, weak crenulation lineation at a high angle to L_m is also occasionally observed on planar S_m surfaces, but no associated, larger scale features have been observed.

Field geometry

1. General

On the present outcrop surface the Simplon Line forms a regional arc (Fig. 2, 6, Pl. 1). As noted above, in the footwall block the foliation S_m is readily discernable for a considerable distance away from the structural discontinuity itself. The strike of this foliation closely parallels the trace of the Simplon Line (Fig. 2). In the hangingwall block, however, the earlier structures are preserved and sharply truncated by the Simplon Line, most clearly in the central region between the Simplonpass and the Bognanco Valley in Italy. It is for this reason that the Simplon Line can be so easily followed in this part. On the limbs of the arc, such a discontinuity is less obvious. To the southeast, the ductile mylonitic gneisses can be followed directly along the strike of S_m from the Bognanco Valley, across the broad Ossola Valley where outcrops are lacking, and into the northern bank of the Isorno River (Fig. 1, Pl. 1). The linear trend of the Isorno–Fenecchio Valley marks the structural discontinuity, separating two distinct lithological units (the Monte Leone Gneiss and the Isorno Series, cf. WIELAND 1966), with markedly shallower dips to the regional foliation in the Isorno Series immediately southeast of the line. The break itself is seldom exposed, occasional outcrops of brecciated medium-grained mylonitic gneiss forming the sole remnants. It is obvious in field exposure that there is a general coarsening of the average grain size in the ductile mylonitic gneisses going eastwards from Zwischbergen to the Bognanco Valley and into the Isorno Valley. This may reflect a broadening of the displacement zone, to produce a lower average strain rate within the deforming gneisses, or it may be due to a gradual change in the ambient P–T conditions. The transition is not entirely regular, with rare zones of very fine grained mylonites still occurring at least until the eastern end of the Bognanco Valley.

In the region towards the other end of the Simplon Line, northeast of the Simplonpass, the exact relationships remain unclear. The smooth trend to S_m within the foot-

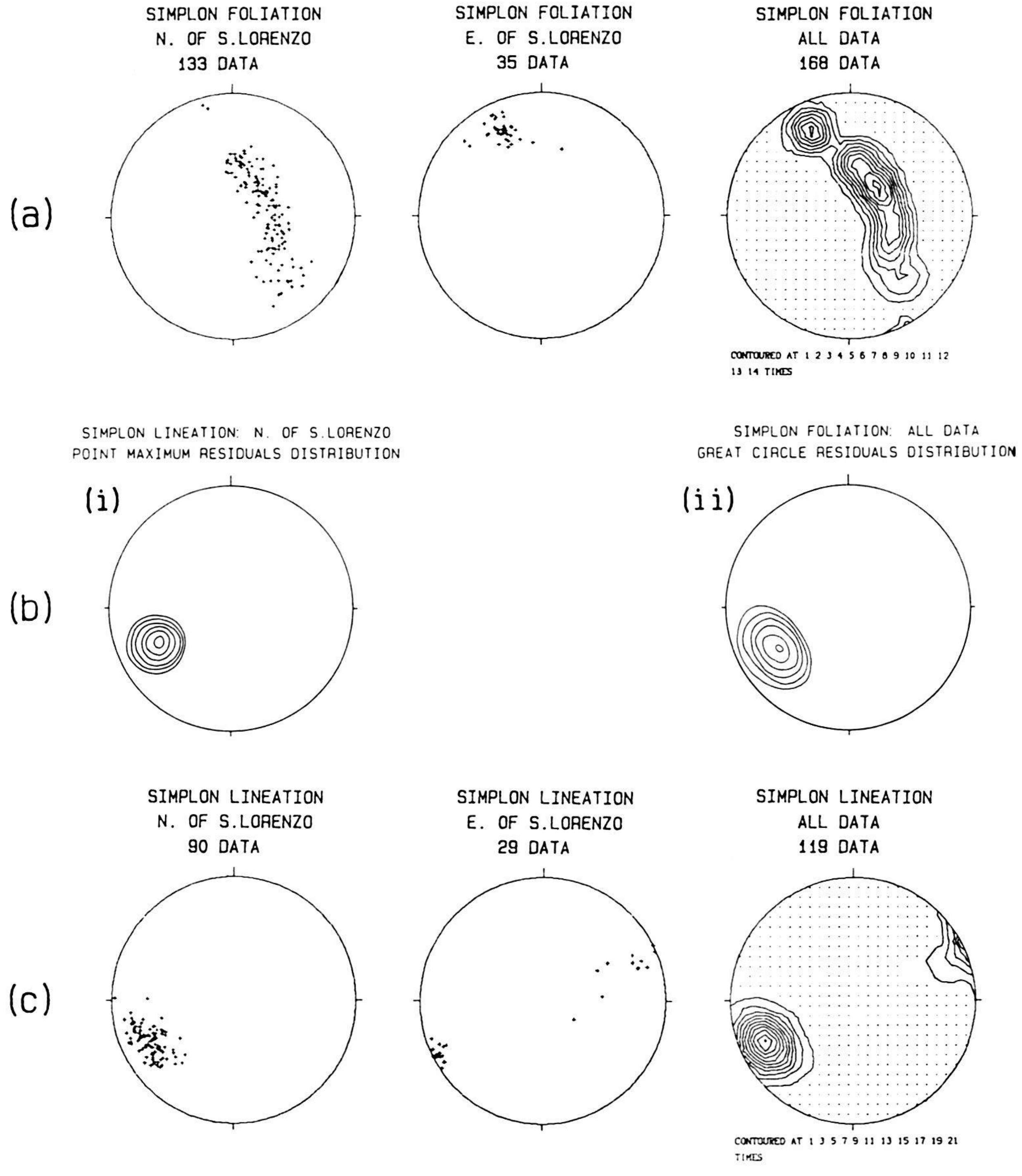


Fig. 6. Orientation data for S_m and L_m along the Simplon Line.

a) S_m foliation data. Plotting and contouring is in the lower hemisphere, using a FORTRAN computer program described by STARKEY (1979).

b) (i) Plot of the least-squares residuals for the best-fit lineation to the L_m data north of San Lorenzo. Contours at 13, 15, 17, 19, 21 and 23°. The best-fit lineation plunges 24° towards 244°M. Standard deviation is 12.5°. The method follows MANCKTELOW (1981).

(ii) Plot of the least-squares residuals for the best-fit pole to a great circle through all the S_m data poles. Contours at 8, 10, 12, 14, 16 and 18°. The pole to the best-fit great circle plunges 22° towards 241°M. Standard deviation is 7.9°.

c) L_m lineation data. Plotting method is the same as for a).

wall block provides one major constraint on the trend of the ductile mylonites (Fig. 2), and the structural discontinuity can be followed directly as far as the area immediately west of the Simplonpass (Fig. 1, Pl. 1). From here to the northeast the planar structures in the hangingwall block are more or less concordant with those in the footwall, the lithologies are similar, and the outcrop incomplete. It has not been possible to define a distinct structural discontinuity in this region. Indeed a single major break may not exist, for the Simplon Phase of deformation in the micaschist-rich Berisal unit (Pl. 1) is very heterogeneous, with scattered zones of high strain (developing fine to medium grained mylonitic schists and cataclasites) separating areas only moderately affected by the Simplon Phase. It appears that the previous single discontinuity has been supplanted by a series of minor high strain zones within this more micaceous unit (as was implied by BEARTH 1973).

2. *Three-dimensional geometry*

As is clear from Figure 6, in three dimensions the S_m foliation forms a quite tightly defined concentric surface. For the section between the Simplonpass and San Lorenzo, at the head of the Bognanco Valley, the foliation contains one dominant lineation L_m with a near constant orientation (Fig. 6, Plate 1). From San Lorenzo eastwards towards the Ossola Valley and into the Isorno Valley, there is a progressive change in the orientation of the lineation from the previously constant 30° southwest through the horizontal to 30–50° NE (Fig. 6, 7). The assignment of a vector direction to the lineation in Figure 7 allows the 3-D orientation of a specimen to be described uniquely by reference to this vector and the foliation S_m. Such a unique orientation for specimens becomes significant when we consider the kinematics of the Simplon Phase (see below).

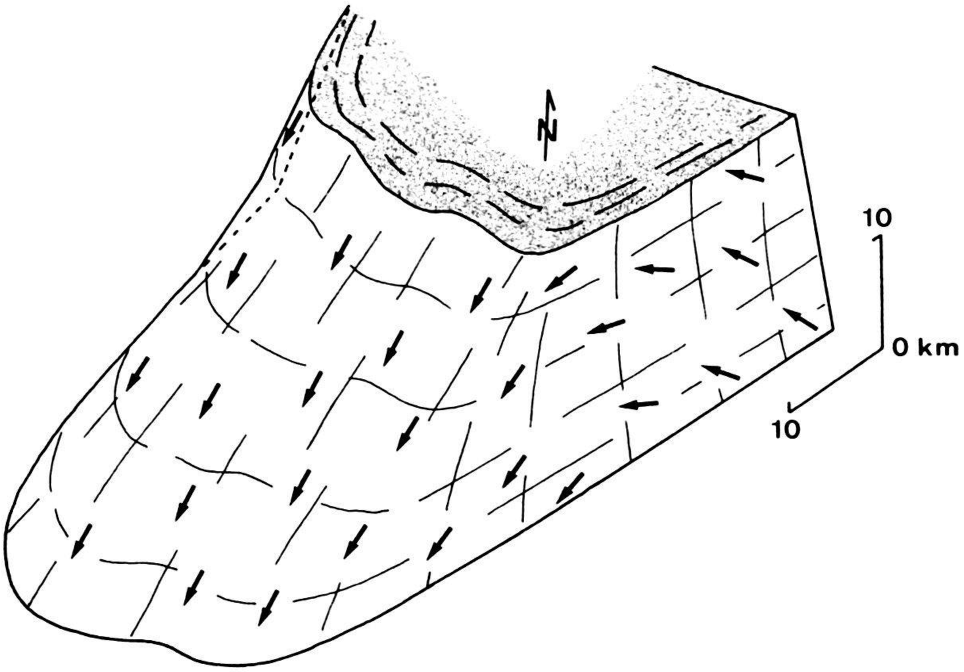


Fig. 7. Three-dimensional representation of the arcuate Simplon Line, with the hangingwall block removed for clarity. The arrows are parallel to the measured lineation, and have been assigned a consistent vector direction to define the orientation of field specimens uniquely in terms of the foliation S_m and the vector lineation.

3. *Relationship to the Centovalli Fault Zone*

In most previous regional syntheses, the Simplon Line has been connected across the Ossola Valley to the Centovalli Fault Zone, which is an approximately vertical zone of breccia and fault gouge running due east from Domodossola (Fig. 1). As discussed above, the ductile mylonitic units associated with the Simplon Line can be mapped directly and do not follow the Centovalli Fault. However, the cataclasites and breccias which mark the Line itself include disoriented clasts of ductile mylonites, indicating that movement in this zone postdated at least some part of the mylonite-forming history. We cannot automatically assume that the brittle and ductile components have identical histories and geometries. In particular, although the kinematics of the ductile mylonites can be inferred from several consistent lines of evidence (see below), there are no equivalent direct criteria available for the cataclasites. As discussed by MILNES (in STECK et al. 1979), there is, however, good independent evidence that no significant component of the displacement associated with the Simplon Line continues along the Centovalli Fault Zone. Should the Simplon Line and the Centovalli Fault be joined as one, it must intersect the trend of the Masera Syncline (of the Vanzone Phase, see MILNES et al. 1981, fig. 3) somewhere in the Ossola Valley. Significantly, there is no discernable offset in the smooth trend of the axial plane of the Masera Syncline across the Ossola Valley. Any movement on the continuation of the Centovalli Fault Zone in this region must be slight. Less direct geometrical evidence also cautions against joining these two structures. As discussed above, the S_m foliation in the ductile mylonites defines a well-constrained concentric surface; i.e. to a good approximation all foliation planes contain the same line and this line parallels the L_m lineation in the central portion. The S_m foliation is effectively concordant with the cataclasite zone (cf. Fig. 2 and 3) and it follows that this more brittle zone is also concentric between the Simplonpass and the Fenecchio River. It is, therefore, possible for the two blocks on either side of the fault surface to move with a relative displacement vector parallel to this ubiquitous line without requiring any internal deformation of the blocks themselves. The orientation of the Centovalli Fault Zone does not lie within this same concentric surface. Significant movement on a combined Simplon–Centovalli Fault surface would require accommodating, presumably brittle, deformation within at least one of the blocks. There is no clear evidence for such deformation.

4. *Regional structural relationships*

A structural framework for the whole of the Penninic Alps has been constructed over a period of years by Milnes and his coworkers (e.g. MILNES 1973, 1974, MILNES et al. 1981). In the hangingwall block (their "Upper Pennine Zone"), they divide the Alpine orogenic history into several broad phases, from youngest to oldest:

4. Vanzone Phase
3. Mischabel Phase
2. Ragno-Randa Phase
1. Basement Nappe Emplacement

The Simplon Line clearly truncates structures which MILNES et al. (1981) assign to the Mischabel Phase, and they suggest that the Vanzone Phase may be related to the development of the Simplon mylonites, though the relationships are not very clear.

In the region of the Simplon rail tunnel (footwall block or "Lower Pennine Zone"), the structural history has been summarized by MILNES (1973) as follows, starting with the youngest event:

5. Faulting (Veglia and Simplon–Centovalli fault zones)
4. Local folding (Rebbio fold zone)
3. Regional isoclinal folding (Monte Leone and Wandfluhhorn fold systems)
2. Basement nappe emplacement (Berisal, Monte Leone and Antigorio nappes)
1. Early thrusting (Lebendun nappe)

However, the results of the current work demonstrate that there is a major ductile imprint within the footwall block of the Simplon Line and that it cannot be described simply as a narrow, discordant feature offsetting the earlier penetrative structures. Indeed, it appears possible that the Simplon Line and the large Wandfluhhorn fold structure are different features of the same, Simplon Phase of deformation. The S_m foliation strikes into the type area, northeast of Domodossola, where the Wandfluhhorn fold was defined (HALL 1972, HUNZIKER 1966, WIELAND 1966), and appears to coincide with the axial plane foliation of this structure. It is significant that HALL (1972) showed that, in the Bosco area, the Wandfluhhorn folding and foliation development took place after the growth of garnet, staurolite, kyanite, and plagioclase porphyroblasts, which grew during the Alpine ("Lepontine") metamorphism. As discussed below, the S_m foliation displays the same relationship.

In the northeastern region around the Simplonpass, such a correlation would conflict with the structural interpretation of MILNES (1973, MILNES et al. 1981, fig. 4), which suggests that the discontinuity marking the Simplon Line truncates major folds of phase 4 above, and therefore must postdate the Wandfluhhorn (phase 3) fold system. This evidence relates to the brittle cataclasites on the Simplon Line discontinuity; the criteria may not be equally relevant to the broader zone of ductile mylonites. In a progressive displacement history, locations within these two zones were only juxtaposed in the very last increment. Early in the history, they would have been at quite different structural levels (see below). The problem remains unresolved. Integration of the regional structural relationships will require a much larger scale field project than has been attempted here, and awaits further work.

Kinematics

1. Displacement sense

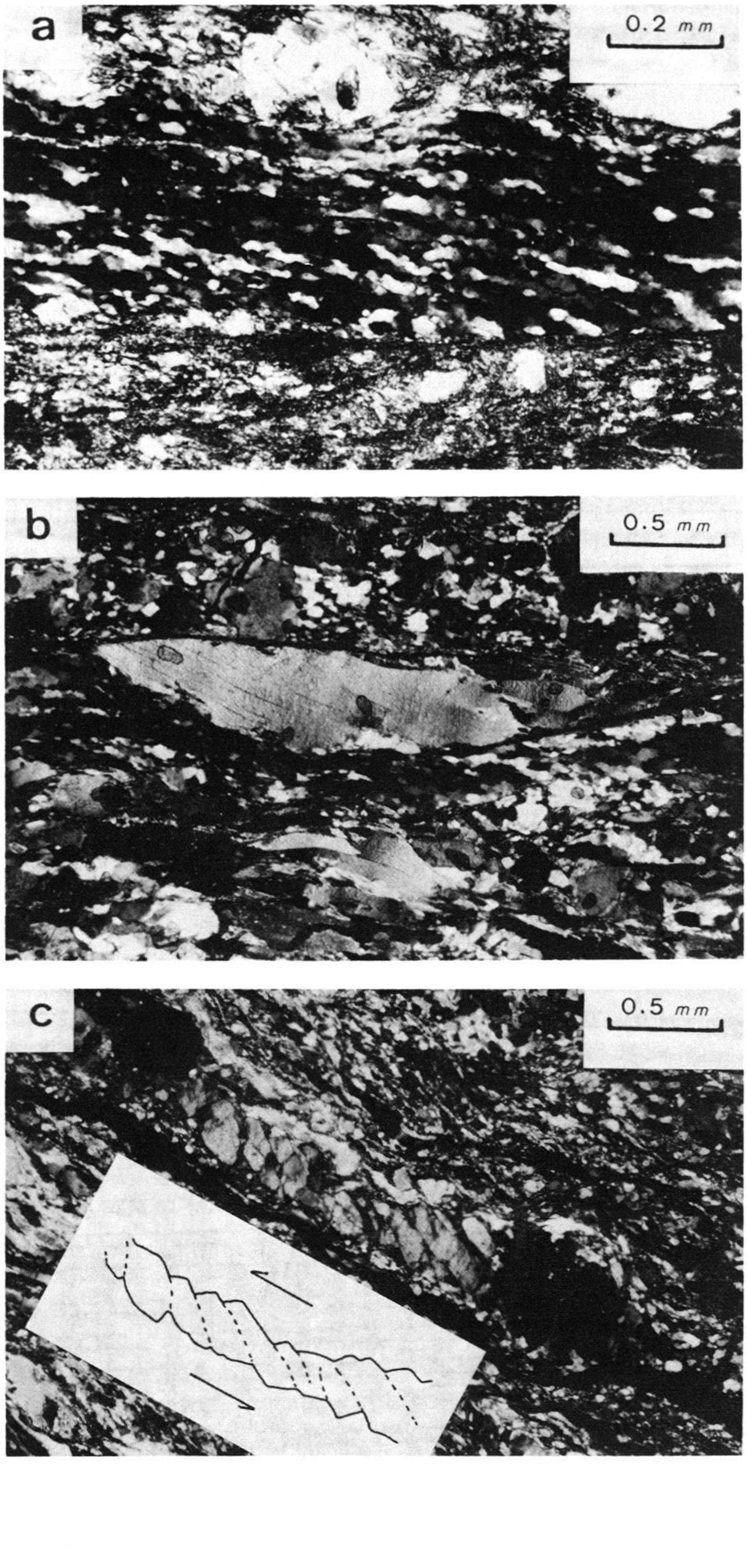
The markedly asymmetric tectonite fabrics developed during the Simplon Phase indicate that there was a major shear component to the deformation. The sense of this

Fig. 8. Photomicrographs of microstructures indicative of the sense of shear. The inferred sense of shear in all three photomicrographs is sinistral.

a) Well-defined trend of recrystallized grains and of subgrains within a thin quartz vein, which is clearly oblique to the E–W oriented S_m foliation. XZ section, location coord. 647.800/116.600, north of Simplon village.

b) Characteristic shape and orientation of muscovite porhyroclasts within the micaceous mylonites. XZ section, location coords. 647.700/116.500, north of Simplon village.

c) K-feldspar porhyroclast which has fractured along cleavage planes. In the continued shear deformation the segments have been bodily rotated, the rotation being accomodated by slip along the fracture planes in the same manner as a row of books which tip over on a shelf. XZ section, location coord. 644.300/119.800, road cutting, main Simplonpass road, opposite Nideralp.


a
0.2 mm
b
0.5 mm
c
0.5 mm

shear is given by several independent criteria (cf. SIMPSON & SCHMID 1984), with remarkable internal consistency.

a) Shear bands

It is commonly observed that strongly foliated mylonites develop a conjugate set of two spaced, overprinting foliations ("shear bands") making an angle of around 30–35° to the mylonitic foliation (e.g. WHITE 1979, fig. 2; GAPAIS & WHITE 1982). In thin section, the foliation is seen to be defined by small shear zones, in which there is a further grain-size reduction, which offset the earlier foliation. The sense of offset on each of the two shear band foliations is opposite and corresponds to an overall extension parallel to the S_m foliation. In shear zones with a well established sense of movement, it is observed that one of the conjugate foliations is always more strongly developed, indeed often exclusively developed; this is the one with the same sense of shear across it as was imposed across the shear zone as a whole (cf. WHITE 1979). Along the Simplon Line, one of the set, with a constant shear sense, is consistently more strongly developed (cf. Fig. 5).

b) Obliquely oriented quartz new grains

Subgrains, new grains and grain boundary bulges in dynamically recrystallizing quartz from monomineralic veins within the Simplon mylonites are invariably elongate and aligned at an angle of between 10° and 25° to the S_m foliation (e.g. Fig. 8a). Empirical observations from other closely studied and well constrained shear zones predict a sinistral sense of movement in Figure 8a (e.g. SIMPSON & SCHMID 1984, fig. 10).

c) Asymmetric mica porphyroclasts and broken feldspars

Mica possesses only a single plane, (001), of easy dislocation glide (e.g. ETHERIDGE et al. 1973). Suitably oriented mica porphyroblasts (the second set of ETCHECOPAR 1974, fig. 8a) deform like books toppling on a bookshelf, to produce asymmetric porphyroclasts characteristic of the sense of shear (Fig. 8b, cf. SIMPSON & SCHMID 1984, fig. 9; BURG & LAURENT 1978, fig. 3; EISBACHER 1970, fig. 8a). Fractured cleavage fragments of feldspar may deform in a similar way (Fig. 8c).

d) Quartz crystallographic fabric asymmetry

Quartz crystallographic fabrics measured from monomineralic veins within the mylonites and mylonitic gneisses show a consistent pattern which departs markedly from orthorhombic symmetry (Fig. 9 and Pl. 2). This is seen particularly clearly in the *c* (0001) and $<a>$ $(11\bar{2}0)$ fabrics. In general, there is a single strong $<a>$ maximum developed between 20° and 30° to the lineation in the XZ plane; the *c*-axes define a single girdle, occasionally with weakly developed vestiges of the missing crossed-girdle segments (e.g. SP16, Pl. 2) Such patterns are common in many deformation zones with a strong shear component. The observed fabric asymmetry in the oriented specimens of Figure 9 and Plate 2 indicates a dextral shear sense (cf. EISBACHER 1970, BOUCHEZ

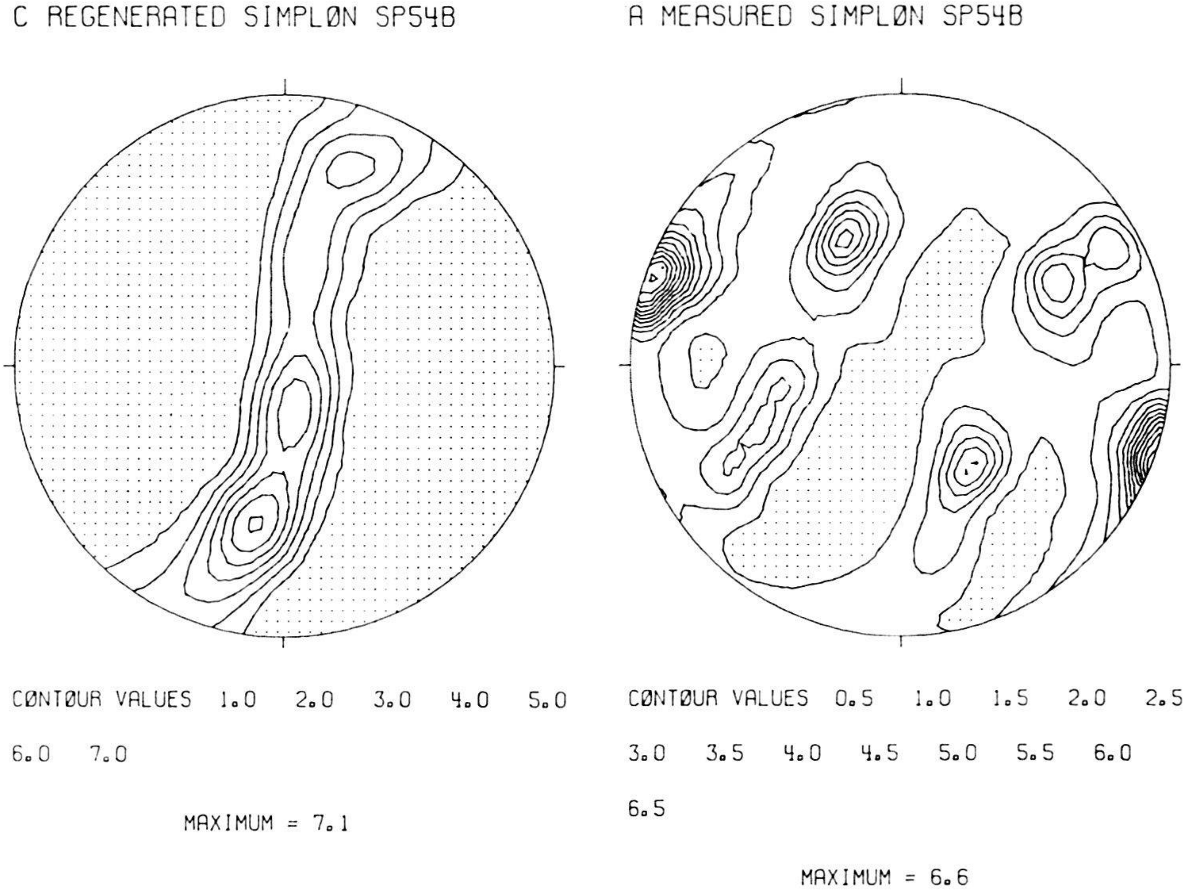


Fig. 9. Contoured upper hemisphere equal area stereoplots of the < *a* > and *c*-axis orientation distribution for specimen SP54B (loc. Simplon Dorf, coord. 647.700/116.300). Orientation of the stereoplots is the same as in Plate 2. The < *a* > pattern was measured directly with a texture goniometer, the *c* pattern regenerated from the ODF, based on measurements of 9 crystallographic planes, following the method of CASEY (1981).

1978, BURG & LAURENT 1978, SIMPSON 1980, BOUCHEZ & PECHER 1981). For the approximately 30 samples so far measured from along the length of the Simplon Line, the observed fabric asymmetry has been fully consistent with the shear sense predictions derived from criteria a, b and c above.

e) Results

The results of all the sense of movement determinations can be summarized by reference to Figure 7: the direction assigned to the lineation vector indicates the displacement direction of the hangingwall (which has been removed for clarity in the diagram) relative to the footwall. The sense of movement in the central NW–SE trending section of the Simplon Line, where the lineation is approximately down-dip on the foliation, is that of a "normal fault".

2. Profile asymmetry and the progressive displacement history

The profile geometry of the Simplon Line in the central portion (Fig. 3) is itself characteristic of a major normal fault zone. As suggested by SIBSON et al. (1979) for the

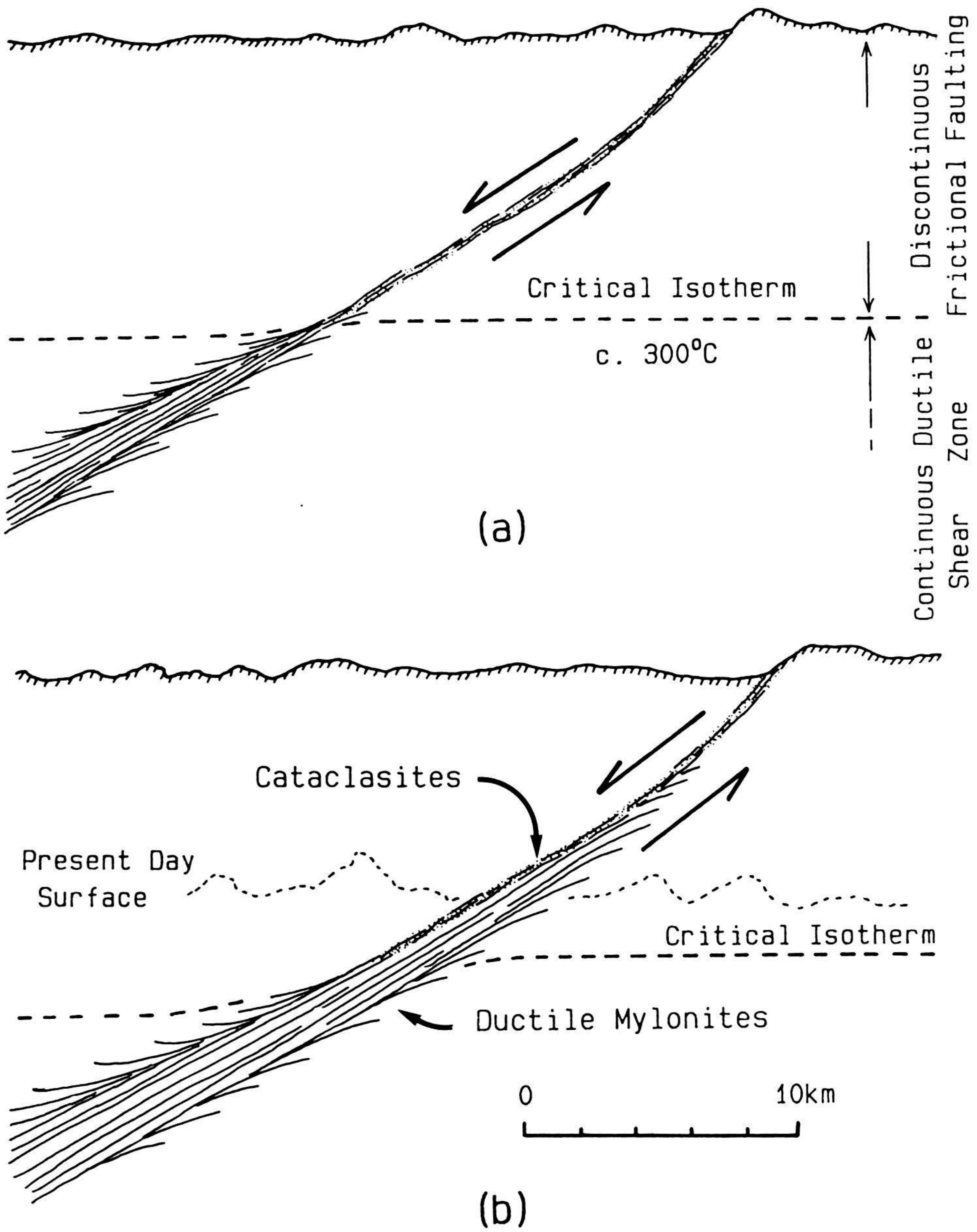


Fig. 10. Simplified representation of the progressive displacement and deformation history in a major normal fault zone (cf. Sibson et al. 1979). a) Initial stage with the development of cataclasites above and ductile mylonites below the critical isotherm. b) The same zone after about 12 km relative displacement.

Alpine Fault Zone in New Zealand, it is possible to interpret the present lateral succession of zones as reflecting the original distribution of rock types with increasing depth below the near surface gouge zone. A simple model for the evolution of such a major fault zone is given in Figure 10. As discussed by Sibson et al. (1979) and White &

White (1984), the critical isotherm marking the gradational brittle to ductile transition probably lies around 300 °C. Progressive displacement on the fault will carry a segment of the broad ductile zone within the upthrown block through the critical isotherm, and further displacement at this level will be accommodated within the cataclasite zone(s). Anastomosing gouge zones may develop within the now passively transported ductile mylonites (cf. Sibson et al. 1979, fig. 2), and clasts of the mylonites may be incorporated within the main cataclasite zone, but overall the broad zone of ductile mylonites will be preserved. The juxtaposition of brittle cataclasites and ductile mylonites will occur within the fault zone over a vertical interval on the order of the vertical component of the fault displacement. With major fault zones, there is therefore a high probability that the present erosion level will lie within this segment.

As the ductile mylonite zone will occur only in the upthrown block, the asymmetric profile geometry provides an indication of the sense of movement. The Alpine Fault Zone in New Zealand, with a significant thrust component, has a generalized profile similar to Figure 11b (cf. Sibson et al. 1979, fig. 2), whereas the Simplon Line corresponds to Figure 11a.

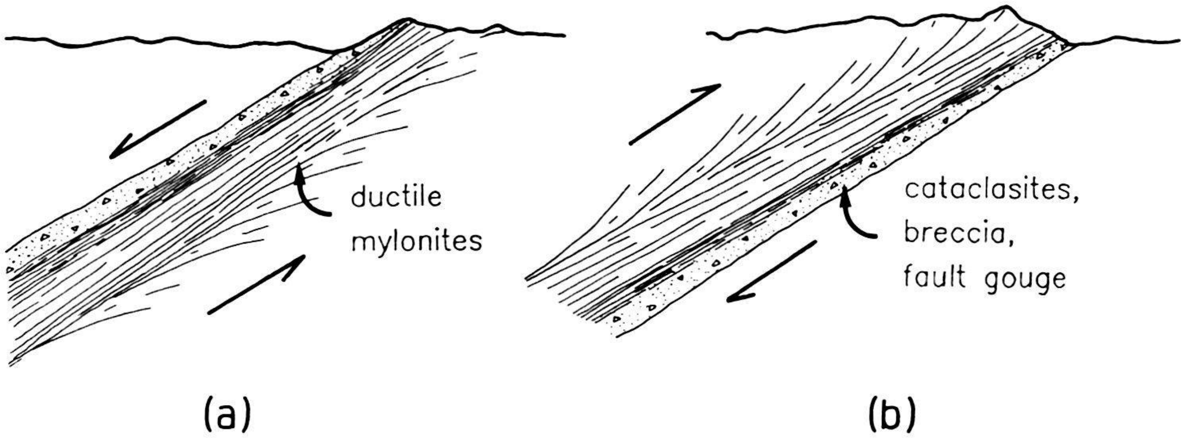


Fig. 11. Asymmetric profiles predicted from Figure 10 for major fault zones with a) normal or b) reverse sense of displacement.

Mineral Deformation and Growth

The Simplon Phase of deformation was a late event relative to the peak of metamorphism. Porphyroblasts, the most common of which is garnet, which presumably grew during the Lepontine event (with a peak around 38–35 Ma, Hunziker 1970, Frey et al. 1976), are obviously older than the S_m foliation, and are commonly fractured and pulled apart during the mylonite-forming event. Under the prevailing metamorphic and tectonic conditions, the mineral components of the deforming rocks show a rather consistent range of behaviour. Quartz is ductile and appears to be the weakest component. The degree of subgrain formation, recrystallization, and grain growth is locally and regionally variable. Within the narrow zone of high strain mylonite between Engiloch and the Passo di Monscera, the size of subgrains and new grains is, in general, small (< 0.1 mm) and incompletely recrystallized, highly elongate ribbon grains are common. Along the continuations northeast of Engiloch and east of the

Passo di Monscera, where the strain appears to be more gradually distributed over a broader zone, recrystallization and exaggerated grain growth are more common, and ribbons are rare. In the field, this transition is seen in the quartz veins as a progression from a flint-like appearance associated with a strong foliation and lineation to a more sugary texture in which the foliation is weak and the lineation often quite difficult to discern. The measured quartz crystallographic textures from these deformed, sugary quartz veins are generally less sharply defined than in the finer grained samples, but have an overall form which is not fundamentally different (Pl. 2). The textural change probably reflects a lower average strain rate associated with the distribution of the finite strain over a broader zone, but may also have been influenced by different ambient conditions (P, T, activity of water, etc.). Diffusion of silica and associated nucleation and growth of new quartz are promoted during the deformation, as evidenced by nonfibrous quartz growth between separating fragments of fractured feldspar.

The coarse white mica and biotite porphyroblasts do not deform easily by dislocation glide, slip being largely restricted to the (001) plane (cf. ETHERIDGE et al. 1973). In rocks where the Simplon overprint is only moderate, most mica grains are strongly bent (marked undulose extinction) and kinked. Increased deformation produces more and more overprinting kink bands, leading eventually to a marked grainsize reduction, with the development of many fine-grained cleavage platelets from the original, larger porphyroblasts. Occasional mica porphyroblasts which are favourably oriented for antithetic slip on (001) (cf. the second cell set of ETCHECOPAR 1974), deform to produce characteristic porphyroblasts with little or no kinking and only slight undulose extinction (Fig. 8b; op. cit., fig. 8a). The grainsize reduction of biotite progresses more rapidly than that of white mica, often resulting in floating white mica porphyroclast "fish" within a "sea" of fine-grained biotite and lesser white mica (Fig. 8b).

Chlorite nucleation and growth apparently occurred before (deformed grains), during (oriented fibres between garnet segments) and most commonly after the main Simplon deformation (undeformed overprinting grains). Feldspar (both plagioclase and K-feldspar) does not deform in a ductile manner during the deformation. Porphyroblasts either remain as rigid relicts or fracture, usually along cleavage planes. Garnet porphyroblast growth was earlier than the Simplon Phase, and may indeed have been partially retrogressed prior to deformation. They are fractured and rotated during the Simplon event. Epidote is a common minor component. Its growth also preceded deformation and it deforms, if at all, in a brittle manner.

Age of movement and amount of displacement

A considerable amount of information on metamorphic mineral and whole rock ages from both sides of the Simplon Line already exists. The problems arise with its interpretation. Jäger and many coworkers (e.g. ARMSTRONG et al. 1966, CLARK & JÄGER 1969, HUNZIKER & BEARTH 1969, WAGNER et al. 1977) have argued strongly that in this region the mineral ages are controlled by the so-called "blocking temperature", which is considered unique (though as yet not very accurately established) for any particular mineral. Minerals which crystallized below their blocking temperature retain a "formation age", whereas those which crystallized above their blocking temperature retain the age at which they eventually cooled through this temperature; i.e. they give a "cooling age". In the general Simplon region, the white mica Rb–Sr, K–Ar, biotite Rb–Sr, K–Ar, and apatite fission track ages do not cluster around a single age (as would be expected for formation ages), but give a consistent series of ages, which may be interpreted in terms of a cooling path. If we accept that such an approach is reasonable, we can construct interpretative cooling paths for two small regions, within the footwall and hangingwall blocks respectively, for the best defined Simplon Line section between Engiloch and Zwischbergen. These are presented in Figure 12. If a particular segment of a cooling path is due to simple uplift with a constant temperature gradient, then as noted by WAGNER et al. (1977), the uplift rate can be calculated by simply dividing the cooling rate by the geothermal gradient. Several points should be noted. Within the footwall block, the cooling rate between the peak of metamorphism (Lepontine Event) and around 20 Ma was apparently very slow, but since this time the rate appears to have been fairly constant at around 20 °C/Ma. The change in slope in most recent times (since ca. 3 Ma) is not well controlled, but may be significant. Considerable uncertainty surrounds the choice of an appropriate temperature for the

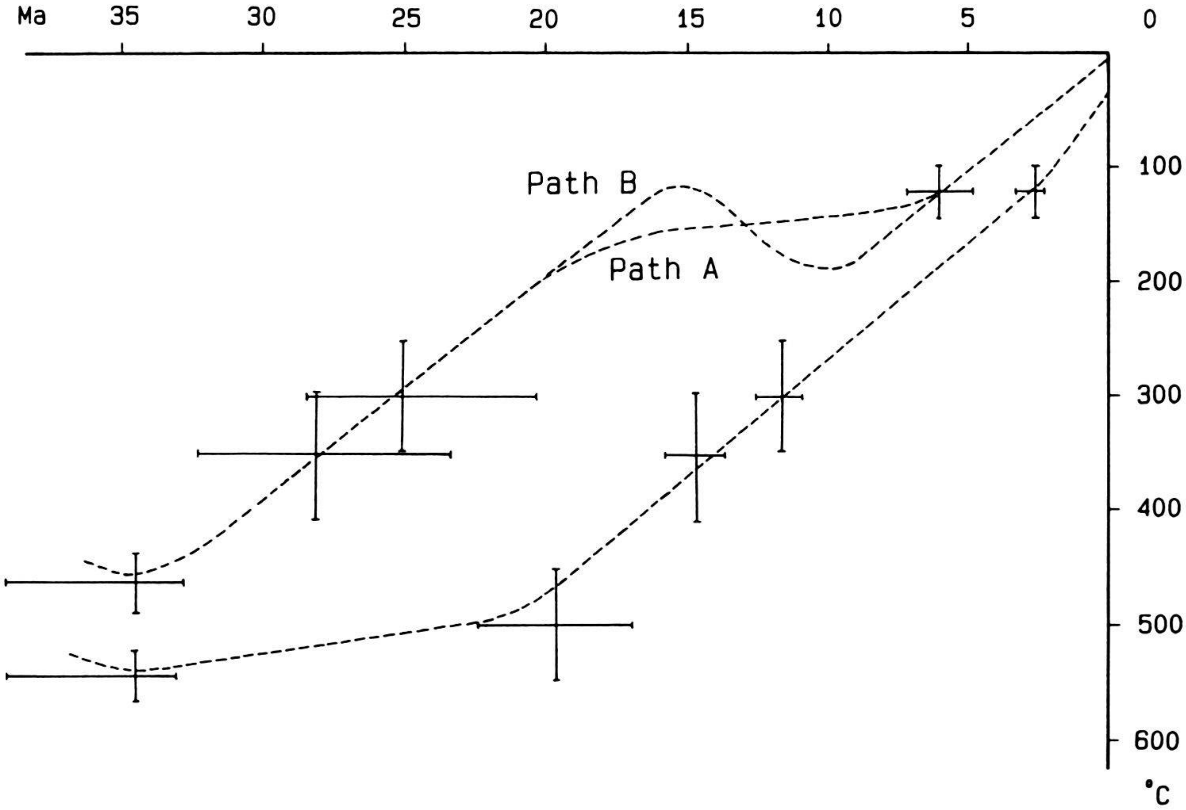


Fig. 12. Cooling paths for two separate regions, one within the hangingwall (upper path) and one within the footwall. The horizontal bars indicate the spread of reported age determinations, the vertical bars are the probable error in the presently accepted blocking temperatures or the uncertainty in peak metamorphic temperatures for formation ages. The isotopic systems and associated blocking temperatures are: apatite fission track (120 °C), biotite Rb–Sr and K–Ar (300 °C), white mica K–Ar (350 °C), white mica Rb–Sr (500 °C). The peak of Lepontine metamorphism is taken to occur around 35 Ma (HUNZIKER 1970), with peak temperatures of ca. 460 °C in the selected hangingwall region (FREY et al. 1976) and ca. 530 °C in the footwall area (FRANK 1983). Sample numbers: hangingwall: KAW 367, 369, 370, 374, 375, 376, 377, 402, 407, 410; footwall: KAW 159, 160, 161, 162, 357, 358. Data from PURDY & JÄGER (1976), JÄGER et al. (1967), HUNZIKER & BEARTH (1969), HUNZIKER (1969), FREY et al. (1976).

present day sampling location. The choice in Figure 12 follows WAGNER et al. (1977) in assigning a mean yearly temperature of 1.5 °C to a hypothetical plane surface of elevation 2200 m, and in using an assumed, regionally constant temperature gradient of 30 °C/km to calculate a temperature for sampling elevations below this surface. This, of course, implicitly assumes that there is no remnant temperature disequilibrium across the Simplon Line. However, the resultant calculated temperature is in good agreement with direct measurements from the nearby Simplon rail tunnel (SCHARDT 1914).

When the cooling paths of the footwall and hangingwall blocks are compared, it is clear that there is a marked divergence in slope between 20 Ma and 6 Ma, the average cooling rates differing in a manner consistent with a "normal fault" displacement across the Simplon Line. The exact shape of the cooling curves is not well constrained by the presently available data, and various interpretative paths can be constructed (cf. examples in Fig. 12). However, as noted in the previous section, the only new mineral growth in the footwall block associated with the Simplon deformation appears to be chlorite and perhaps white mica, suggesting that the temperature during deformation was not very high. At the same time, the extensive ductile quartz deformation in the mylonites and mylonitic gneisses of the footwall block indicates that initially these rocks were above the critical temperature for thermally activated ductile flow in quartz. This is thought to be around 300 °C by SIBSON et al. (1979) and in the range 300–400 °C by ATKINSON (1982). The juxtaposition of cataclasites and ductile mylonites suggests that the footwall rocks passed through this isotherm during the displacement history. The cooling curve for the footwall block during Simplon Line activity should therefore bracket this critical temperature. For a maximum temperature of 450 °C within the footwall block during the Simplon deformation phase, relative movement could not have commenced before 19 Ma, for 350 °C, not before ca. 14 Ma. Control on the timing of the most recent significant movements is not good. Glacial moraine deposits, of probable age around 10,000 years, are clearly continuous across the Line (cf. HANTKE 1983), and the apparent equilibrium of geothermal gradients throughout the region suggests a much longer period of little relative movement. Assuming from the previous arguments that movement across the Line did not commence before 20 Ma, the cooling curves can be used to obtain a rough idea of the total relative vertical displacement. Correcting for the present-day altitude difference in the sampling localities and assuming a constant regional geothermal gradient of 30 °C/km at time 20 Ma, the 205 °C temperature difference between the cooling curves converts to an original elevation difference of ca. 7 km between localities which are now adjacent. For the central segment of the Simplon Line, which dips around 30° (cf. Fig. 3), this corresponds to a displacement parallel to the zone of about 12 km. Examples of two possible cooling paths are presented in Figure 12. These paths would have the following characteristics:

Path A

a) Relative movement between 19 Ma and 6 Ma.

b) Temperature range: hangingwall 170 °C to 120 °C
footwall 450 °C to 190 °C

c) Average relative displacement rate: 0.94 mm/year.

Path B

a) Relative movement between 16 Ma and 9 Ma.

b) Temperature range: hangingwall 120 °C to 190 °C
footwall 390 °C to 250 °C

c) Average relative displacement rate: 1.74 mm/year.

For still shorter periods of relative displacement (and correspondingly faster relative displacement rates), a more and more significant prograde heating of the hanging wall block should result. It must be remembered that the above exercise is entirely dependant on the assumption that the mineral ages represent cooling ages. However the results are quite reasonable, and provide a basis for further work.

Conclusion

The recognition that a ductile imprint associated with the Simplon Line extends for a considerable distance into the footwall block has had several consequences. It has allowed the continuation of the higher strain zone, constrained by the trend of the S_m foliation, to be mapped away from the classic section between Engiloch and the Passo di Monscera. In particular, it can thereby be demonstrated that the Simplon Line continues along the Isorno–Fenecchio River valleys northeast of Domodossola and cannot be joined directly with the steeply-dipping breccias of the Centovalli Fault Zone (cf. MILNES in STECK et al. 1979).

However, several important aspects of the Simplon Phase remain to be resolved. The change in orientation of the lineation L_m from southwest to northeast plunging in the sector from the Passo di Monscera to the northeast into the Isorno Valley is documented but not well understood. Sense of shear criteria indicate movement of the hangingwall relative to the footwall as depicted by the arrows in Figure 7. Further information on the timing of this change in lineation orientation may be provided by future isotopic mineral dating. There are two possibilities which could be tested:

a) Relative movement between the two blocks occurred with a more or less constant movement direction, which was then later folded into the present arcuate pattern. The displaced blocks could have behaved rigidly. The mineral cooling ages should then display a consistent jump across the line, irrespective of the current orientation of the lineation, with the younger ages always in the footwall block.

b) Relative displacement occurred with a curved movement direction. This would have required accommodating deformation within the blocks themselves. The step in mineral ages across the line should then display a more complex pattern related to the orientation of the movement direction.

A third possibility, which is not easily tested, is that the observed lineation no longer parallels the movement direction in the Bognanco, Isorno and Fenecchio Valleys. No abrupt changes in the orientation and nature of the lineation have been observed along this section, but that does not necessarily exclude the possibility that the lineation gradually rotates away from the Simplon Phase incremental extension direction. The continued consistency of the quartz crystallographic fabrics when referred to specimen coordinates dependent on this lineation would, however, argue against such a change (Pl. 2).

A curved lineation pattern within a major displacement zone is not unique to the Simplon region. In particular, the geometrical relationships observed along the Simplon Line in the western Lepontine Alps are very similar to those reported for the Cordilleran metamorphic core complexes from western North America: a structural discontinuity separating a weakly overprinted hangingwall block from an extensively mylonitized footwall block, with the stretching lineation in the mylonites describing an arcuate or domal pattern (e.g. CRITTENDEN et al. 1980). In these examples, the present-day doubly plunging orientations of the main lineation across the gneissic domes also reflects an "up and over" movement of the hangingwall block, similar to that described by the present-day geometry of the Simplon Line northeast of Domodossola. The origin of this domal or arched shape is still a matter of discussion and conjecture. However, SPENCER (1984) has recently presented an interesting and plausible model, in which the arching is explained as isostatic uplift due to the crustal thinning associated with displacement on a major, low-angle normal fault zone. In this model, the updoming would occur after considerable movement on the fault and would quickly make continued, consistent movement along the entire fault zone unfavourable. The predicted age patterns across the Simplon Line would therefore follow a) above.

The other important aspect of the Simplon Line still to be resolved is its integration into a consistent regional structural and tectonic history of the Pennine Zone.

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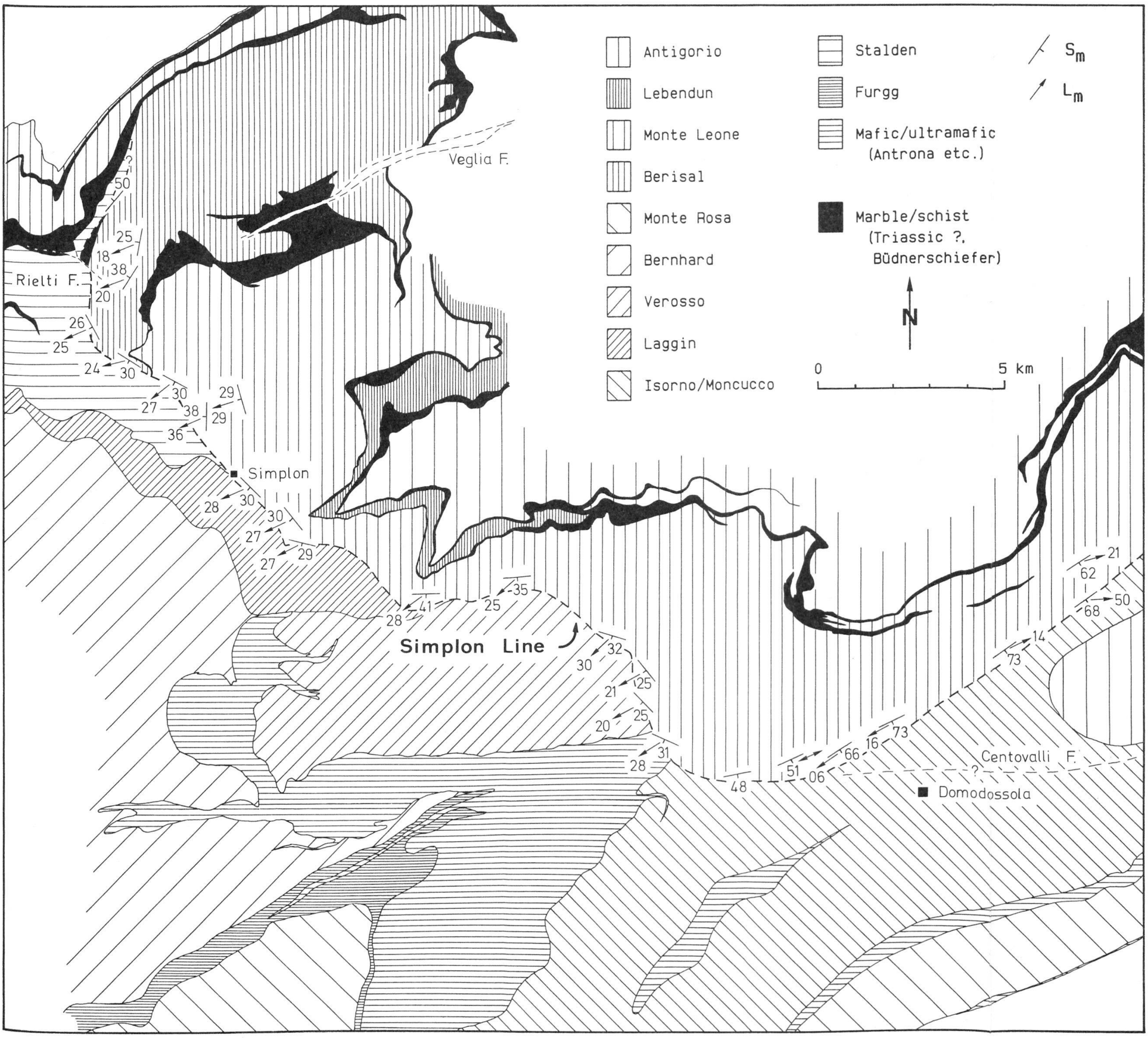
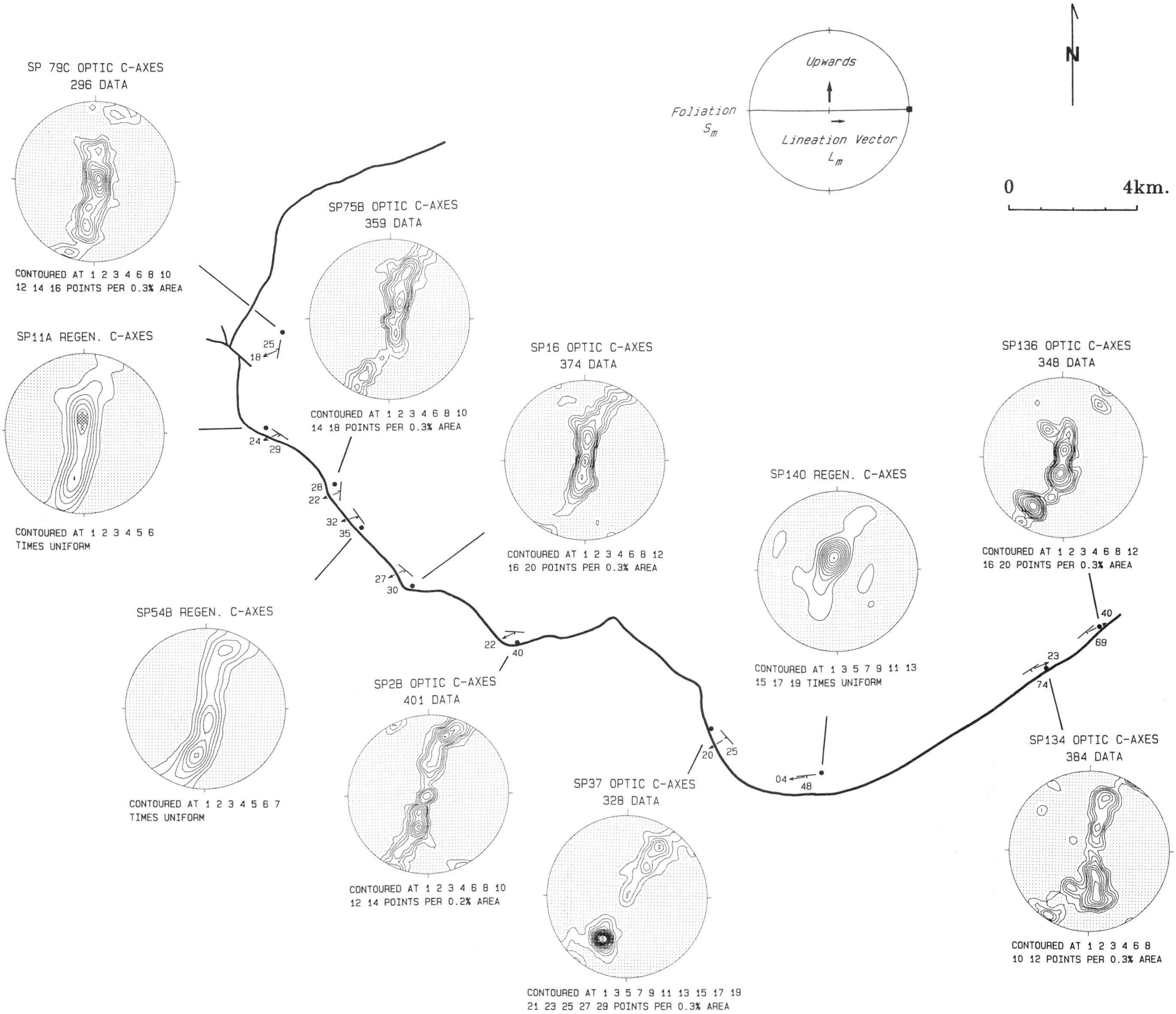


Regional geological map of the Simplon region. For a detailed description of the tectonic units, see MILNES et al. (1981).



Contoured quartz c-axis orientation diagrams for samples along the studied length of the Simplon Line. Note the consistent asymmetry to the patterns, indicating a dextral sense of shear from this particular viewpoint. Equal area, upper hemisphere stereoplots, S_m vertical left-right, lineation vector (cf. Fig. 7) horizontal, directed to the right. Plots with a stated number of data points were measured optically, the others were regenerated from ODF's as in Figure 9.