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Early deformation of Ultrahelvetic mélanges in the Helvetic nappes (Western Swiss Alps)

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Abstract—The Ultrahelvetic mélanges represent an important clue for understanding the Tertiary Alpine orogeny, particularly in the external Alps of western Switzerland. The remarkable architecture of the Upper and Lower Ultrahelvetic units is classically explained by an important phase of gravity sliding and orogenic sliding accompanied by the formation of chaotic complexes and olistostromes (wildflysch), a phenomenon called 'diverticulation'. A structural analysis reveals evidence for early phases of deformation, despite strong overprinting by late Alpine deformation. These early fabrics are observed in foliated pebbly-mudstone (a tectonic breccia, part of the mélange matrix), in disrupted flysch sequences and in dark shales. They attest to brecciation related to a complex pattern of veining, with several generations of calcite cement and several stages of failure during lithification, and they show the important role of fluids during the deformation. They present numerous analogies with the fabrics described in association with thrusts in accretionary prisms.

Considering the tectonic fabrics and the relations among the infra-Prealpine mélanges, a tectonic model to explain the emplacement of the Ultrahelvetic units is proposed in which the décollements developed in three weak levels. The early fabrics evolved within a basal thrust formed in a final stage of the Valaisan subduction.

INTRODUCTION

THE Alpine chain has a complex collisional history beginning in the Middle Cretaceous. Both sedimentological and structural evidence attest to the diversity of the Alpine orogeny. Unfortunately, late Tertiary deformations have made it very difficult to establish the paleogeography of the Tethys (particularly its north margin) and the early evolutionary features such as accretionary prisms and their related deformations. Hence, there are still several basic problems of paleogeography and tectonic evolution in the Alps. For instance, the paleogeography (e.g. Trümpy 1980, 1988) remains uncertain, particularly concerning possible oceanic domains like the 'Valaisan', because there are many rootless nappes (e.g. the Prealpine nappes, sometimes called 'exotic blocks', Figs. 1 and 2) and because of numerous zones with chaotic complexes, slivers and blocks separating nappes (e.g. the Ultrahelvetics, the wildflyschs of the Prealps, and several zones in the Penninic Units, cf. Spicher 1980). The importance of these exotic blocks and related chaotic complexes was recognized by Schardt (1898). However, their origin has remained very controversial ever since, particularly in the external Alps. These chaotic complexes, also called 'wildflysch' or mélanges, are often considered as frontal, thrust-related olistostromes (e.g. Kerckhove 1975, De Lepinay 1981), although other authors have proposed a purely tectonic genesis (e.g. Bayer 1982, Hsü & Briegel 1991, Jeanbourquin *et al.* 1992).

To determine the significance (gravitational or tectonic?) of these mélanges and their role in the orogeny, this paper presents a brief summary of the mélanges in the western Alps and then focuses on fabrics (outcrop- to sample-scale) of mélange matrix in the Lower Ultrahelvetics. This approach has permitted me to place new constraints on the wildflysch interpretation and kinematics. The western Alps of Switzerland provide an excellent profile (Escher *et al.* 1993) for discussing the interrelationships between Alpine kinematics and the mélanges of the north Tethys margin, owing to the presence of rootless nappes (the Prealpine nappes) and because of the combination of high relief and significant plunge of the fold axes. Consequently, this profile allows us to compare the weakly metamorphosed (mostly diagenesis and anchizone, Mosar 1991) sequences of the Prealpine nappes with their metamorphic equivalents in the Penninic Units.

MÉLANGES IN THE WESTERN SWISS ALPS

The mélanges in the western Alps can be distinguished by the presence or the absence of ophiolites, their relationships with flysch and their tectonometamorphic setting. They crop out either in the Penninic nappes, in the Prealps, or in both (Figs. 1 and 2).

Mélanges with ophiolites from the Piemont–Ligurian Ocean (1′ *of Fig.* 2)

The Upper Penninic nappes (Tsate, Zermatt-Saas Fee and Antrona zones, Escher *et al.* 1993) contain mélanges characterized by metaflysch and oceanic sequences which represent the remains of the Piemont–Ligurian ocean. Following the ideas of Treves (1984) developed in the Apennines, Stampfli & Marthaler (1990) interpret these zones as mid-Cretaceous accretionary prisms. Relics of Cretaceous high pressure–low temperature (HP–LT) metamorphism are indeed present in some lithologies (see Stampfli & Marthaler 1990 for a review). However, the overprinting by Tertiary deformation has strongly modified the relationships between the units. Consequently, our understanding of the Cretaceous deformation is still poor.

The Prealpine equivalent unit (1 of Fig. 2) of the Upper Penninic nappes is the Get nappe (e.g. Escher *et al.* 1993). It contains mélanges of flysch and ophiolites in which deformation is weak. No HP–LT paragenesis is recorded in the Get nappe. Parts of the other upper Prealpine nappes, the Dranse and the Simme nappe also contain mélanges with ophiolites and abyssal sediments (Caron 1972, and my own observations).

Mélanges of the Préalpes médianes and Brèche nappes (6 of Fig. 2)

The stratigraphic sequences of these Prealpine nappes are terminated by thrusts. From the base, we observe the following succession (Caron *et al.* 1989): Upper Cretaceous–Lower Tertiary hemipelagic sediments; Late Eocene flysch (Préalpes médianes only, ?Priabonian); wildflysch; the upper Prealpine nappes, for instance the Dranse nappe. These mélanges (also called wildflysch or flysch à lentilles de Couches-Rouges) contain blocks and slivers of the underlying hemipelagic sediments (mainly 'Couches-Rouges'), rarer clastic fragments from the overriding nappes and blocks from flysch turbidites. The matrix is a dark schist with locally a well marked scaly fabric. The deformational microstructures are sometimes well preserved with veins and patterns of shear bands. No important metamorphism is recorded. Penninic equivalents of these wildflyschs are present in the Middle Penninic nappes (Marthaler 1984) where they are affected by Tertiary epizonal metamorphism.

Basal mélange related to thrusting of the Prealpine nappes is frequent; either it is 'infra-Prealpine' wildflysch (Homewood & Caron 1982), or possibly it bounds the Zone Submédiane (Weidmann *et al.* 1976). Finally, some mélanges of the Prealps may be associated with strike-slip fault zones (e.g. Jeanbourquin *et al.* 1992). These contain various blocks derived from the Prealpine nappes and a matrix of schist or gypsum.

Mélanges with ophiolites from the Valaisan Ocean (2 of Fig. 2)

Mélanges with greenstones and serpentinites are preserved in the Lower Penninic units. The 'Versoyen' of the Sion–Courmayeur zone presents a mélange facies with black schists rich in manganese and blocks of greenstones and serpentinites (Jeanbourquin & Burri 1991). Together with the thick and continuous clastic sequence of the Sion–Courmayeur zone (Flysch trilogy), they may represent a Late Cretaceous–Early Tertiary accretionary prism (Ackermann *et al.* 1991, Jeanbourquin & Burri 1991, Stampfli 1993). Nonetheless, a detailed map of the Simplon–Brigue zone (Burri *et al.* in press) and data from Antoine (1971) reveal a remarkable geometry in which the whole sequence is upside down (Jeanbourquin & Burri 1991). Consequently, we have to expect some complex kinematics in this zone. A

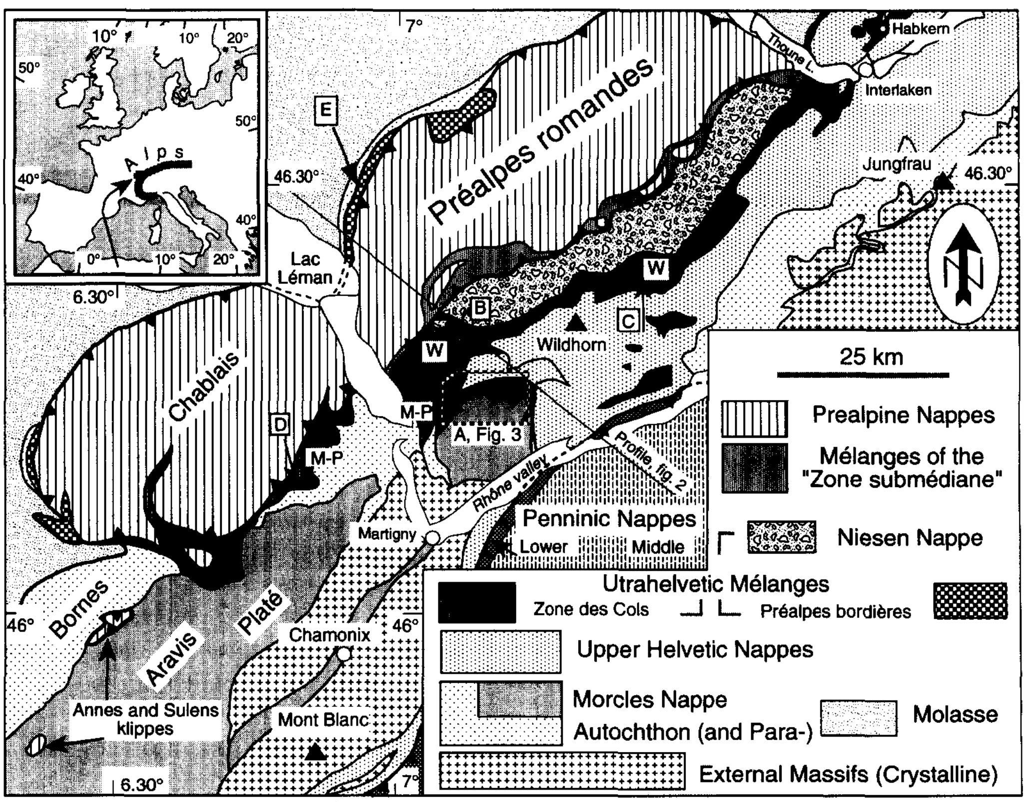


Fig. 1. Tectonic map of the Helvetic units and Prealps in Haute-Savoie (France) and western Switzerland; A = Frontal part of the Morcles nappe, M-P = Ultrahelvetic supra-Morcles and Parautochthon (D = in the Val d'Illiez, E = in the "Préalpes bordières"), W = Ultrahelvetic supra-Wildhorn (C = Rawyl-Lenk area), B = Ultrahelvetic supra-Diablerets.

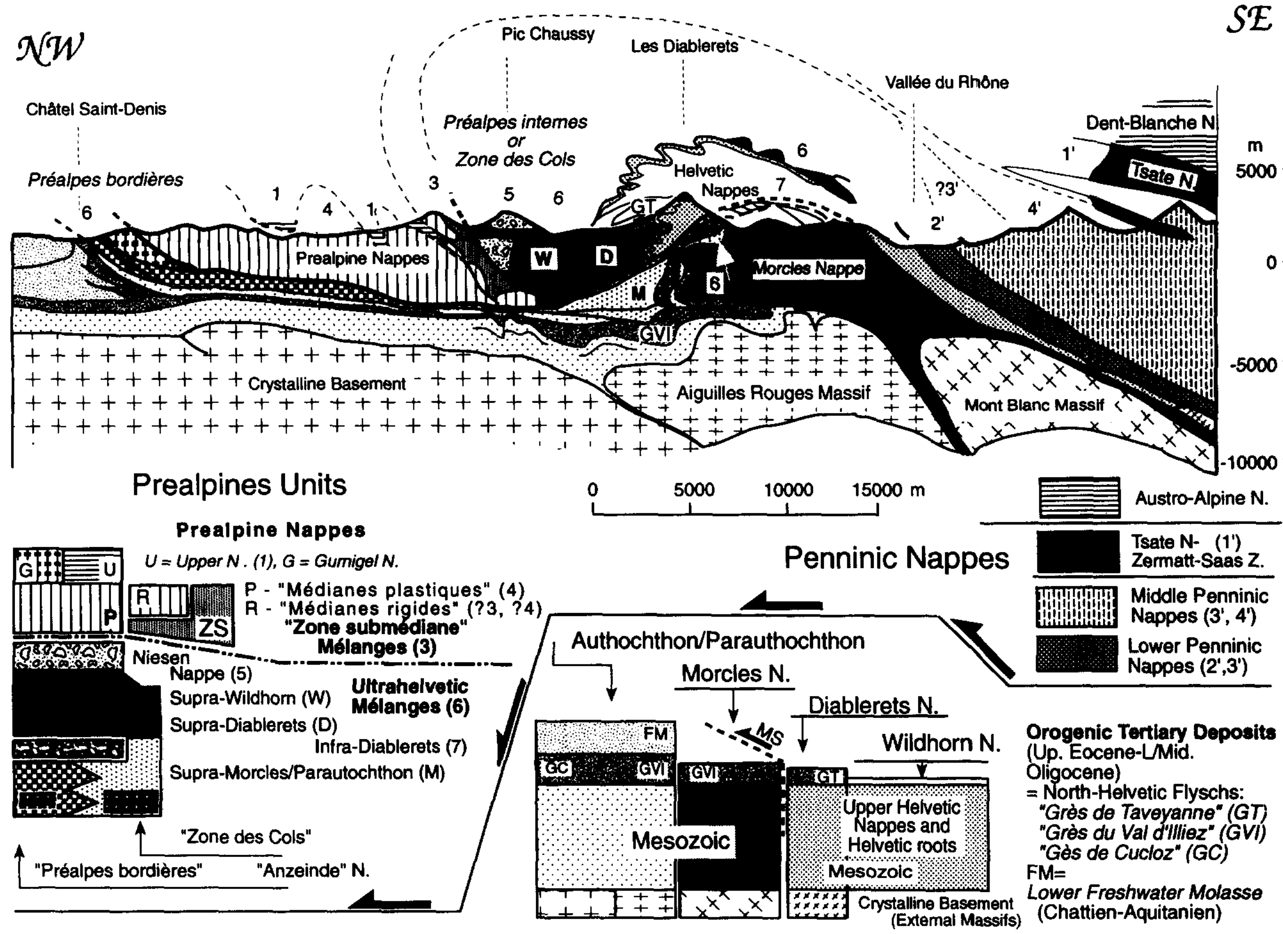


Fig. 2. Cross-section of the Alps in western Switzerland (line of section given in Fig. 1). The numbers 1–7 are references for the mélanges discussed in the text (modified from Escher *et al.* 1988).

few high pressure–low temperature parageneses are observed in the Versoyen and neighboring units; their age is possibly Late Cretaceous–Lower Tertiary (Schürch 1987, Ackermann *et al.* 1991, Burri *et al.* in press). Equivalents of the Versoyen mélange and the flysch trilogy are absent in all Prealpine nappes, but atypical lithologies may be present in the Zone Submédiane (Weidmann *et al.* 1976).

Mélange of the Zone Submédiane (3 *of Fig.* 2) *with rare greenstones*

The Zone Submédiane (ZS) is a remarkable mélange of various blocks in a matrix of fine clastics or gypsum outcropping poorly between the Prealpine nappes and the Niesen nappe (Weidmann *et al.* 1976). The lateral extent of the ZS is not defined; it may have equivalents in the Val d'Illiez (mélange infra-brèche or Upper Ultrahelvetics, Jeanbourquin *et al.* 1992). It contains a large variety of block lithologies, possibly suggesting sedimentary sequences from the Pre-Piedmont, Briançonnais, North Valaisan to Helvetic domains and some greenstones possibly from the ?Valaisan ocean. The metamorphism is very low grade, and the matrix is strongly deformed. The age of the rocks forming the blocks, and possibly also the age of the matrix, ranges from Triassic to Eocene. The relationship of the ZS to the Penninic nappes is unclear. We can tentatively postulate that it represents parts of the Valaisan domain (Trümpy 1988), and that it can be correlated with the Lower Penninic nappes, although characteristic facies of the flysch trilogy of the Sion–Courmayeur zone have not been described here.

The nature of the lower contact of the ZS and the Niesen nappe is well known, whereas that of the upper contact with the Prealpine nappes is not clear. Weidmann *et al.* (1976) suggest that parts of the Prealpine nappes, the 'rigides', should be included in the Zone Submédiane. Their work suggests that the Zone Submédiane mélanges are related to a major thrust, the sole of the Prealpine nappes, and that they likely resulted from fragmentation and mixing that occurred along the décollement of the Prealpine nappes in being transported to their present-day position. Unfortunately, because of the poor outcrop quality, this mélange and its kinematics remain enigmatic.

Niesen nappe and infra-Niesen mélanges (4 *of Fig.* 2)

The Niesen nappe, a thick flysch sequence of Late Cretaceous and Early Tertiary age derived from the external Valaisan (Jeanbourquin & Burri 1991), lies over a complex zone of mostly Tertiary flysch units and Lower Mesozoic rocks (McConnell 1951, De Raaf 1934). Escher *et al.* (1993) call this the infra-Niesen zone, but they do not formally define this new unit, and their profile suggests that the infra-Niesen zone also includes a large part of the Upper Ultrahelvetics. The relationship of this mélange to the underlying Ultrahelvetic units is unclear because of many uncertainties regarding age and lithology. Hence, for practical reasons and because of many similarities with the Upper Ultrahelvetics, I tentatively group the Niesen nappe and its infra-mélange with the Upper Ultrahelvetic units.

Mélanges of the Ultrahelvetics (6 *of Fig*. 2)

The Ultrahelvetic 'nappes' lie between the Helvetic units and the Prealpine nappes. They represent a complex zone of chaotic units, slivers and small nappes derived from Mesozoic and Cenozoic sequences of the South Helvetic (Badoux 1963) and external Valaisan domains (Homewood 1977, Jeanbourquin & Burri 1991). They can be observed in the 'Préalpes bordières', in the 'Zones Des Cols' and over the Wildhorn nappe (Figs. 1 and 2). Based on the present-day position in the Zone Des Cols and the composition of the slivers, the Ultrahelvetics are divided into Upper Ultrahelvetics and Lower Ultrahelvetics (Badoux 1963). The Upper Ultrahelvetics mostly contain small nappes of Triassic–Lower Jurassic sequences and minor 'block-in-matrix' fabric, whereas the Lower Ultrahelvetics consist of a chaotic complex with slices of younger sequences (Upper Jurassic–Lower Tertiary). These small nappes, sometimes called *diverticules* (Lugeon 1943), are piled up in inverted stratigraphic order, but each sliver or nappe consists of upright stratigraphic sequences. Postulating that all these slivers originated from the same sequence, Lugeon (1943) and Badoux (1963) have proposed a mechanism of submarine gravity sliding, comparable to a 'game of leapfrog' ('jeu de saute-mouton' in France), to explain this arrangement. They called it *diverticulation* (see Debelmas & Kerckhove 1973, Lemoine 1973).

The metamorphism of the Ultrahelvetic units is weak. A recent study of fluid inclusions by Mullis (1989) emphasized the importance of the separation between the Lower and Upper Ultrahelvetics, the Upper Ultrahelvetics having recorded higher temperatures. Together with the basal slices of the Niesen nappe, the Upper Ultrahelvetics indeed record anchizonal and even epizonal conditions with retrograde metamorphism (Frey *et al.* 1980, Mullis 1989), whereas the Lower Ultrahelvetics display only prograde diagenetic conditions (Mullis 1989, Jeanbourquin 1991b).

The kinematics in much of the Ultrahelvetics is closely related to the emplacement of the Helvetic nappes. Because the Ultrahelvetic units were folded and deformed passively with the Helvetic nappes, Lugeon (1901) first proposed that their emplacement was earlier. Each Helvetic nappe has its own Ultrahelvetics. This is particularly true for the Lower Ultrahelvetics; hence Mercanton (1963) first proposed the following nomenclature: Ultrahelvetic-Morcles, Ultrahelvetic-Diablerets and Ultrahelvetic-Wildhorn (see map of Badoux *et al.* 1990). In a similar manner (Fig. 2), the terms supra-Morcles/Parautochthon, supra-Diablerets and supra-Wildhorn have sometimes been used to specify the Ultrahelvetic mélanges (e.g. Jeanbourquin *et al.* 1992).

The *Upper Ultrahelvetics* are only present in the Zone de Cols and they consist of several slivers—called 'nappe de Bex-Laubhorn', 'nappe d'Arveyes', and 'Meilleret and Höchst nappes or flyschs'. These units are characterized, respectively, by huge volumes of Triassic evaporites (locally with halite) with a few Liassic limestones, by an ubiquitous sequence of 'Aalenian' black shale with Dogger lithologies and by Tertiary flysch. The Upper Ultrahelvetics include a few bands of dark flysch showing 'block-in-matrix' texture and rare blocks of hemipelagic Cretaceous limestone (e.g. zone du Rard, McConnell 1951, Badoux *et al.* 1990). The flysch facies together with the Mesozoic sequences suggest that these units were derived from the external Valaisan domain where the flysch deposition transgressed over a variably eroded basin (Badoux 1963, Homewood 1977, Jeanbourquin & Burri 1991). Hence, we have included the Niesen nappe in the Upper Ultrahelvetics.

The evaporites and overall the Aalenian shale represent important décollement zones in which other lithologies are frequently mixed (Furrer *et al.* 1956). This is particularly clear southwest of the Rhône Valley (Jeanbourquin *et al.* 1992) where the Aalenian shales divide the Ultrahelvetics over large distances. The main consequence of this particular décollement is that the Upper Ultrahelvetics cannot be systematically associated with a specific Helvetic nappe, unlike the Lower Ultrahelvetics. This suggests that the kinematics of the Upper Ultrahelvetics is closely related to the Prealpine nappes.

The *Lower Ultrahelvetics* consist of small nappes of Upper Jurassic to Upper Cretaceous strata (Anzeinde nappe), of Upper Jurassic strata with Lower Tertiary flysch (the Sex-Mort nappe) and of wildflysch (or mélange) with blocks of all the lithologies present in the slivers (the Plaine-Morte wildflysch or nappe) (see Badoux 1963, 1967, or Jeanbourquin & Goy-Eggenberger 1991, lower suprahelvetic mélange). The Lower Ultrahelvetics are often interpreted as olistostromal deposits above the North Helvetic flysch sequence (e.g. Homewood & Caron 1982 or Caron *et al.* 1989).

As the characteristics of the Lower Ultrahelvetics (also recently called supra-Helvetic melanges, e.g. Jeanbourquin *et al.* 1992) are very constant over the Helvetic nappes, and as the Anzeinde and Sex-Mort nappes are very similar, I am going to use the supra-Morcles Ultrahelvetics as reference units.

The supra-Morcles Ultrahelvetics (*Fig*. 3)

Above the North Helvetic flysch, the supra-Morcles mélange consists mostly of Lower Ultrahelvetics, with a lower chaotic unit (corresponding to the 'Plaine-Morte nappe') and an upper big slab of Mesozoic limestones (Oxfordian–Senonian, corresponding to the Anzeinde nappe). This is overlain by a mélange unit called the 'Infra-Diablerets mélange' (Jeanbourquin 1991a), poss-

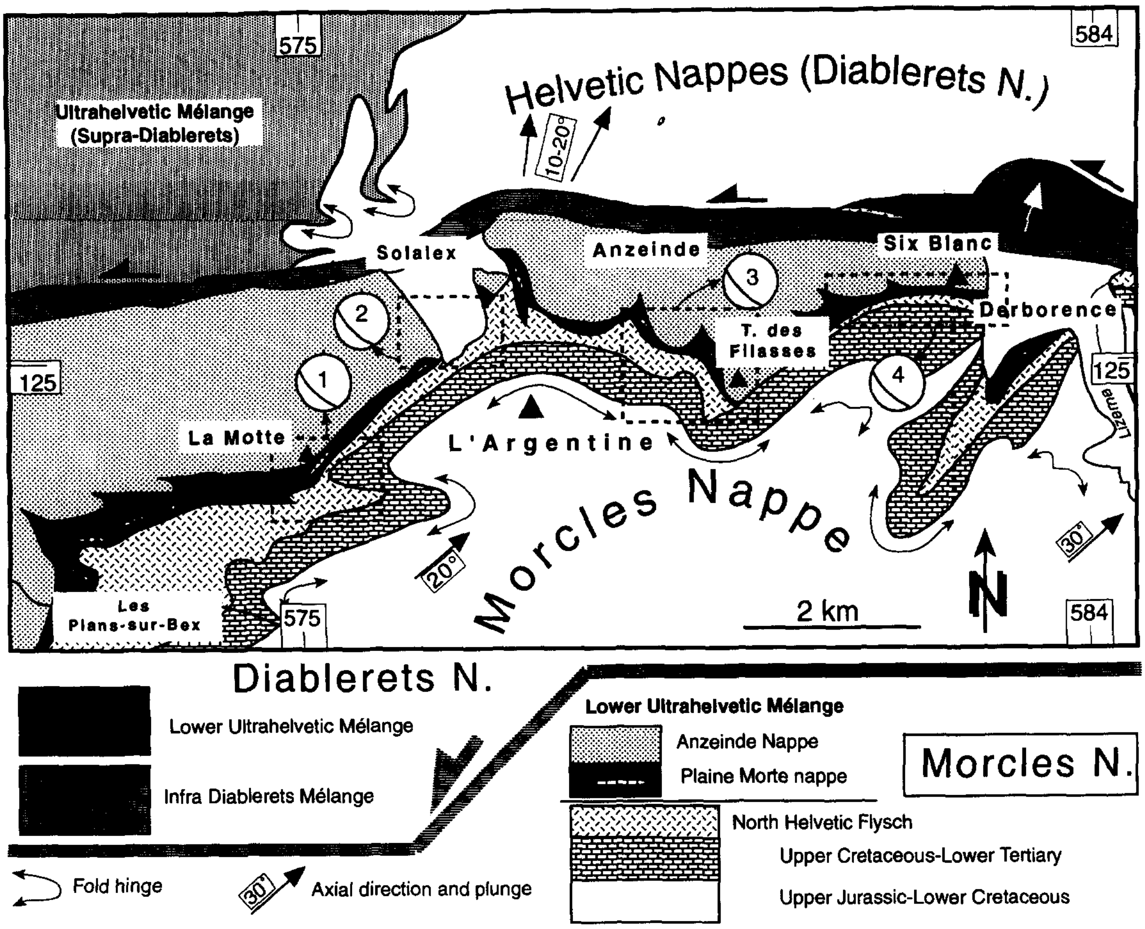


Fig. 3. Tectonic map of the frontal part of the Morcles nappe (rectangle A, Fig. 1) with the supra-Morcles Ultrahelvetics (geographic data from the Swiss Cartographic Atlas); locations for the structural data presented in Fig. 4 are shown by dashed rectangles and numbered 'stereograms'. The half arrows above the infra-Diablerets mélange indicate thrusting of the upper Helvetic nappes. The duplex structure of the infra-Diablerets mélange is from Jeanbourquin (1991a).

ibly a few remnants of the Zone Submédiane (Bovonne klippe and rocks in the Avançon river, Badoux *et al.* 1990) and finally the Upper Helvetic nappes (Fig. 2).

Contrary to common belief, the basal contact of the mélange with the North Helvetic flysch formations ('Grès de Taveyanne', 'Grès du Val d'Illiez' and 'Grès de Cucloz') is tectonic, as demonstrated in a number ways (outcrop relationships, arguments based on the biostratigraphy, sedimentology and petrography; see Jeanbourquin & Goy-Eggenberger 1991, Jeanbourquin *et al.* 1992).

The chaotic unit contains large blocks (maximum size around 100 × 400 m) of Upper Jurassic–Cretaceous limestones, and Tertiary marlstones (Upper Cretaceous blocks being the most common), sandstones and conglomerates in a more or less scaly matrix (see Gabus 1958 or Jeanbourquin & Goy-Eggenberger 1991 for a detailed description). All these limestones have an affinity with the rocks of the South Helvetic domain, whereas the sandstones, commonly attributed to the Ultrahelvetics, have an affinity with external Valaisan flyschs as proposed by Jeanbourquin & Burri (1991). Blocks of Tertiary conglomerates (disorganized gravelly-sands) with immature crystalline and shelf carbonate components occur frequently. Within the mélange, the sandstones often occur either as monomictic zones of completely disrupted flysch sequences, or as a significant component of the mélange matrix. Besides this broken flysch type, the matrix is a dark schist with a fine, closely-spaced, wavy or anastomosing cleavage, sometimes with shiny surfaces. It locally resembles the scaly fabrics but, it generally tends to be more planar. In weakly deformed zones, it is possible locally to recognize lithologies like: (1) calcareous muddy breccias (between gravelly mud and muddy gravel, Figs. 5a–f); (2) flysch sequences, frequently fine facies B–D, rarely facies A (Pickering *et al.* 1989), siliceous sandstones, more or less disrupted, broken-flysch (Fig. 5g); and (3) variably veined and sheared scaly silty-clay (very common), with intact dark marls in some places (probably lenses which cannot be clearly differentiated from the matrix, Fig. 5h). These lithologies display signs of early deformation.

EARLY DEFORMATION IN THE CHAOTIC COMPLEXES OF THE LOWER ULTRAHELVETICS

Early deformational fabrics in mélanges (possibly the phase ?Plaine-Morte of Burkhard 1988) are observed in the Lower Ultrahelvetic units. Their recognition is based on their cross-cutting relationships with structures of the various phases of the Helvetic deformation

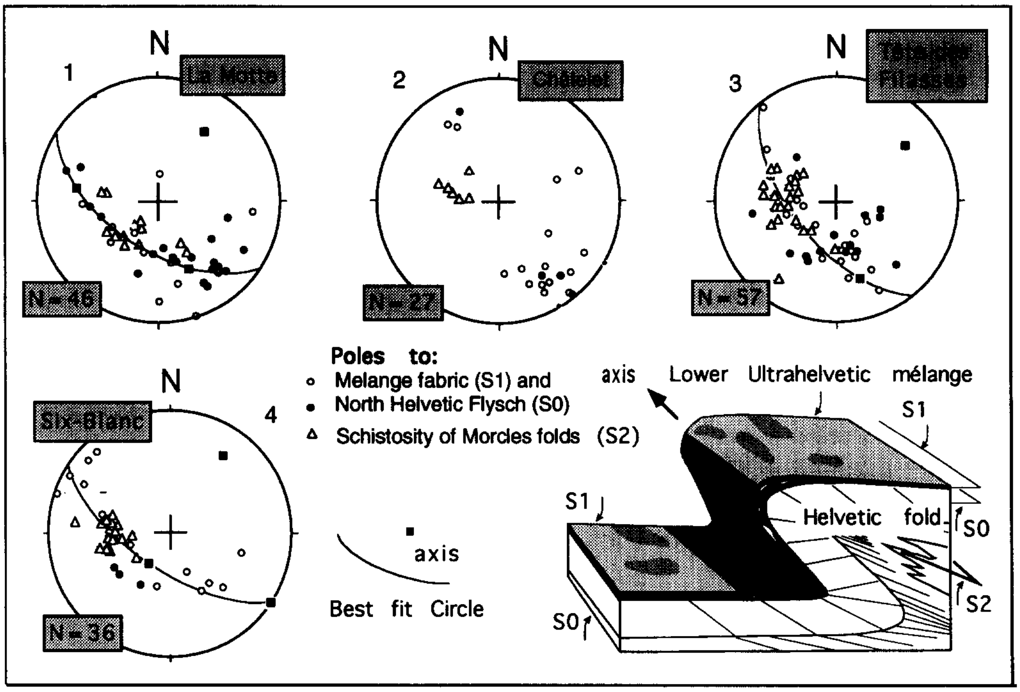


Fig. 4. Relationships between the planar fabrics of the Helvetic deformation in the Morcles nappe (?'Phase Kiental') and the early fabrics. Stereograms are equal-area, lower-hemisphere projections. The bedding in the flysch (S_0) and the foliation in the mélange (S_1) are approximately parallel. They are folded by the Morcles folds (best-fit circles).

(Prabe, Trubelstock and Kiental phases of Burkhard 1988). Due to the good and continuous outcrops of the Lower Ultrahelvetics related to the Morcles nappe, the descriptions herein are focused on that area (Fig. 3). Relationships in other Lower Ultrahelvetic mélanges are similar and some examples from these have been included to show the wide distribution of the early deformation.

Since the Ultrahelvetics were deformed together with the Helvetics, the Helvetic 'axial-surface' slaty cleavage (Ramsay 1981) is a significant fabric for the understanding of deformation in the mélange. It is marked by alignment of mineral grains and pressure-solution seams, and its intensity and characteristics vary through the nappe pile. Generally, all early planar fabrics of the Ultrahelvetic mélanges (sedimentary or tectonic) are transposed parallel to this main Helvetic slaty cleavage, except in particular localities. The mélange matrix may indeed show locally a pre-existing fabric demonstrated by a foliation in breccias with oriented clasts, veins and cleavage-parallel veins. This pre-existing fabric has been preserved:

—in 'pressure shadows' around blocks, and in the hinges of small secondary folds in the Ultrahelvetic mélanges (Diablerets-Wildhorn);

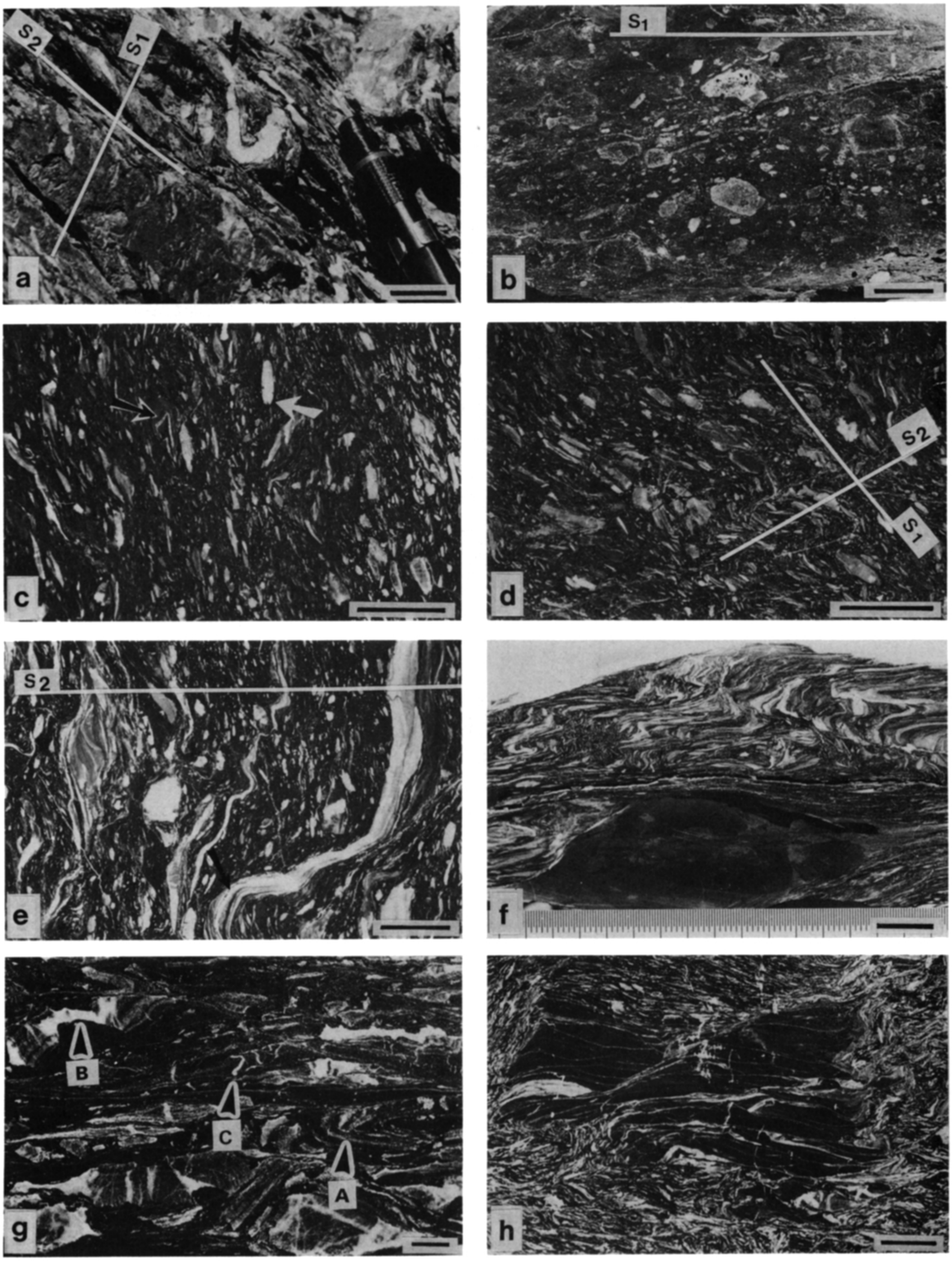
—in frontal folds of the Morcles nappe where the competent Urgonian and Lower Tertiary layers have shielded the neighboring flyschs and mélanges from the main Helvetic penetrative deformation (Fig. 4);

—in many places in the 'Préalpes bordières' where the deformation is less intense.

Early fabric marked by a foliation in muddy-breccias

Outcrop observations of the mélange matrix often reveal a granular texture intimately associated with a very fine anastomosing cleavage. Generally, only sawn sections permit the observation of well-developed brecciation structures (Figs. 5c–e), but careful field inspection sometimes permits direct observation of these

Fig. 5. Illustrations of the early meso-scale deformation in the Lower Ultrahelvetic mélanges; all scale bars are 1 cm. (a) Relations between axial-plane cleavage of the Morcles nappe (S_2) and the foliation (S_1) of pebbly mudstone in an outcrop of the supra-Morcles Ultrahelvetics (locality 4, Fig. 3). Note the folded calcite vein (arrow) with an axial surface parallel to the S_1 foliation. (b)–(d) Sawn sections of gravelly muds in the supra-Morcles mélange ('La Motte and Solalex areas'). (b) Weak preferred orientation of the clasts in a breccia of possible sedimentary origin, with slight pressure solution and some shear veins (cf. also Fig. 6b). (c) & (d) Well marked foliation defined by the association of cleavage and flattened clasts in tectonic pebbly mudstone of location 1, Fig. 3; barrel-shaped element with necking (white arrow), folded calcite vein (black arrow), S_1 = early orientation of the mélange fabric, S_2 = axial-plane cleavage of the Morcles nappe (see Fig. 4). (e) & (f) Sawn sections of gravelly mud of tectonic origin in the supra-Diablerets and supra-Wildhorn Lower Ultrahelvetics respectively. (e) Foliated muddy-gravel. Note the very flattened clasts of mudstone with veins parallel to the clasts (black arrow = calcite fiber laminate infill) and phacoidal structures. The white line indicates the orientation of the cleavage of the Helvetic deformation (supra-Diablerets mélange, 'Alpes de Chaux'); (f) Shaly phacoids and laminates of micritic mud and calcite veins, sheared and folded by a subsequent deformation event, possibly the Helvetic deformation (supra-Wildhorn mélange, 'Ammertengrat', locality C in Fig. 1). (g) Sawn section of broken flysch with significant shear-planes (supra-Morcles Ultrahelvetic). Carbonate cementation, possibly associated with shearing, began early as attested by the poorly defined bedding-parallel zones within the sandstones. These are sometimes folded (A). More discrete veins appeared later to accommodate boudinage (B); a few are folded (C). (h) Sawn section of the strongly veined shaly matrix containing a preserved chunk of shale (supra-Morcles mélange). Each white area is a broken piece of calcite vein.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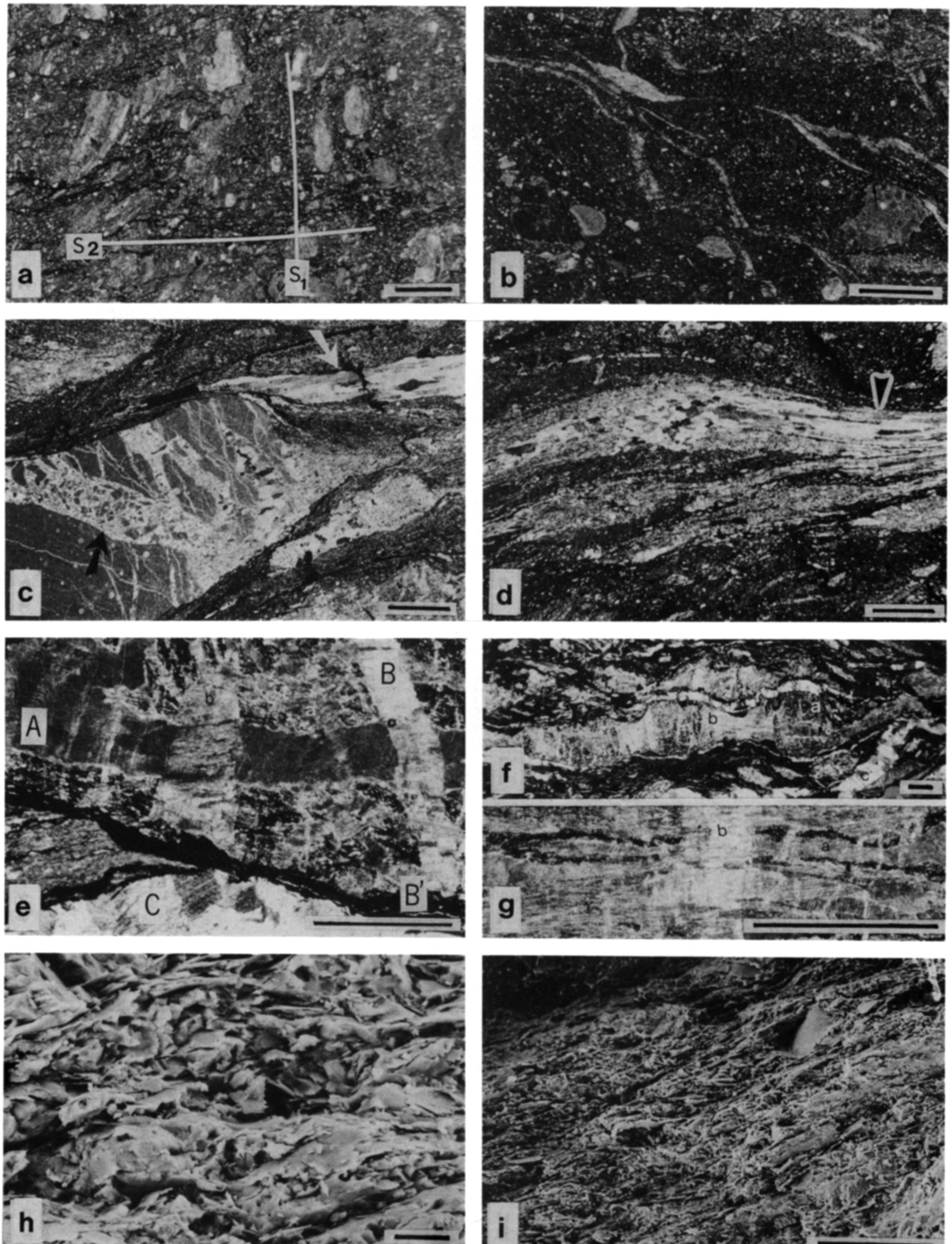
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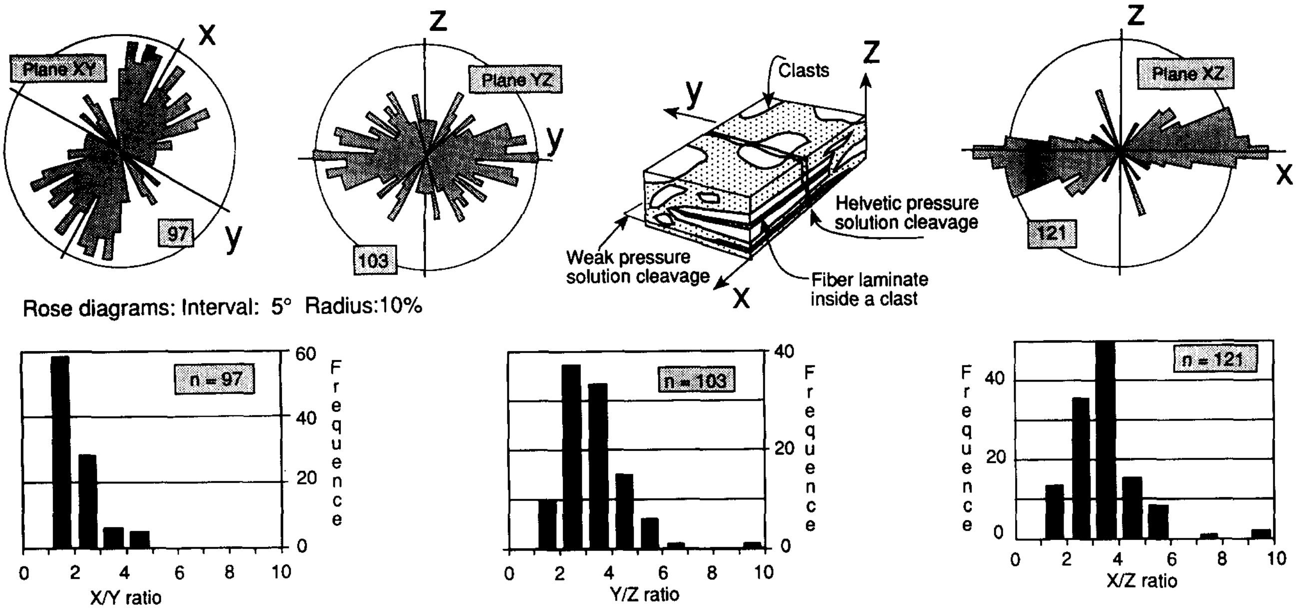

Fig. 7. Foliated pebbly mudstone: preliminary shape analysis of clasts at location 1 in Fig. 3.

breccias (Fig. 5a), for instance at the localities marked in Fig. 3. The contact of these brecciated zones with the ubiquitous dark shaly matrix of the mélange seems to be gradual. The breccias are disorganized gravelly muds with a matrix of sandy mud (Qz<10%) and fragments of micritic limestone. Both clasts and matrix contain a few foraminifera suggesting an Early Tertiary age or possibly a Middle to Late Eocene age (R. Wernli written communication). The facies is comparable to the 'Fleckenmergel' (Herb 1988) or, perhaps the 'Leimerenkalk' (Bayer 1982). Despite some uncertainty about the ages, the most reasonable inference is that these lithologies were derived from Lutetian–Priabonian rocks (= Fleckenmergel) of the South Helvetic domain (Herb 1988, Jeanbourquin & Burri 1991). In a few places, some gravelly muds with isolated fragments of shelf carbonates have been observed (Fig. 5b).

The grains and pebbles are mostly angular, and their shape is rectangular, showing local swelling or necking at the edges (Fig. 5c). Diamond-shaped or phacoïdal elements, sometimes with asymmetrical tails (Fig. 5f), are common on every scale, but they are more frequent among the large blocks. A few blocks several centimeters long (up to 1 m) and less than one centimeter thick, are of contorted laminated mudstones, including thin calcite veins parallel to the laminations (Fig. 5e). Most clasts have a flat shape in surfaces perpendicular to the cleavage (*XZ* and *YZ* planes of Fig. 7), and are fairly equidimensional in surfaces parallel to the cleavage. This microscale flattening, together with the cleavage and the shape and orientation of blocks, define the characteristic well-displayed foliation of the mélange (S_1 in Figs. 4, 5 & 7). This foliation was folded during the Morcles nappe deformation and is clearly overprinted by the axial-plane cleavage S_2. These relationships are shown in Figs. 5(a) & (d) and the fabric due are plotted on stereograms (Fig. 4).

As the fragments are veined Eocene hemipelagic sediments and the matrix is fine terrigenous sediment of almost the same age, these breccias most likely were derived from the shearing of a sequence of interlayered biogenic oozes and very distal turbidites, each lithology being more or less lithified during the subsequent deformation. Alternatively, they could represent former bedded hemipelagites mixed with very mobile silty slurries.

Broken flysch

The Tertiary clastic deposits, mainly carbonate sandstones, are often disrupted into blocks, commonly of phacoïdal shape or as elongate lenses and slabs. These broken formations often present a 'block-in-matrix' structure forming monomictic outcrops within the mélange. Folds may be present inside the blocks (Fig.

Fig. 6. Photomicrographs (optical and electron) of the early deformation in the Lower Ultrahelvetic mélanges; (a–f) scale bars are 1 mm, polarized light; (h) scale bar is 10 μm; (i) scale bar is 100 μm. (a) Tectonic pebbly-mudstone with veined micritic clasts in the supra-Morcles mélange. S_1 = early foliation (subvertical), marked by the elongation of clasts and a clay fabric in SEM; S_2 = pressure-solution cleavage (subhorizontal), axial planar to the Morcles nappe. (b) Gravelly mud of a possible sedimentary origin (see, Fig. 5b) affected by shear veins or slickensides with fibrous calcite infill, showing the beginning of formatCon of fiber laminate in the flats and antitaxial veins in the steps. (c) clasts and veins in a tectonic pebbly mudstone with an early extensional veining and a dilatational breccia (black arrow, hydraulic fracturing?) inside the element and fiber laminate within the muddy matrix (white arrow). (d) Fiber laminate (arrow) in the laminated mud shown in Fig. 5(e). (e) Relationship among veins in a shaly part of a broken flysch. A—First, early dirty sparitic vein commonly associated with diffuse fiber laminate within the sandstone and a three-dimensional network evolving to; B—a second generation of similar veins associated with a three-dimensional network; B′—Syn- to post-B pressure solution; and C—transparent late veins. All crystals have an imprint of Helvetic deformation. (f) & (g) Details of pinch and swell structures and veins in a broken flysch, same legend as in e. (h) & (i) SEM microtexture of the tectonic pebbly mudstone (Fig. 5c) showing at least one, and probably two preferred tectonic orientations of the clay particles, possibly due to shearing.

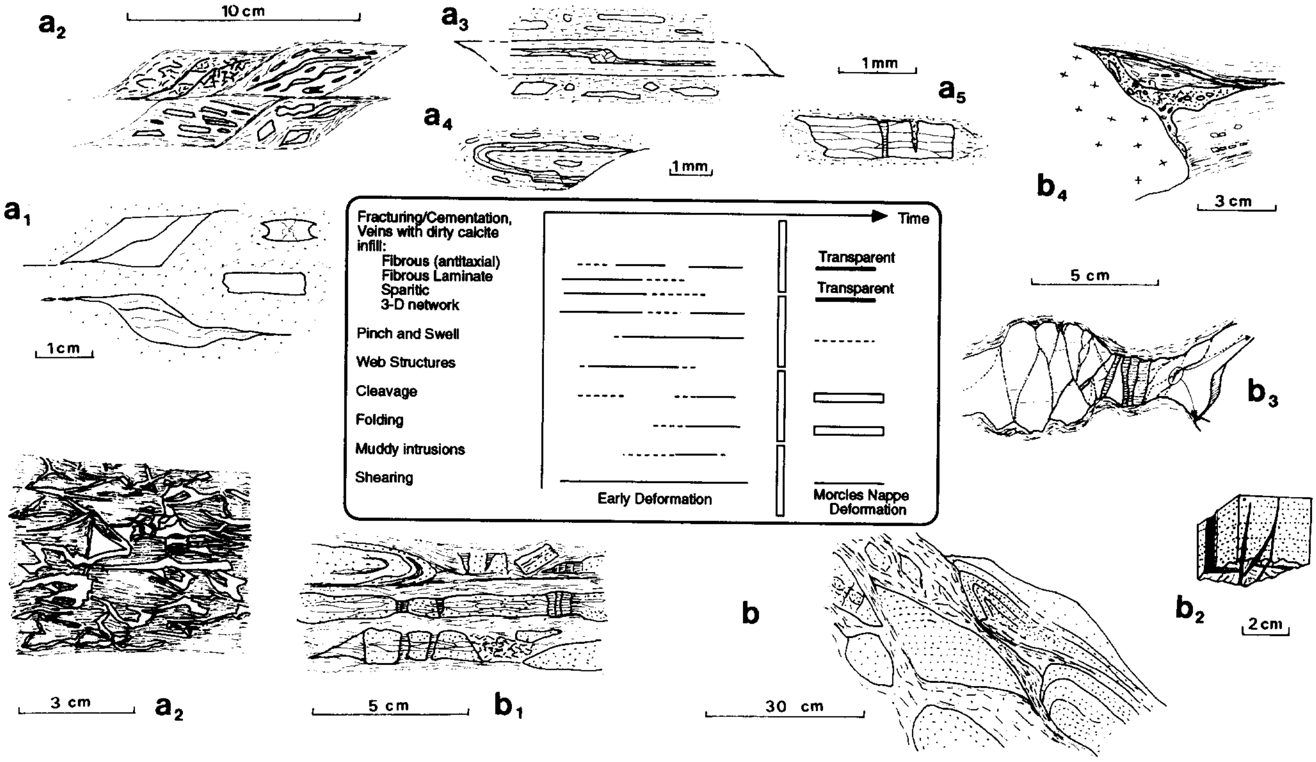

Fig. 8. Sketch of the chronology of the different micro- and meso-scale structures of the early deformation in the lower Ultrahelvetics, drawn from photographs or directly from samples, (a) in muddy-breccias and (b) in broken flysch. (a0) Deformation partitioning to explain the local preservation of the brecciated fabric during the early deformation in the tectonic pebbly mudstone and in the shaly lithologies (supra-Diablerets Ultrahelvetic). (a1) Shapes of the elements in the pebbly mudstones; (a2) two-dimensional sketch of three-dimensional network of calcite veins in shale, some showing a fibrous infill perpendicular to the wall; (a3) 'fibrous laminate' (calcite) within a laminated mud element; (a4) folded 'fibrous laminate' within the matrix; (a5) fractured element of 'fibrous laminate' with a secondary infill of fibrous calcite and silty clay. (b) Broken flysch with 'fibrous laminate' as vein/cement components inside the beds, locally folded, followed by classical extensional veining (antitaxial). (b1) Broken flysch with folded and phacoidal features; (b2) mud injections associated with calcite veins in a coarse sandstone; (b3) web structures cross-cutting small early calcite veins responsible for 'en croûte de pain' structure on the bed surface and late fibrous veining; (b4) cataclastic tail resulting from the disaggregation of a granite pebble in a zone of strong shear, the pebble being extracted from a gravelly sand channel.

8b). The crude preferred orientation of elongate grains and blocks, together with the cleavage in the shaly lithologies define a foliation (S_1). As in the pebbly-mudstones, S_1 pre-dates the Morcles nappe deformation.

Although the broken sandstones can occur as mélange matrix, they are usually restricted to relatively monomictic areas, probably representing dislocated larger slices or lenses. Locally, it is often possible to delimit areas with consistently upright lenses alternating with areas of upside-down blocks, probably resulting from the shearing of a folded sequence.

Boudins, phacoïds and 'pinch and swell' structures are generally associated with vein development (Figs. 5g, 6f and 8b1). Only rare instances of 'soft-sediment' deformation have been observed (e.g. Fig. 8b). Small mud-filled dykes (Fig. 8b2) are rare, probably because they have been obliterated by the strong subsequent deformation. Dykes cutting across calcite veins (Jeanbourquin 1991a) indicate a great differential lithification of sandstone lithologies and possible liquefaction of silty clays. Micro- or mesoscale observations of calcite infillings suggest progressive cementation during shearing, explaining this brittle behavior.

Probably due to the poor outcrop quality, evidence of cataclasis in sandstones is rare. Discrete shear zones, very similar to the 'web structures' in mélanges (Cowan 1981, Byrne 1984), have been recorded in a few blocks. Locally, some blocks have peculiar centimeter-thick hard crusts (Jeanbourquin 1991b). The crusts are finer grained so they likely result from a combination of shearing and cementation. Isolated blocks of graywackes showing very strong cataclastic fabrics occur at the base of the mélange. As they have the andesitic composition and texture of the Taveyanne Sandstones (Lateltin written communication 1987), they provide a good argument for strong shearing of consolidated North Helvetic graywackes at the contact between North Helvetic flysch and supra-Morcles mélange.

Chaotic facies related to the sole of the Anzeinde nappe

The Anzeinde nappe is a large slice of Oxfordian to Senonian marlstones and limestones. The basal alternation of Argovian limestones–marls and Oxfordian Marls is often strongly disrupted. The Argovian limestones show a complete range of structures from slightly disturbed strata with dominant pinch and swell structures, to a 'block-in-matrix' structure with abundant blocks. Locally, the dark Oxfordian shales contain blocks of Jurassic and Cretaceous limestones (Gabus 1958). As this 'block-in-matrix' formation resembles the underlying chaotic unit, the contact looks gradual, suggesting a progressive mixing of two similar lithologies.

Calcite veins are very rare in the shaly matrix, suggesting a weaker influence of the fluids during deformation of this unit than the pebbly-mudstone. The whole matrix exhibits a complex pattern of shear planes (comparable to *S–C* structures). All these facts suggest a relatively dry deformation.

CEMENTS AND VEINS RELATED TO THE EARLY DEFORMATION

Significantly early veining in the Ultrahelvetic mélanges can be observed in the clasts and the matrix of the mudstone breccias (Figs. 5a–f and 6a–d), in blocks and schists of the 'broken flyschs' (Figs. 5g and 6e & f) and in shales (Fig. 5h). Unlike the situation in the Helvetic structures (Durney & Ramsay 1973, Ramsay 1981), the vein patterns in the Ultrahelvetic mélanges do not allow a systematic structural approach. Nevertheless, study of localities where deformation is weak allows worthwhile observations concerning the early events of veining and cementation. The recognition of vein generations is based on cross-cutting relationships, crystal habit and cathodoluminescence fabric. Transparency of the crystals, related to the number of tiny inclusions, varies significantly: early cements are very 'dirty' (milky), whereas successively younger infillings become increasingly cleaner (Fig. 6e & f). Similar observations have frequently been made in accretionary complexes, where they are interpreted as the result of progressive fluid-related lithification of clastic sediments (e.g. Byrne 1984, Vrolijk 1987, Orange *et al.* 1993). Due to the subsequent brecciation, the relationship between veining in the matrix and veining in the clasts is hard to establish on the meso-scale and regional scale. A cathodoluminescence (CL) study has shown that the CL fabric for all dirty crystals (homogenous dark yellow) is different from that in the later transparent veins (brighter yellow, homogeneous). The crystals mostly have an undulatory extinction and/or twin lamellae resulting from subsequent (Helvetic) deformation.

Veining in mud breccias

A striking feature of veining in the pebbly-mudstones is the occurrence of relatively narrow (less than 1 mm thick to several centimeters long) discrete veins or veinlets, more frequent within the clasts (Figs. 5a, d & e and 6a & d) than in the matrix (Figs. 5a and 6b & c). These veins are generally parallel to the long dimensions of the clasts, and possibly sub-parallel to the original bedding in some clasts. Furthermore, the veins often exhibit a very peculiar type of calcite infilling: in thin section crystals are very elongate (Figs. 6b, c & d) parallel to the wall of the vein; *c*-axes are not necessarily parallel to this elongation. Some of the matrix veins exhibit small steps with oblique opening and fibrous antitaxial calcite (Durney & Ramsay 1973) (Fig. 6b). Folded veins present 'stretched crystals' in the hinge. This vein pattern fits very well with what has been described as 'fiber laminate' by Elliott (1976). Hence, we propose to relate these veins to early shearing events associated with 'pressure-solution slip' and diffusion along sliding surfaces characterized by discrete, hydrous films.

Blocky calcite or fibrous infills perpendicular to the vein walls are secondary. They occur mainly in extensional vein systems perpendicular to the bedding; elsewhere they occur in association with microbrecciation, resembling dilatation breccias ('hydraulic fracturing', Fig. 6c).

Early cements in broken flysch

Veins are volumetrically important (locally up to 50%). They are associated with boudinage or sometimes pre-date it. Early veins are sometimes folded (Fig. 5g). The extensional boudinage is mostly accommodated by veins growing in pinch structures (Figs. 5g and 6e & f). The veins are generally perpendicular to the bedding surface or rarely oblique. The vein infill is usually dirty fibrous calcite. In thinly bedded broken flysch (centimeter thick), strong deformation led to the development of very long (a few centimeters) trails of calcite (B, Fig. 5g) that record at least two major episodes of failure and infill as shown by two distinct generations of dirty fibrous calcite.

'Fiber laminate' is also well developed in the sandstone blocks where tabular crystals of dirty calcite (subparallel to the bedding) invade the sand, and sometimes the whole micro-bed (Figs. 6a, f & g). This crystal habit indicates progressive lithification in which cementation happened under differential stress. Then, better delimited veins may develop.

Further extensional fracturing in more brittle sediment is recorded by discrete veins (perpendicular to the bedding) with a classic fibrous infill (Fig. 6f); infills are generally antitaxial, possibly caused by hydraulic fracturing (Ramsay & Huber 1983, p. 242) and crystals are somewhat cleaner than those of the first generation (Fig. 6f). These veins are also associated with a network of fine veinlets. A three-dimensional network of very fine veins is developed in some places (Fig. 6e), generally in finer-grained sediment, suggesting that fracturing associated with low differential stress and high fluid pressure may have occurred during cementation.

Veining in shales

Inside relatively homogeneous parts of silty or shaly lithologies (matrix or blocks?), veins are developed as complex, pervasive and diffuse three-dimensional networks of calcite, as discrete veinlets or as isolated veins deposited along weak surfaces of the scaly fabric (Fig. 5h). Cross-cutting relations show several episodes of brittle failure and cementation. Crystal habit and microfabrics are analogous to those in the broken sequences.

Vein-related cleavage

Pervasive shearing surfaces (Figs. 5f & g) with discrete shear bands (comparable to *S–C* structures) and Riedel structures are common, parallel or subparallel to the foliation. However, as these surfaces are easily reactivated by the later deformation events in the late fold hinges; their correlation with the early deformation is often uncertain.

In mud breccias, a weak penetrative cleavage has only been detected in outcrop and in a few thin sections. The slabs or the sawn surfaces do not clearly show a cleavage parallel with the elongation of the clasts; only the later S_2 pressure solution cleavage of the Morcles nappe is evident. Nevertheless, when the rock is broken, it disaggregates into small chips (a few millimeters in size) with a scaly shape and locally shiny and striated surfaces, possibly corresponding to an original scaly fabric. Backscattered electron microscopy (BSEM) images of polished thin sections and scanning electron microscopy (SEM) images of broken chips indicate two main orientations of clay particles and micas with some sigmoidal flakes (Figs. 6g & h). The earlier one may have resulted from the compaction processes (or tectonic processes), but the second is clearly related to a reorientation of the clay flakes. BSEM imaging also clearly shows that the micrite of elongate microclasts is affected by pressure solution. Small-scale folds are frequent in the pebbly-mudstone (Figs. 5a & c). Their axial-surface is parallel to the foliation and they are related to the pressure-solution cleavage. Moreover, BSEM reveals a few folded dissolution surfaces.

Finally, it is important to mention a local weak cleavage affecting the upper few meters of the North Helvetic flysch. As it is subparallel to bedding, and as it is cut by the axial-surface cleavage of the Morcles nappe, it is related to the foliation (S_1) of the supra-Morcles mélange.

SIGNIFICANCE OF THE MELANGÉ MICROFABRICS AND INTEGRATION INTO THE STRUCTURAL HISTORY OF THE WESTERN ALPS

Muddy breccias (pebbly mudstones) and chaotic complexes of the Lower Ultrahelvetics are generally considered as olistostromes or parts of olistostromes (e.g. Caron 1966, De Lepinay 1981, Weidmann *et al.* 1982, Lateltin 1988, Caron *et al.* 1989). However, most of the observations point towards a tectonic origin, even though the distinction between 'tectonic' and 'sedimentary' is somehow tricky in the mélange problem (e.g Cowan 1985). Generally, two questions have to be answered: what is the style of deformation during the mélange fragmentation and mixing, and what are the forces responsible: tectonic of gravitational? Mélange microfabrics in the Lower Ultrahelvetics give good information to help answer the first question whereas integration of the Ultrahelvetic units into the large-scale framework gives possible elements to answer the second.

Significance of the mélange microfabrics

Among the microfabrics, the veins are very informative. Whatever the lithologies, veins are volumetrically important before and during every step of the deformation, particularly before and during the fragmentation and mixing of the wildflysch. Thus the role of fluids and the amount of fluid flowing through the sediments were important. Calculations performed by Berner (1980) and Larue *et al.* (1989) show that a defined volume of calcite infilling needs a volume of fluid 10^6–10^4 times greater to precipitate it. This is particularly true for the earliest veins (Figs. 6c & d and f & g), unrelated or less related to pressure-solution cleavage. Later stages of veins are often associated with strong pressure-solution cleavage; they can be explained by in situ diffusive mass transfer (plate IA of Jeanbourquin 1991a). The development of veins subparallel to the bedding or subparallel to weak pressure-solution surfaces indicates that the fluid pressure was probably high, close to the lithostatic stress.

The occurrence of veins in the clasts and the matrix show that the sediment was consolidated and deformed (e.g. folded veins, Figs. 5a, c & g) when the fragmentation occurred. Hence, the muddy breccias (or pebbly mudstones) are tectonic breccias (or tectonic pebbly mudstones) occurring during non-coaxial deformation of hemipelagic or clastic sediments combining layer-parallel extension (Figs. 5c & g), shear zones (Figs. 5f–h and 6b, g & h) and weak pressure solution. Rare injection structures (Fig. 8) and a few 'soft-sediment' features demonstrate that the lithification was locally incomplete during that time. The mechanisms of deformation are diffusive mass transfer and particulate flow (Borradaile 1981, Knipe 1989). I believe that cataclasis was of very minor importance, even though grain-breakage is difficult to evaluate in these lithologies.

Because of the importance of veining, I dismiss the olistostrome hypothesis to explain wildflysch formation. The records of veins in slumps and olistostromes are indeed rare and they generally present infills of mud (e.g. Cowan 1982, Ritger 1985). On the other hand, recent studies of the Ocean Drilling Program (ODP) provide interesting results about veining in shallow décollement zones and thrust zones of accretionary prisms (Barbados: Behrmann *et al.* 1988, Brown & Behrmann 1990, Vrolijk & Sheppard 1991). The fabrics in core described by these authors compare very well with the tectonic fabric of the pebbly mudstone described here, as well as with the pattern of syntectonic calcite veins (pervasive, diffuse networks, discrete veinlets and folded veins). The sedimentary facies of the parent sediment (mudstone) are also similar. Comparisons of the wildflysch microstructures with structural

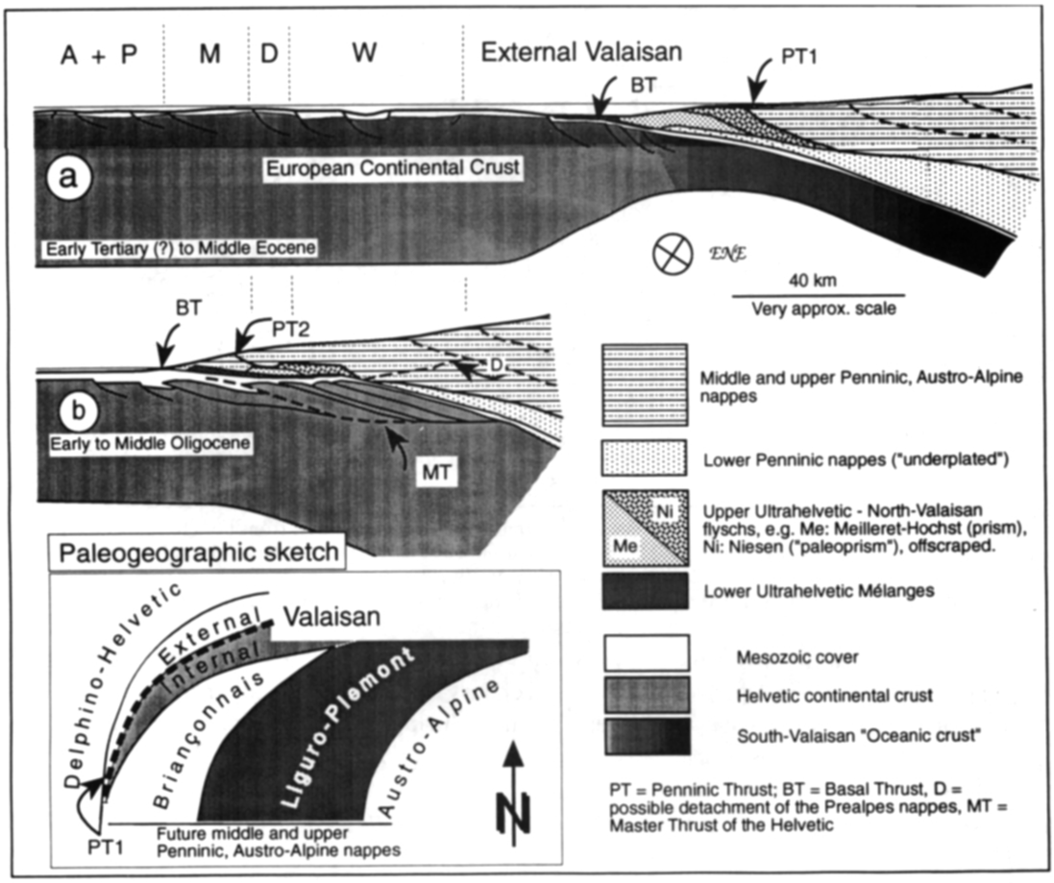

Fig. 9. Pre-orogenic paleogeography and a large scale, highly simplistic, sketch to illustrate the formation of the Ultrahelvetic mélanges and related deformations, assuming an evolution from a North Valaisan accretionary prism to a 'fold and thrust belt' with the collision of the Helvetic and Briançonnais continental crusts; Delphino-Helvetic domain: A + P = Autochthonous and Parautochthonous; M, D, W = Morcles, Diablerets and Wildhorn domains. (a) Early Tertiary situation at the edge of the North Valaisan basin, with offscraped materials (North Valaisan flysch) and underplated masses (Lower Penninic); (b) Eocene–Oligocene transition and development of a fold and thrust belt with the Tertiary foreland clastics and a possible detachment (D) of part of the Penninic nappes leading to the Prealps; MT future 'master thrust' of the Upper Helvetic nappes.

fabrics of ancient accretionary prisms such as those exposed in the Kodiak Islands (Moore & Wheeler 1978, Byrne & Fisher 1990) or in the Shimanto belt of Japan (Agar 1988, 1990) also provide insights into the Lower Ultrahelvetic deformation. For instance, the small-scale fabrics recording progressive lithification, with some muds remaining very mobile even after significant calcite veining, are very similar (e.g. compare Fig. 8b2 with fig. 16 of Fisher & Byrne 1987). The contrast between the weak deformation in the footwall and a strong deformation involving layer-parallel extension is another feature common to both areas (Jeanbourquin & Goy-Eggenberger 1991). The Kodiak accretionary complex (Byrne & Fisher 1990) is comparable in numerous other ways to the Ultrahelvetic mélanges; for instance in the very short time span between deposition, burial and accretion (around 4 Ma?), in thermal evolution and in thrust geometry.

In general, I believe that veining with mineral infilling is critical among the criteria available to distinguish between sedimentary and tectonic deformation. Important volumes of crystal infilling necessitate a fluid amount and duration perfectly compatible with thrust environments. On the other hand, olistostrome deposition (particularly the type of disorganized mud flow, facies A1; Pickering *et al.* 1989) occurs too rapidly and does not provide enough fluid flow. Macro-scale analogies with accretionary prisms and related mélanges are also striking, but they have to be discussed at a larger scale, including the Valaisan flyschs and the Briançonnais domain; a complete discussion would go beyond the aims of this paper. A few key points, with many oversimplifications, are presented here in an effort to integrate the Ultrahelvetic mélanges and their deformational features into the structural history of the Western Alps. Also, a possible model for tectonic diverticulation is presented in Figs. 9, 10 and 11.

The paleogeographic framework

I have adopted a palinspastic reconstruction of the North Tethys which display a Cretaceous Valaisan transtensional ocean basin (Kelts 1981) and Late Cretaceous–Early Tertiary subduction (Fig. 9) of this ocean with some part of a (?thinned) European crust (Jeanbourquin & Burri 1991). The importance of the Valaisan ophiolites was recognized by Trümpy (1980, 1988) but their subduction, together with some crystalline slices, is a relatively new interpretation (see Schürch 1987, sketch in fig. 2 of Ackermann *et al.* 1991, Jean-

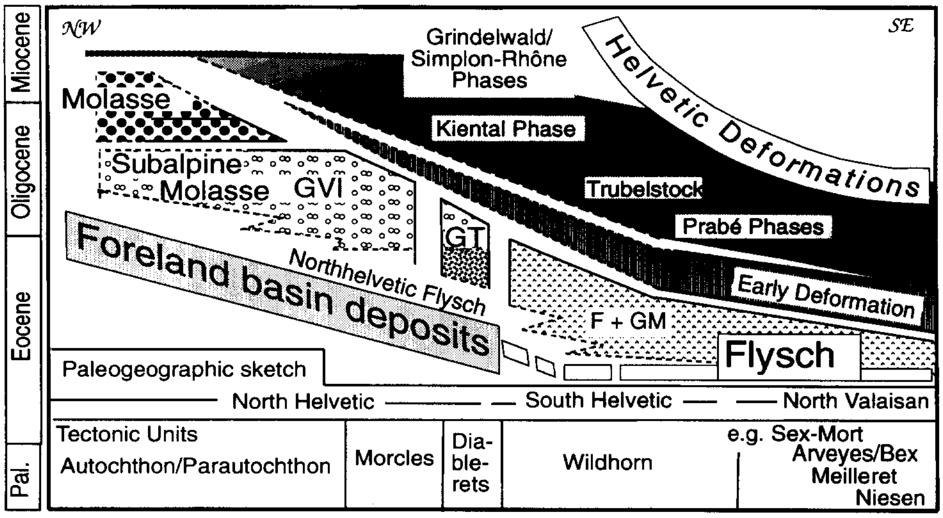

Fig. 10. Sketch of the time relationships between orogenic sedimentation (the transition from Flysch to Molasse), early deformation and Helvetic deformation. GVI = Val d'Illiez Sandstones, GT = Taveyanne Sandstones, F + GM = Flysch and Globigerine Marls. The phases of Helvetic deformation are from Burkhard (1988); foreland basin conception is from Homewood & Lateltin (1988) and the stratigraphic time scale is from Harland *et al.* (1989).

bourquin & Burri 1991, Burri *et al.* in press, and a review in Stampfli 1993). This hypothesis, in which the Lower Penninic flysch (or north Penninic flysch) would represent a large part of a Late Cretaceous–Early Tertiary accretionary prism, seems to be a good solution, even though the flysch sequence and a few bounded slices appear to be upside down in many of their present day positions (Jeanbourquin & Burri 1991).

Most of the Ultrahelvetic nappes, originating in a domain between the South Helvetic (nappe du Wildhorn) and the Valaisan ocean (Fig. 10), are characterized by a flysch 'transgression' upon a variably eroded Mesozoic basement (Badoux 1963): the external Valaisan (Jeanbourquin & Burri 1991). The main feature of the external Valaisan domain is the flysch transgression upon a variably eroded basement during the Lower Tertiary. This could result from the inversion of older faults during the Late Cretaceous–Early Tertiary, as presented by Homewood (1977).

Structural framework for a possible tectonic diverticulation

The concept of Alpine orogeny is evolving toward a model with two stages of subduction: the classic 'eoalpine' event occurring in the Piemont–Ligurian Ocean from the Middle Cretaceous (Deville *et al.* 1992), and a Late Cretaceous–Early Tertiary event, closing the Valaisan ocean. The structural history of the transition between these events in the western Alps is poorly

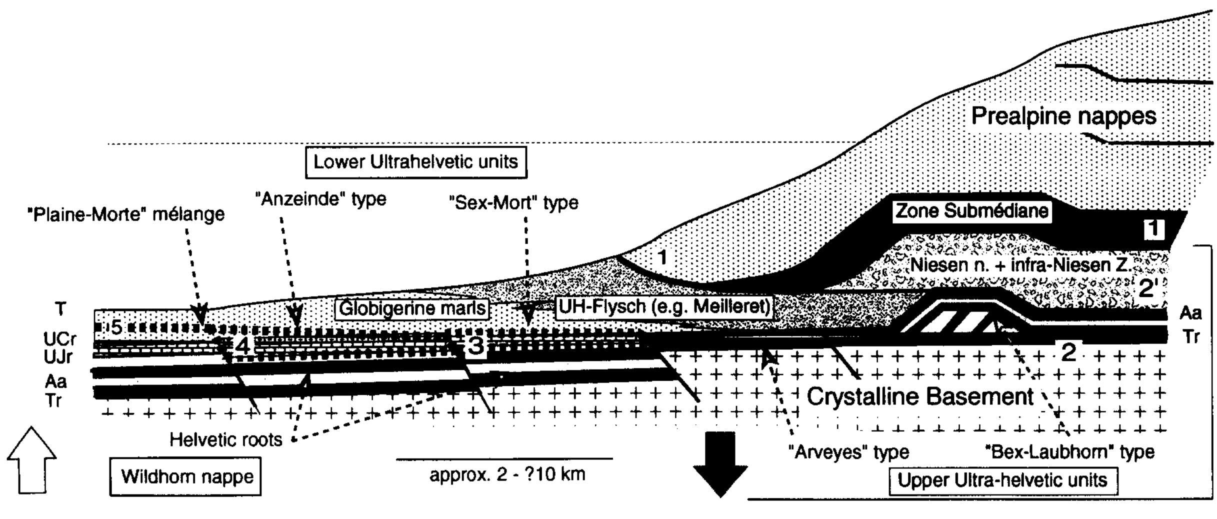

Fig. 11. Sketch of the tectonic diverticulation occurring between Middle and Late Eocene, i.e. between (a) and (b) of Fig. 9, based on a propagation thrust in the External Valaisan–South Wildhorn basin. Compare this with the diverticulation by gravity gliding in Debelmas & Kerckhove (1973) and Lemoine (1973). The different stratigraphic sequences are based on Badoux (1963) (see fig. 4 of Debelmas & Kerckhove 1973, also Lemoine 1973) and the inversion of faults during the early Tertiary follows Homewood (1977). 1 = thrust of the Prealpine nappes, future roof thrust of the 'Ultrahelvetic Duplex'; 2 = duplexing in the Upper Ultrahelvetic; 2′ = Niesen thrust (?); 3–4 = propagation of thrusting into the future Lower Ultrahelvetic units, and finally over the Wildhorn nappe (5). The early deformation is bounded by thrusts 3 and 4. The early chronology is in the sequence 1, 2, 3, 4 and 5, but one could postulate that 'out of sequence' translation may occur later, particularly for thrusts 1 and 2 (possibly gravity), and also deeper in the Helvetic pile of nappes, for instance the 'master thrust'. The large arrows indicate a flexural response of the European lithosphere to orogenic loading, as proposed by Homewood & Lateltin (1988).

studied; detailed and reliable published syntheses are non-existent. The early deformation in the Ultrahelvetic mélanges is probably associated with thrusting of the Prealpine nappes at the end of the Valaisan subduction and mostly before the main Helvetic deformation (Figs. 9 and 10).

I have adopted a tectonic model for diverticulation, already suggested by Ferrazzini (1981), in which the Ultrahelvetic units evolved from an initial stage of propagating thrusts (Fig. 11) to a final stage of a foreland dipping duplex (Boyer & Elliott 1982). In an oversimplified view of the present-day position, the roof thrust is the Zone Submédiane and the sole thrust is the Lower Ultrahelvetic mélange. In addition to the basal sole thrust and the roof thrust, the Ultrahelvetic duplex includes a major median thrust marked by the décollement in the Aalenian shale and Triassic evaporites that clearly emphasizes the separation between the 'warm' Upper Ultrahelvetics and the 'cool' lower units.

The relative chronology of these various thrusts is difficult to establish. We assume that they are heterochronous (Fig. 10), illustrating a progressive increase in the deformation toward the foreland, as presented by Burkhard (1988). Geometrical relations between the Prealpine nappes, the Zone Submédiane and the Upper Ultrahelvetics in the Zones Des Cols (Burkhard 1988, Jeanbourquin *et al.* 1992) show that the roof thrust ('Zone submédiane') and the median thrust (Aalenian) were active during the Helvetic tectogenesis, possibly after the uplift of the external massifs (post-Kiental phase, ?post-Grindelwald phase, Burkhard 1988). One could postulate that only these late movements were related to gravity sliding of the whole Prealps over the foreland basin. Such gravity sliding might have had several causes, for instance the gradual uplift of the external massifs (Grindelwald, Simplon-Rhône phases of Burkhard 1988).

The early deformational fabrics of the Lower Ultrahelvetics appear within the duplex sole thrust (possibly the 'phase Plaine Morte' of Burkhard 1988); they began to form in consolidating Globigerine marls and flysch turbidites as suggested by many authors (e.g. Hsü & Briegel 1991) and they continued to the end of the Paleogene (Figs. 10 and 11). The volumetrically important veining in the Lower Ultrahelvetic mélange suggests that this basal sole thrust was an important channel for the dewatering of the underlying sediments during the early stages of thrusting and possibly during movement over the North Helvetic flysch. High fluid pressure, facilitating the displacement, could slow down consolidation and keep the mud deforming by independent particulate flow (Knipe 1989) with locally minor cataclasis.

Finally, new fragmentation and mixing of older Ultrahelvetic mélanges took place during the thrusting of the Helvetic nappes over the 'Infrahelvetic'. For instance, the infra-Diablerets mélange includes Ultrahelvetic mélanges and slices of the North Helvetic flysch sequence (Jeanbourquin 1991a). It results from thrusting of the Diablerets-Wildhorn nappes, equivalent to the master thrust in eastern Switzerland (fig. 2 in MS of A Pfiffner written communication). Nevertheless, its geometrical relationship to the Morcles nappe suggests that it is younger (Masson *et al.* 1980), and consequently its translation is, at least partly, out of sequence.

CONCLUSION

Despite strong overprinting by late Alpine deformation, it is still possible to find evidence of the first stages of deformation in the Ultrahelvetics, particularly in the lower units dominated by block-in-matrix fabrics. These preserved meso- and micro-scale structures represent deformation in mélanges, and they suggest a tectonic origin for the pebbly-mudstones composing the matrix. The ubiquitous veining indicates the important role of fluids during the early deformation in most lithologies and a rapid progressive cementation in sandstones.

Together with recent data from the Upper Ultrahelvetic and Lower Penninic domains, these observations afford the opportunity to soundly counter the diverticulation concept (nappe emplacement by gravity) with a tectonic model based on propagating thrusts and duplexing. I tentatively propose the association of these early fabrics with a décollement occurring in the sole thrust at the top of the Tertiary sequence of the South Helvetic–North Valaisan domains; this décollement, related to the end of the Valaisan subduction, probably remained active late into the Helvetic deformation.

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