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The significance of the Schams nappes for the reconstruction of the paleotectonic and orogenic evolution of the Penninic zone along the NFP-20 East traverse (Grisons, eastern Switzerland)

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Key words. – Schams nappes, Alpine paleotectonics, Alpine tectonics, Pennine zone, eastern Switzerland.

Abstract. – The Middle Penninic Schams cover nappes have been detached from their crystalline substratum, parts of the present day Tambo and Suretta nappes, during a first deformational event D1. This event is associated with isoclinal folding within these detached sediments. It is probably of early Tertiary age and associated with the stacking of middle and north-Penninic nappes during the final stages of collision between Europe and Apulia, which commenced in the Cretaceous within the south-Penninic units and the Austroalpine. A second phase of large scale refolding inverted and backthrusted a D1 stack of N-Penninic units (ophiolites, Bündnerschiefer and flysch) above the subhorizontal axial trace of a large scale F2 fold (Niemet-Beverin fold). This refolding of a previously emplaced stack of nappes is due to a heterogeneous simple shear pattern within the viscous Pennine units below a rigid orogenic lid of previously emplaced Austroalpine units. This postcollisional reworking is caused by additional shortening across the southern steep belt of the Alps during the Insubric phase in the late Oligocene and Neogene. It severely modified the collisional stacking geometry and its effects have to be considered for the interpretation of reflection seismic profiles.

Stratigraphic and sedimentological investigations, when combined with a kinematic inversion of Alpine deformation, suggest that the southern part of the Schams paleogeographical realm (Tschera-Kalkberg unit) represents the eastern continuation of the Briançonnais domain. Sinistral transpressional movements initiating in the Middle Jurassic and continuing into the early Cretaceous at the northern margin of this platform cause the fracturation of Lower Jurassic and older formations. Basement-rich breccias, shed as submarine rock-falls and turbidites, are re-deposited into a basin occupying the northern part of the Schams realm (Gelbhorn unit). This basin represents the south margin of the Valais trough. This paleotectonic activity leads to extremely rapid facies changes but by Mid-Cretaceous time all the Schams subunits exhibit the same sedimentary evolution. We regard the Schams realm as a continental fragment caught between the eastwards terminating Piemont-Liguria ophiolitic domain (Arosa, Platta, Malenco-Lizun ophiolites, Avers Bündnerschiefer) and the westwards terminating Valais trough and associated ophiolitic zones (Chiavenna, Areua, Martegnas ophiolites and N-Penninic Bündnerschiefer and Flysch).

Il significato delle falde dello Schams per la ricostruzione dell'evoluzione paleotettonica ed orogenetica della zona penninica lungo la traversa est del PNR-20 (Grigioni, Svizzera orientale)

Parole chiave. – Falde dello Schams, Paleotettonica alpina, Tettonica alpina, Zona penninica, Svizzera orientale.

Riassunto. – Le falde medio-penniniche di copertura di Schams sono state scollate dal loro substrato cristallino, ora parte delle falde di Tambo e Suretta, durante un primo evento deformativo D1 cui sono associate pieghe isoclinali nei sedimenti scollati. La fase D1 è probabilmente di età terziaria inferiore e collegata all'impilamento delle falde medio- e nord-penniniche negli stadi finali della collisione tra Europa ed Apulia cominciata già nel Cretaceo nelle unità sudpenniniche ed austroalpine. Una seconda fase di piegamento determinò il rovesciamento ed il retrocarreggiamento di un pila D1 costituita da unità nord-penniniche (ofioliti, Bündnerschiefer e flysch) al di sopra della traccia assiale suborizzontale della piega F2 Niemet-Beverin. Questo piegamento, posteriore alla messa in posto delle falde, si svolse in un contesto generale di taglio semplice eterogeneo alle spese delle unita penniniche che si comportarono in modo viscoso, al di sotto di un "lid" orogenico costituito dalle unità austroalpine precedentemente messe in posto. Questa rielaborazione post-collisionale fu causata da un ulteriore raccorciamento attraverso la fascia sub-verticale meridionale delle Alpi nel corso della fase Insubrica del Terziario superiore. Essa modificò la geometria dell'impilamento collisionale; gli effetti di questa fase vanno tenuti presente nell'interpretazione dei profili sismici a riflessione.

Analisi stratigrafiche e sedimentologiche, combinate al retrosviluppo cinematico delle deformazioni alpine, mostrano che la parte meridionale del dominio paleogeografico della falda di Schams (unità Tschera e Kalkberg) rappresenta la prosecuzione orientale del dominio brianzonese. Movimenti transpressivi sinistri al margine N della piattaforma, iniziatisi nel Giurassico medio e continuatisi fino al Cretaceo inferiore, determinarono la fratturazione delle Formazioni giurassiche e piu' antiche. Brecce ricche in elementi di cristallino furono risedimentate come rock-falls e torbiditi in un bacino localizzato nella parte settentrionale del dominio di Schams (unità del Gelbhorn) posto al margine sud del solco vallesano. Questa attività paleotettonica determinò variazioni di facies estremamente rapide che però si esaurirono nel Cretaceo medio: tutte le sotto-unita di Schams mostrano a questo punto un'evoluzione sedimentaria simile. Secondo la nostra interpretazione, il dominio di Schams rappresenta un frammento continentale inquadrato tra la terminazione orientale della zone ofiolitica ligure-piemontese (Arosa, Platta, ofioliti di Malenco-Lizun, Bündnerschiefer di Avers) e la terminazione occidentale del solco vallesano con le ofioliti associate (Chiavenna, Areua, ofioliti di Martegnas, Bündnerschiefer e flysch nord-penninici).

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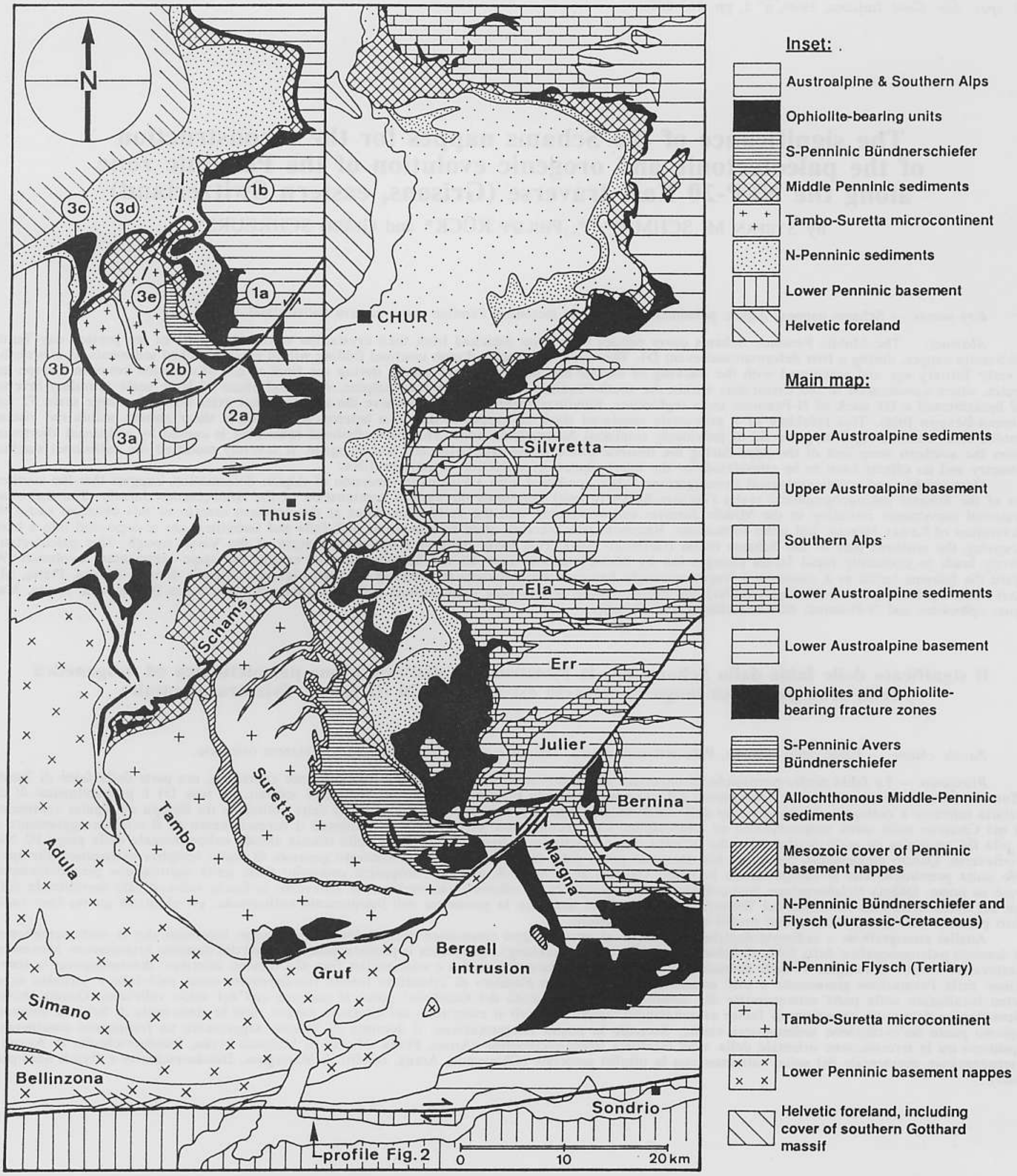

FIG. 1. – Tectonic map of Grisons (Graubünden), SE-Switzerland and adjacent parts of Italy and Austria. Encircled numbers in inset refer to the following ophiolite-bearing units: 1a: Platta; 1b: Arosa; 2a: Malenco; 2b: Lizun and Avers; 3a: Chiavenna; 3b: Misox "synclinal" zone; 3c: front of Adula nappe; 3d: Areua-Bruschghorn; 3e : Martegnas.

I. – Introduction

The investigated area belongs to the Penninic nappe system of eastern Switzerland. This Penninic structural zone is of heterogeneous composition. Firstly, it consists of basement nappes derived from the northern continental margin of the Tethys. Secondly, this zone encompasses a great variety of mostly detached Mesozoic cover rocks belonging to, from external to internal, the Valais, Briançonnais and Liguria-Piemont paleogeographical domains. Thirdly, ophiolites are found within several Penninic units, particularly near the suture with the southern continental margin of the Tethys (Austroalpine nappes, southern Alps).

It must be emphasized that these Penninic paleogeographical domains are well established in western Switzerland only [Trümpy, 1960, 1988]. The Valais trough does not exist in the French western Alps [Lemoine *et al.*, 1986]. Sediments of the N-Penninic trough form a massive pile of complexly folded and poorly dated calcareous, shaly and sandy schists (called Bündnerschiefer in eastern Switzerland). Hemipelagic sedimentation predominates from the Middle Jurassic onwards and grades into flysch-type deposits in the Mid-Cretaceous [Pantic and Gansser, 1977]. Sediments from Middle Penninic platform areas, similar to the Briançonnais domain *s.s.* are also found in western (e.g. Préalpes) and eastern Switzerland (Schams, Falknis-Sulzfluh and Tasna nappes). However, the Swiss equivalents of the Briançonnais are now separated by the Valais belt from the proximal N-European margin and shelf (Helvetic zone). This Valais belt broadens towards E-Switzerland where the N-Penninic Bündnerschiefer and flysch volumetrically predominate over all other Penninic sediments (fig. 1 & 2). In many places the S-Penninic Liguria-Piemont domain (Arosa-Platta units in eastern Switzerland) is characterized by low sedimentation rates during the Jurassic, leading to the deposition of radiolarian cherts and pelagic limestones. However, in this S-Penninic domain lithologies referred to as Bündnerschiefer or Schistes lustrés may also be found (Combin zone in the west, Avers Bündnerschiefer in the east of Switzerland) but their paleotectonic setting may be completely different from that of the N-Penninic sediments. They possibly represent the remnants of an accretionary prism evolving during subduction in the late Cretaceous [Marthaler and Stampfli, 1989]. No sediments younger than Turonian occur in the S-Penninic domain in eastern Switzerland [Lüdin, 1987].

While the existence of ophiolites representing fragments of oceanic crust is undebated in case of the Liguria-Piemont ocean, opinions are divided on the nature of the crust in the N-Penninic domain. Trümpy [1988] advocates for relicts of oceanic crust, becoming more widespread towards the east (eastern Switzerland, Tauern window). Others [Laubscher, 1971; Weissert and Bernoulli, 1985] regard the Valais trough as a marginal basin of thinned continental crust of the proximal European margin. In this view the Briançonnais *s.l.* of eastern Switzerland would still represent the distal part of the European passive margin, analogous to the situation in the western Alps. The Piemont-Liguria ophiolites could then be directly correlated with ophiolites found in eastern Switzerland and Austria (Tauern window). The prime reasons for these uncertainties are due to (1) insufficient petrological and geochemical data on the ophiolites in the Valais trough, and, (2) uncertainties about the original structural position of some ophiolites in tectonically low positions within the nappe pile (Antrona, Chiavenna) in view of post-nappe folding, so characteristic of the Pennine structural zone [Milnes, 1974].

Numerous attempts have been made to correlate Penninic units of western Switzerland with those of eastern Switzerland. It is generally accepted that the structurally highest

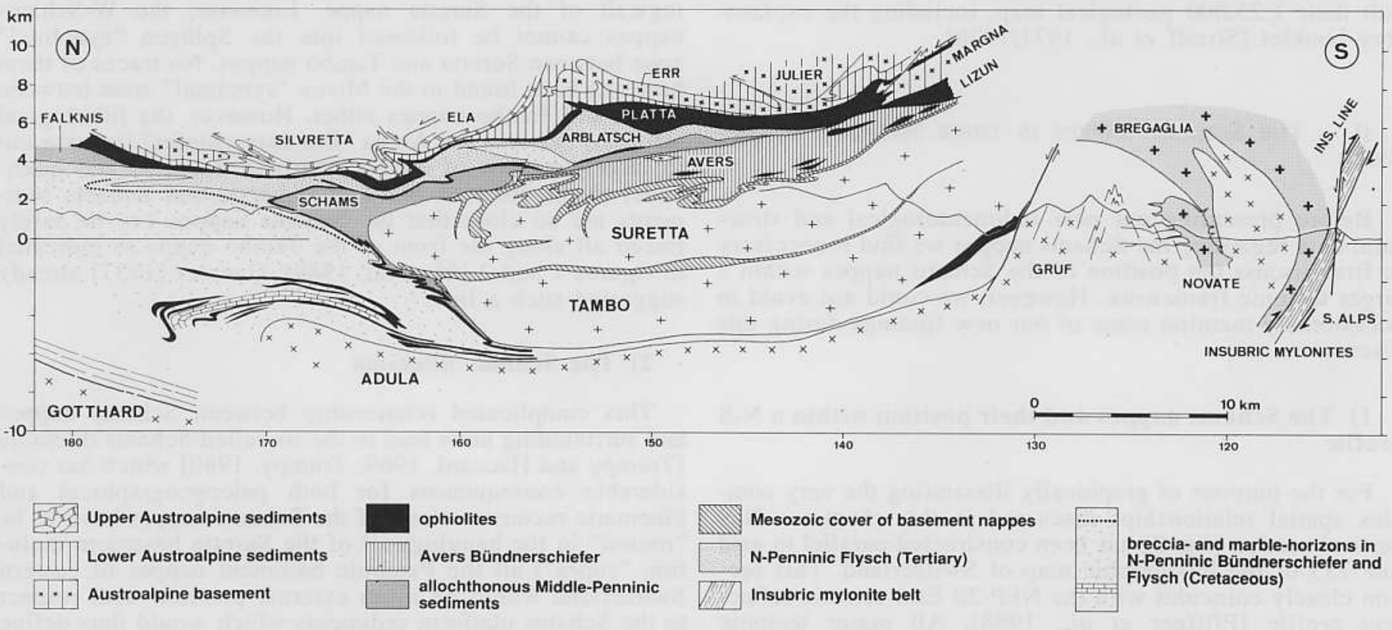

Fig. 2. – N-S cross-section parallel to grid line 755 of the topographic map of Switzerland; for location see figure 1. Basement signatures correspond to those used in figure 1, except for the Bregaglia and Novate intrusions marked with bold crosses.

S-Penninic Saas-Zermatt ophiolitic units find their eastern continuation in the Platta-Arosa units. In regard to tectonic correlations of all other Pennine units the prime obstacle is the co-called Lepontine dome of the central Swiss Alps. There, the structurally higher basement nappes, and most of the cover rocks, are missing because of erosion. The lower Penninic nappes in their turn have been deformed into a particularly complex geometry with two subdomes divided by the Maggia synclinorium running obliquely across strike [Merle *et al.*, 1989]. This absolutely precludes geometric correlations of tectonic units. Paleogeographical correlations are made difficult by non-parallelism between paleogeographical domains and the strike of the future Alpine orogen. It is very likely that some of the striking differences between structural sections across western and eastern Switzerland are due to first-order paleotectonic differences.

In view of these considerable uncertainties with cylindristic structural and paleogeographical correlations the situation in eastern Switzerland has to be analysed in its own right. The particular section discussed in this contribution is a crucial one for Alpine geology because further east, Penninic units only occur in isolated windows (Engadine, Tauern). We shall try to first unravel the structural complexities within and around the Schams nappes. This analysis will then be complemented with sedimentological investigations, with special emphasis on the paleotectonic environment. It will not always be possible to separately treat structures and sedimentology and some of the stratigraphical results will have to be already incorporated when analysing the structures during the following chapters.

We would like to emphasize that we were able to base our investigations on the pioneering work of Jäckli [1941], Streiff [1939, 1962] and Neher [*in* Streiff *et al.*, 1971/1976]. Their excellent work provided an indispensable foundation for our investigations. The reader will find it useful to consult their 1:25,000 geological map, including the explanatory booklet [Streiff *et al.*, 1971/1976].

II. – The Schams nappes in their tectonic framework

Before presenting our new sedimentological and structural data regarding the Schams nappes we find it necessary to first discuss the position of the Schams nappes within a larger tectonic framework. However, we could not avoid to occasionally mention some of our new findings during this discussion.

1) The Schams nappes and their position within a N-S profile

For the purpose of graphically illustrating the very complex spatial relationships discussed in this chapter a N-S vertical section (fig. 2) has been constructed parallel to grid line 755 of the topographic map of Switzerland. This section closely coincides with the NFP-20 East seismic reflection profile [Pfiffner *et al.*, 1988]. All major tectonic boundaries have been projected up and down plunge and strictly parallel to a direction N070 E. This direction approximates the over-all azimuth of most of the large-scale fold structures relevant to the section. A notable exception are first phase folds restricted to the Schams nappes proper and too small to be depicted in figure 2. A series of sections parallel N070E, based on structure contour maps including those of Pfiffner *et al.* [1990], allowed for projections with variable plunge (10°-35°). This allowed stacking of tectonic units under the simplifying assumption that there is no change in the thickness of tectonic units parallel to the projection direction. No cosmetic alterations were applied subsequently except for the front of the Tambo nappe which had to be moved further to the north by 2 km in respect to its position predicted by the contour maps [Pfiffner *et al.*, 1990] in order to achieve a real compatibility with surrounding units.

After detachment the rootless Schams nappes have been wrapped around the front of the Suretta nappe (figs. 1 and 2) by a second phase fold (Niemet-Beverin fold). Our structural data suggest that the axial plane of the Beverin fold [Jäckli, 1941] corresponds to the Niemet phase axial trace mapped out within the Suretta basement by Milnes and Schmutz [1978]. As will be shown later this fold of impressive dimensions is a D2 structure and postdates the D1 decollement of the Schams nappes. Nappe refolding was already envisaged in earlier work of Staub [1958], Streiff [1939, 1962] and Milnes and Schmutz [1978]. Parts of the Schams nappes came to lie above the axial trace of the Niemet-Beverin fold and they will be referred to as the east-Schams nappes since they largely outcrop in the eastern Schams area, due to the general east directed plunge of all structural units in the area depicted in figure 1. Likewise, the Schams nappes below this axial trace will be referred to as the west-Schams nappes.

Structural and stratigraphic arguments indicate that the E-Schams nappes in the Avers valley cannot be traced further to the south and into the Margna nappe in the hangingwall of the Suretta nappe. Likewise, the W-Schams nappes cannot be followed into the Splügen "synclinal" zone between Suretta and Tambo nappes. No traces of them have yet been found in the Misox "synclinal" zone between Adula and Tambo nappes either. However, the lithological affinities between the Areua "Bündnerschiefer" (turning out to largely consist of sericite marbles, breccias and quartzites) at the front of the Tambo nappe and Schams sediments are so close that the Schams nappes can be safely traced all along the front of the Tambo nappe as indicated in figures 1 and 2 [Mayerat, 1989]. Gansser [1937] already suggested such a link.

2) The Schams dilemma

This complicated relationship between Schams nappes and surrounding units lead to the so-called Schams dilemma [Trümpy and Haccard, 1969; Trümpy, 1980] which has considerable consequences for both paleogeographical and kinematic reconstructions. If the Schams nappes have to be "rooted" in the hangingwall of the Suretta basement (solution "supra") all the Penninic basement nappes of eastern Switzerland would be in an external position with respect to the Schams platform sediments which would thus define the northern continental margin adjacent to the Liguria-Piemont oceanic crust (Platta tectonic unit). The Avers Bündnerschiefer, structurally between Suretta and E-Schams nappes would also be of N-Penninic origin unless one postulates the famous backfolding geometry in the structurally higher parts of the Suretta nappe (fig. 2) as due to an early phase of top to the south transport as suggested by Milnes and Schmutz [1978]. However, our new data preclude such an interpretation.

Streiff [1962] proposes to root the Schams nappes below the Suretta nappe (solution "infra") and, additionally, he structurally connects the sediments of the Schams nappes with other platform sediments now further to the north (Falknis-Sulzfluh nappes). This connection between Schams and Falknis-Sulzfluh units asks for an additional S-closing, but severely disrupted hinge above the Avers Bündnerschiefer, responsible for and identical with the southern termination of the E-Schams nappes. The earlier mentioned Niemet-Beverin fold, together with the S-closing fold at the southern termination of the E-Schams nappes define a Z-shaped megafold (looking east) of enormous dimensions with top to the S-backfolding and backthrusting restricted to the short middle limb (E-Schams nappes). Thus this solution "infra" postulates refolding of initially lower structural elements (W-Schams) into a structurally higher position (E-Schams) around the Niemet-Beverin fold. Restoring the original nappe pile before this large scale refolding leads to a situation whereby the Suretta basement and its autochthonous cover now forming the backfolds above the Niemet-Beverin axial trace are structurally below the Avers Bündnerschiefer while the Schams nappes will be found in a structural position below the Suretta and Tambo nappes. The paleogeographic consequence of restoring the original nappe pile according to the solution "infra" is that the Suretta and Tambo basement and, additionally, the Avers Bündnerschiefer would be of more internal origin in respect to the Schams nappes. Of course this paleogeographic deduction is subject to the validity of a "normal" stacking order during early nappe formation.

The contacts with all surrounding tectonic elements are strictly tectonic. The Schams nappes are allochthonous with respect to both Tambo and Suretta basement cores and their occasionally preserved Mesozoic cover ("Mesozoic cover of Penninic basement nappes" in figure 1). Their contacts with the other Penninic sedimentary units to the north are marked by extremely thin ophiolite-bearing mélange zones (units 3d & e in figure 1, thickness exaggerated in both figures 1 and 2). Because these mélange zones play a crucial role for both structural and paleogeographic reconstructions and because they will not be discussed in detail within the following chapters a closer look at their structural position and their lithological compositions will now be given in the following section.

3) Mélange zones in tectonic contact with the Schams nappes

The Areua-Bruschghorn mélange zone (3d in fig. 1) delimits a tectonic contact with the N-Penninic Bündnerschiefer and flysch in the footwall of the W-Schams nappes. This mélange has a characteristic association of lithologies: serpentinites, meta-basalts, quartzo-feldspatic gneisses and mylonites, Triassic sediments. Triassic sediments and gneisses have strong affinities to similar lithologies in the Tambo and Suretta basement, and various sediments also found in the Schams nappes.

The Martegnas mélange zone (3e in fig. 1) delimits the tectonic contact of the E-Schams nappes with the N-Penninic Tertiary flysch found in the hangingwall: the so-called Arblatsch Flysch, where Eocene fossils were found by Ziegler [1956] and Eiermann [1988]. This mélange contains a large variety of oceanic lithologies which are lithologically undistinguishable from those found in the Platta unit (1a in fig. 1) which occurs in a structurally higher position. These lithologies include serpentinites, gabbros, pillow lavas, radiolarian cherts and pelagic limestones. Thus they undoubtedly represent fragments of oceanic crust and sediments. Since these oceanic lithologies merely indicate the offscraping of flakes of oceanic material it is questionable that their identical composition within Platta and Martegnas mélange zones is a sufficient condition for postulating a direct paleogeographical and tectonic connection between these two mélange zones. In fact, the non-oceanic elements within the Martegnas mélange zone have very strong affinities to the Suretta and Tambo basement and to sediments also found in the Schams nappes (Triassic quartzites and dolomites, Jurassic ? marbles and breccias which locally contain basement boulders characteristic for the Vizan breccia to be described in detail in a later chapter), while the same non-oceanic constituents are absent in mélange zones of the Platta unit. There the non-oceanic material comprises lithologies of Austroalpine affinity.

This difference in composition of the non-oceanic constituents of the mélange and, additionally, the presence of Tertiary flysch between Martegnas and Platta units, suggests a paleogeographically and structurally different position for Martegnas and Platta units in spite of the similar oceanic lithologies. These two units were only brought into relatively close spatial contact during Tertiary deformation.

Such a view is supported by our new structural data (presented in some detail in a later chapter) suggesting that the Martegnas mélange connects with the Areua-Bruschghorn mélange around the Niemet-Beverin fold. The Areua-Bruschghorn mélange can be further traced into the Misox "synclinal" zone (3b in fig. 1), together with other ophiolitic lithologies wrapped around the front of the Adula nappe (3c in fig. 1) [Nabholz, 1945; Dietrich *et al.*, 1974]. Further to the south these ophiolite bearing units (3b-e in fig. 1) come to lie into a structural position in the footwall of the Tambo nappe, together with the Chiavenna Ophiolite (3a in fig. 1) [Schmutz, 1976].

The axial trace of the Niemet-Beverin fold, refolding the Schams nappes together with the ophiolite-bearing Areue-Bruschghorn and Martegnas mélange zones can be traced further to the north where a N-closing but S-facing fold affects the N-Penninic Bündnerschiefer and Tertiary flysch, including a characteristic conglomerate-bearing formation (N margin of profile in fig. 2) described by Jäckli [1941]. The Tertiary Arblatsch Flysch, together with a small slice of Cretaceous flysch [Ziegler, 1956] thus connects with the

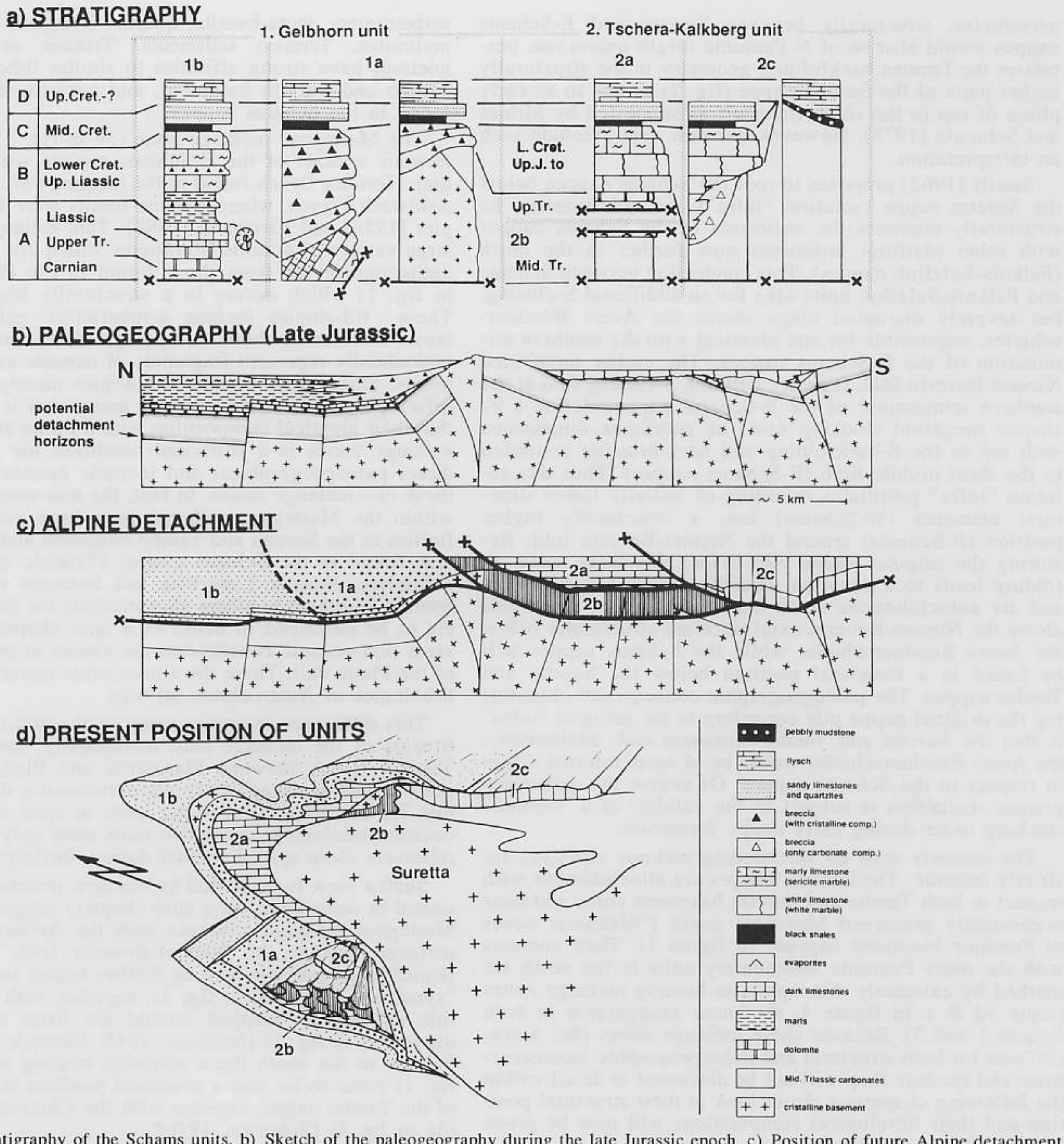

FIG. 3. – a) Stratigraphy of the Schams units. b) Sketch of the paleogeography during the late Jurassic epoch. c) Position of future Alpine detachment horizons. d) Schematic cross-section through the Schams nappes.

main body of N-Penninic sediments around the Niemet-Beverin fold.

4) The tectonic units in the hangingwall of the Schams nappes

The Platta and Arosa Ophiolite units (1a & 1b in fig. 1) form a continuous zone in the hanging-wall of the N-Penninic sediments and the Schams-Sulzfluh platform sediments. Suturing of this ophiolite zone with the Austroalpine units occurred already in the Cretaceous [Deutsch, 1983] and due to W-directed thrusting [Ring *et al.*, 1988]. However, the presence of the Tertiary Arblatsch Flysch below that suture indicates reworking of the same suture during the Tertiary when the transport changed into northerly directions [Ring *et al.*, 1988]. The distance between the southernmost occurrence of Tertiary sediments in the cross section of figure 2 and the front of the northern calcareous

Alps (Upper Austroalpine) amounts to over 50 km and gives a minimum estimate for the amount of Tertiary thrusting.

Whereas the Platta unit can be traced further to the south and into the hangingwall of the Margna nappe there is yet another ophiolite bearing unit in the footwall of the Margna nappe: the Malenco serpentinite body, structurally above the Suretta nappe and generally accepted to be of S-Penninic origin. In fact, the Malenco serpentinite forms the largest ultramafic body of the Alps (2a in fig. 1). This ophiolitic unit can be traced through the Forno series [Peretti, 1985] and into the Lizun Ophiolites (2b in fig. 1). The latter are in direct tectonic contact with the Avers Bündnerschiefer complex which also contains ophiolitic slivers. Such a connection argues for a S-Penninic origin of these Avers Bündnerschiefer and is in agreement with the same deduction made from assuming the solution "infra" of the Schams dilemma to be valid.

Contrary to some of the earlier interpretations the Margna nappe represents an Austroalpine element. This is suggested by the facies of the Margna cover rocks and the fact that all major deformations are of Cretaceous age [Montrasio and Trommsdorf, 1983; Liniger and Guntli, 1988]. Thus, a Tertiary age for a possible tectonic duplication by backthrusting of the ophiolite zone 1 above ophiolite zone 2 (fig. 1) can be ruled out. The southern continuation of the Tertiary thrust bringing the Platta unit over the Arblatsch Flysch must be looked for somewhere between the Lizun Ophiolites and the Suretta nappe, but no data are available yet. It is also not clear yet if this duplication into two ophiolite-bearing units above and below the Margna nappe (1a and 2a in fig. 1) is due to Cretaceous backthrusting [Liniger and Guntli, 1988] or to a primary paleogeographical configuration with the Margna unit forming a microcontinent.

5) Concluding remarks

In view of these considerable structural and lithological complexities there is no doubt that the simple method used for many paleogeographical reconstructions, consisting in assigning a more internal origin to tectonically higher elements cannot always be applied. Phenomena such as large scale refolding of previously emplaced nappe units (Niemet-Beverin fold), backthrusting of the Schams nappes over the Suretta nappe and Tertiary reactivation of the Cretaceous suture between Austroalpine units and Platta unit obviously seriously affect the original nappe pile. However, we do not share the recently proposed "nihilistic" approach, suggesting that the present day position of ophiolitic units is absolutely meaningless for paleogeographic reconstructions due to chaotic mixing within a huge accretionary wedge [Polino *et al.*, 1990].

The following chapter adresses the structures within the Schams nappes and surrounding units more closely and will provide constraints for the kinematic evolution. Another aim of the following detailed structural analysis is the restauration of the paleogeographical configuration within the Schams area and surrounding units, allowing a discussion of paleotectonics and associated sedimentological processes.

III. – Structures within the Schams nappes and adjacent tectonic units

1) The effect of the three main phases of deformation recorded in the Schams area

The metamorphosed sediments (lower greenschist facies) of the Schams nappes have undergone a polyphase Alpine deformation history, which is superimposed on an already complicated paleotectonic evolution. For an extensive discussion of the paleogeography the reader is referred to later chapters. At this stage it will only be noted that, based on stratigraphic evidence, two Jurassic paleogeographic domains can be differentiated (fig. 3b shows a simplified section through these domains). The Tschera-Kalkberg unit represents a platform sequence, whereas the Gelbhorn unit represents the proximal and distal part of a sedimentary basin. The paleogeography determined to a large extent the future position of detachments, which developed during early stages of Alpine deformation.

Overprinting relationships allow us to clearly distinguish three Alpine deformation phases within the Schams nappes. The relative deformation events are numbered with respect to the deformation history of the Schams nappes and refer to Alpine deformation only. Unravelling the structures is essential for a correct interpretation of the stratigraphical and sedimentological data. A structural study of the Schams nappes must also consider the deformation in the surrounding basement nappes, Bündnerschiefer and flysch units, which can, in part, be correlated with those in the Schams nappes. The geometrical analysis of the structures also puts constraints on the kinematic evolution. Three parallel NNW-SSE oriented vertical sections were constructed to illustrate the geometry (fig. 5).

The second phase N-closing Beverin fold, with a slightly E to SE dipping axial plane and a 10-20 degrees E plunging fold axis, wraps the Schams nappes around the flat-lying Suretta and Tambo nappes (fig. 2). Both nappes consist of a pre-Alpine basement core, made up of ortho- and paragneisses, enveloped by Mesozoic sediments. The Niemet phase axial trace within the Suretta nappe [Milnes and Schmutz, 1978] correlates with the axial trace of the Beverin fold (figs. 4 & 5). As mentioned before we make a distinction between those parts of the Schams nappes that lie above the Niemet-Beverin axial trace (east-Schams nappes) and those parts that lie below (west-Schams nappes) to allow for a better structural description.

The second phase Niemet-Beverin fold overprints isoclinal folds and thrust contacts, which developed during a first deformation phase as the Schams sediments were detached from their basement. The incompetent Triassic evaporitic sediments (Carnian corgneule) act as the principal decoupling horizon for the Gelbhorn unit. In case of the Kalkberg-Tschera unit detachment also takes place near the interface between Middle Triassic carbonates and Triassic quartzites. In those places where the Carnian evaporite horizon was eroded during the Jurassic, Alpine detachment occurred along other horizons and locally basement rocks together with (? Permo) Triassic quartzites are sheared off from their substratum (fig. 3c) [Streiff, 1939]. During the first deformation phase the now allochthonous Schams sediments were stacked in a pile of fold and thrust nappes.

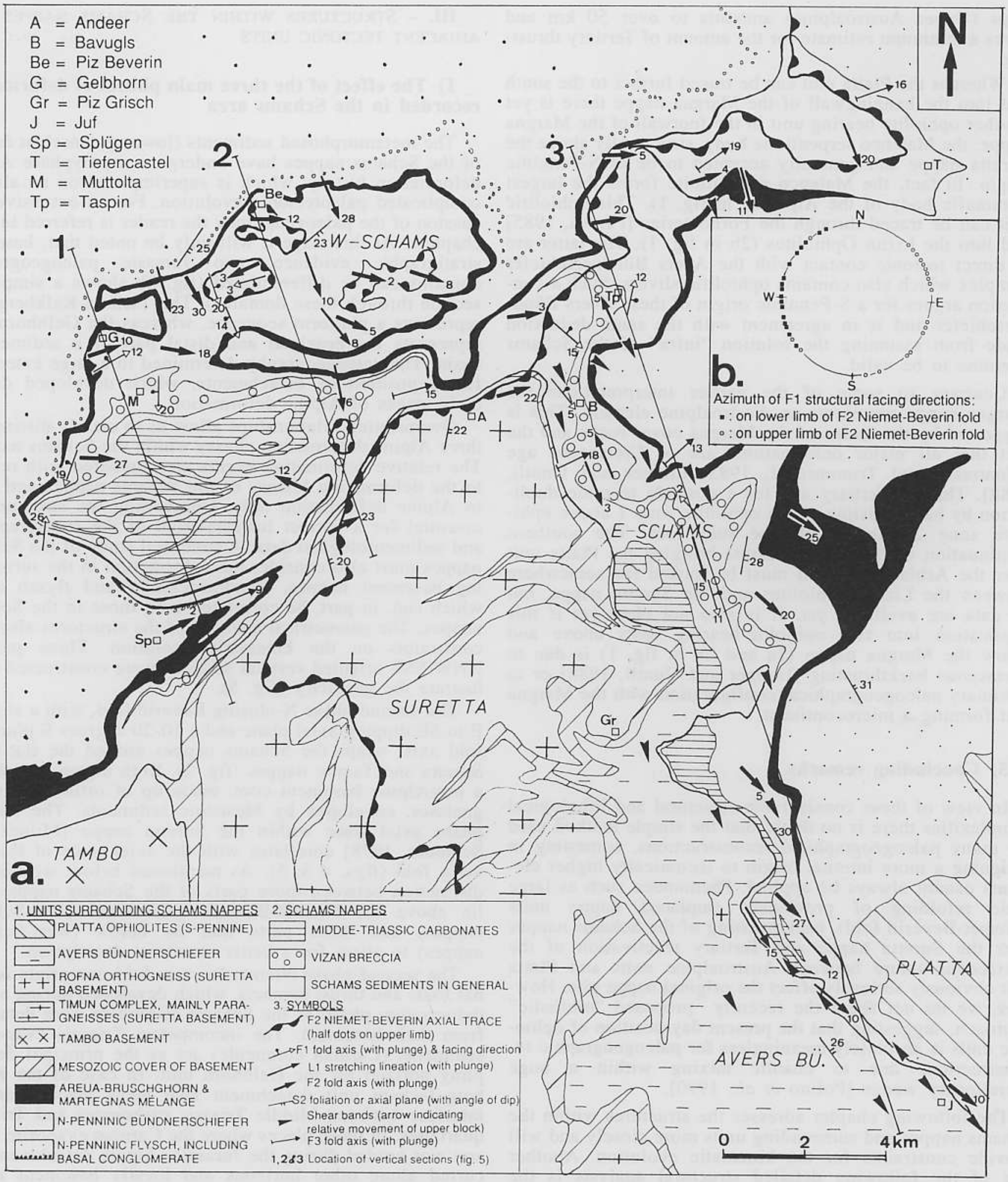

FIG. 4. – a) Schematic tectonic map of the Schams nappes and adjacent tectonic units. b) Azimuth of F1 structural facing directions. For a discussion see text.

A large-scale first phase fold nappe essentially comprises the Gelbhorn unit. Across the fold hinge a rapid Jurassic facies change takes place, from a thick series of proximal breccias on one limb (Gelbhorn unit 1a) to thin distal turbidites and hemipelagic sediments on the other limb (Gelbhorn unit 1b). Within the Gelbhorn unit stratigraphic repetitions are common, especially in the Upper Jurassic and Cretaceous sediments. Isoclinal F1 folding has often to be inferred from changes in younging directions which systematically change between units 1a and 1b with the Carnian evaporites in between. Due to the extremely isoclinal nature of the F1 folds actual hinges are difficult to detect, but their observation was crucial for the discussion of facing directions in regard to F1 folding. Certain repetitions might also be due to internal thrusting.

The Jurassic platform domain (Tschera-Kalkberg unit) is partitioned into 3 tectonic subunits (fig. 3c) due to the first phase Alpine deformation. The Tschera subunit consists of Upper Triassic to Cretaceous sediments and generally lacks the Middle Triassic carbonates. The latter form a subunit of their own (Kalkberg subunit 2b), often intimately associated with basement slivers similar to the geographically nearby Rofna Gneiss of the Suretta nappe or the far-away Truzzo Gneiss of the Tambo nappe [Gulson, 1973]. Finally the Weissberg subunit 2c consists of the entire Middle-Triassic to Cretaceous sedimentary pile. This subunit is often sliced into a tectonic mélange [Pauli, 1988], containing ophiolitic elements.

The west-Schams nappes consist from bottom to top of firstly a F1 fold nappe, generally comprising Gelbhorn unit 1b in its lower overturned limb and Gelbhorn unit 1a in the upper normal limb, and secondly the tectonic sub-units of the Tschera-Kalkberg domain. Due to intensive post-nappe folding of the Tschera-Kalkberg subunits 2a, 2b & 2c it is difficult to discriminate their original individual tectonic position. Subunit 2c seems to occupy the highest tectonic position. The east-Schams nappes, however, show the reverse order from bottom to top (fig. 3d).

The youngest phase D3 shows a regionally consistent NNW fold and cleavage vergence. The F3 fold wavelengths vary in scale from millimetres to several hundred meters with steep SE dipping axial planes and ENE plunging fold axes. D3 does not only affect the Schams nappes, but all the surrounding tectonic units, including the basal thrust of the Austroalpine nappes (fig. 2). This phase can be correlated with the Domleschg phase [Pfiffner, 1977] further north, which probably is of Miocene age. Since this phase does not significantly alter the large scale geometry seen in figure 2 it is of minor tectonic significance.

The Schams dilemma questions whether the stack of the present day west-Schams nappe sequence represents the original D1 nappe configuration (solution "infra") or, alternatively, whether the east-Schams nappe sequence depicts the D1 situation (solution "supra") before the development of the second phase Niemet-Beverin fold.

Associated with D1 is the development of a penetrative schistosity and a stretching lineation (fig. 4a), which trends approximately NNW-SSE in both east- and west-Schams nappes (i.e. above and below the F2 Niemet-Beverin axial trace). The analysis of the F1 structural facing directions (fig. 4a), i.e. younging direction projected normal to the fold axis and lying within the axial plane, provides us with kinematic constraints. In the west-Schams nappes the F1 facing directions vary between SW and NW, whereas in the east-Schams nappes they mostly lie between SSE and NE (fig. 4b).

In regions of high D1 strain F1 fold axes rotate toward the NNW-SSE trending L1 stretching lineation and their facing directions are SW to WNW for the west-Schams nappes and ENE to NE for the east-Schams nappes. The reason for this change in facing direction between west- and east-Schams nappes is the fact that apart from the Niemet-Beverin fold hinge region, where F2 fold axes trend approximately E-W, most F2 fold axes on both limbs deviate from this orientation and trend subparallel to the L1 stretching lineation. In such cases coaxial refolding around approximately NW-SE axes produces the switch in F1 facing directions.

However, in competent lithologies or areas of relatively low D1 strain F1 fold axes generally do not rotate toward the stretching lineation, but remain more or less perpendicular. Then the F1 facing direction is NW to NNW in the west-Schams nappes and SSE to SE in the east-Schams nappes (if F1 and F2 axes are subparallel). An example of such a situation is shown in the inset of profile 2 (fig. 5), where a F1 fold in the Gelbhorn unit is coaxially folded by the F2 Niemet-Beverin phase.

Thus the analysis of these F1 structural facing directions suggests that two possible scenarios remain, assuming D1 transport of the Schams nappes parallel to the L1 stretching lineation and perpendicular to F1 fold closures in competent lithologies or areas of low D1 strain.

a) A solution "supra" : the D1 movement direction is toward SE to SSE in the hanging-wall of the Suretta nappe and Avers Bündnerschiefer (as proposed by Milnes and Schmutz [1978], based on structural analysis of the Suretta nappe complex). F2 folding of the Schams nappes changes the F1 facing to NW to NNW on the lower Niemet-Beverin limb (west-Schams nappes).

b) A solution "infra" : movement during D1 is toward NW to NNW in the footwall of the Suretta and Tambo nappes. Back-folding and back-thrusting during D2 causes the inversion of the F1 facing to SE to SSE on the upper limb of the Niemet-Beverin fold (east-Schams nappes).

Note that the solution "supra" implies SE to SSE directed movements during the first Alpine deformation phase recognized in the area. Although backthrusting is widespread in many parts of the Alps it is usually associated with later post-collisional events which postdate the main nappe emplacement. Additionally, the solution "supra" would imply that almost the entire volume of the N-Penninic Bündnerschiefer and Flysch, now situated north of the Schams area (commonly assigned to the Valais belt) would only come to lie into the fottwall of the Schams nappes (commonly accepted to represent the Briançonnais) during F2. The F1 nappe pile would then have sediments of the Valais belt in a structurally higher, i.e. more internal position with respect to the Briançonnais, a situation which completely contradicts findings in western Switzerland.

However, although the solution "supra" appears unlikely it is still a possible solution in principle. Primary S-directed transport cannot be excluded a priori and large scale cylindristic correlations between eastern and western Switzerland across the Lepontine dome are extremely dangerous.

2) Arguments in favour of a solution "infra" of the Schams dilemma

In view of the remaining uncertainties the following series of additional arguments in favour of solution "infra" is provided.

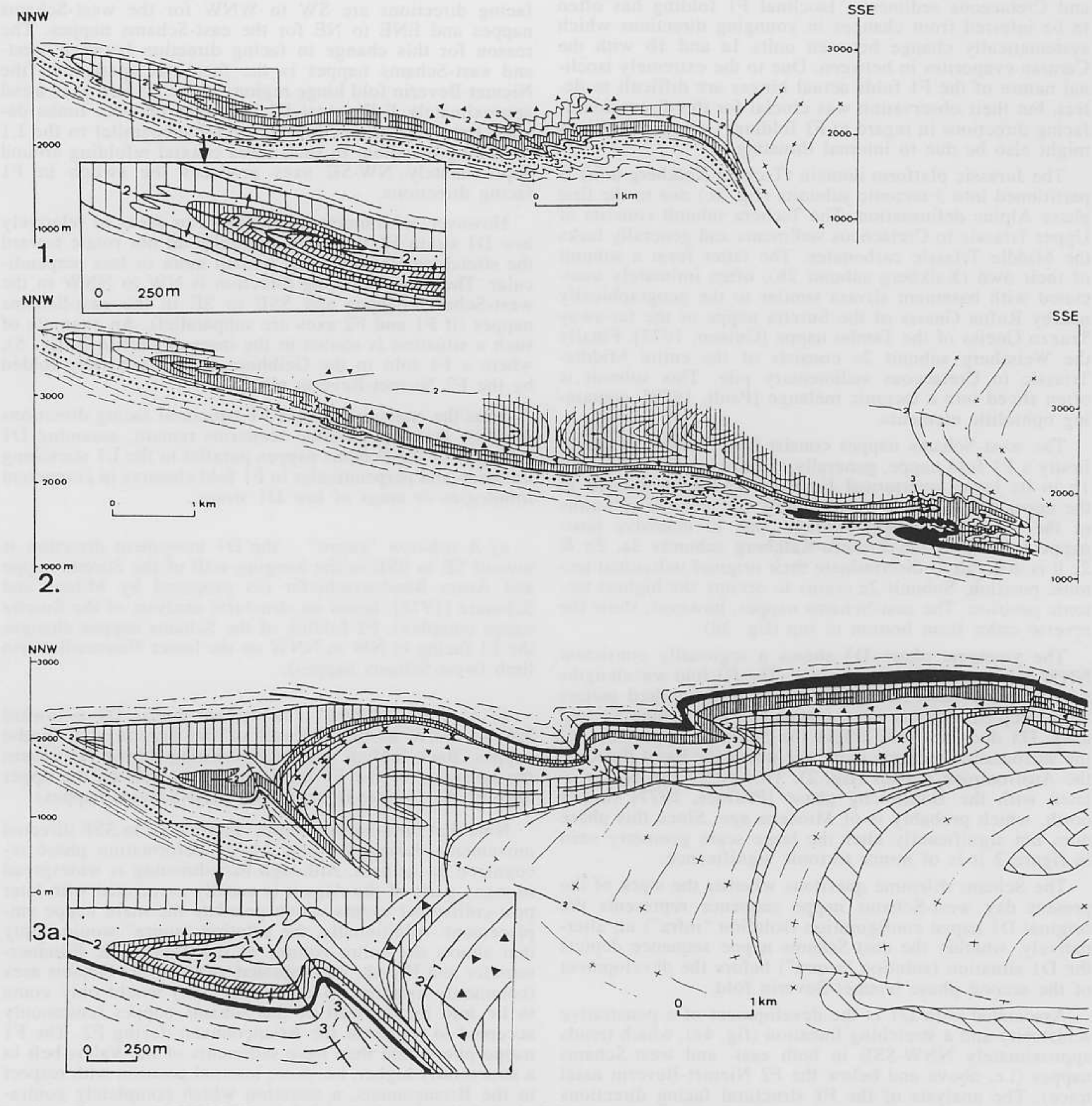

FIG. 5. – Three parallel NNW-SSE oriented vertical sections through the Schams nappes. For location of the sections see figure 4.

a) Basement slivers within the Schams nappes show great petrographic similarities to orthogneisses of the Suretta and Tambo nappes. Detachment from the upper part of the Suretta nappe (above the F2 axial plane) is not possible, because of the presence of the autochthonous Triassic cover rocks in the north and the Avers Bündnerschiefer in the south.

b) Another argument against the solution "supra" is based on the structural analysis of the Areua-Bruschghorn mélange. This mélange separates the west-Schams nappes in the hanging-wall from Bündnerschiefer and Flysch sediments in the footwall, including a conglomerate-bearing unit (fig. 2) at the base of the flysch [Jäckli, 1941; Streiff *et al.*, 1971/1976]. The mélange is isoclinally folded by parasitic folds of the second-phase Niemet-Beverin phase (profile 1 in fig. 5) and, therefore, the superposition of west-Schams nappes on the N-Penninic sediments must have originated during D1. In case of a solution "supra" with SE to SSE directed D1 movement, the Bündnerschiefer and Flysch sediments would occupy a pre-D2 position in the hanging wall of the Suretta and Schams nappes. Due to the D2 Niemet-Beverin folding the Bündnerschiefer and Flysch sediments would become inverted in the present-day footwall of the west-Schams nappes. However, observations by Jäckli [1941] indicate a normal way up of this sequence.

c) The crystalline basement and Permotriassic autochthonous cover in the upper part of the Suretta nappe, as well as the Avers Bündnerschiefer are isoclinally folded [Ferrera phase of Milnes and Schmutz, 1978]. A penetrative schistosity in the Rofna Orthogneiss is axial planar to the Ferrera folds and is thought to be contemporaneous with the first phase penetrative foliation in the Schams nappes (D1). The basal thrust of the east-Schams nappes is not affected by the Ferrera phase and clearly postdates it (profile 3 in fig. 5). The D2 Niemet-Beverin phase, which overprints the Ferrera phase (D1) and produces the characteristic S-vergent back-fold geometry in the upper part of the Suretta nappe, must be contemporaneous with the back-thrusting of the east-Schams nappes on top of Suretta nappe and Avers Bündnerschiefer.

d) Kinematic indicators, such as shear bands and asymmetric porphyroclasts occur only in the upper limb of the Niemet-Beverin axial plane. They are associated with the D2 deformation and show predominantly a top to the SE

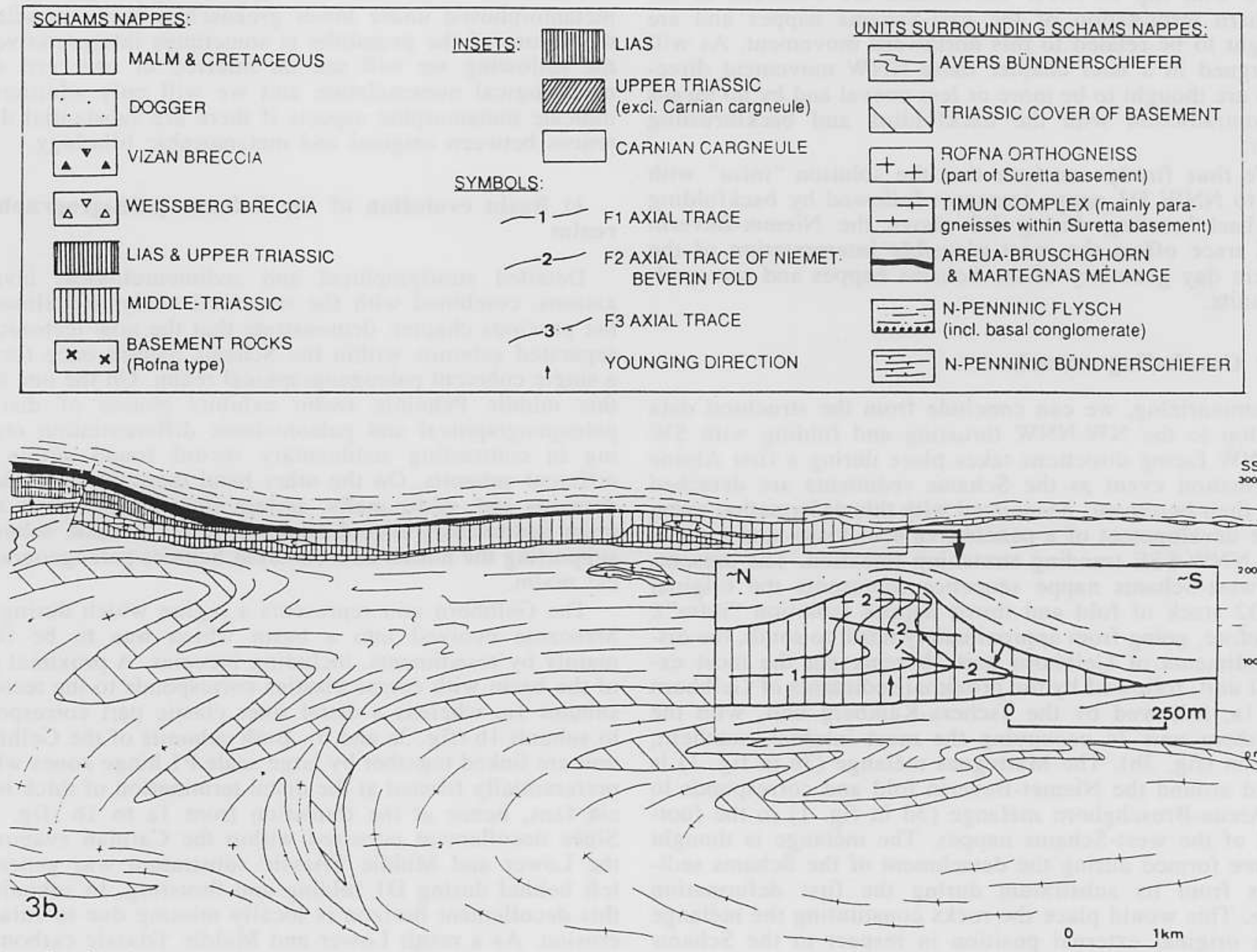

FIG. 5. – Continued.

movement in the Martegnas zone, east-Schams nappes and Avers Bündnerschiefer and support the concept of back flow (i.e. back-folding and back-thrusting) during D2. It is important to note that both east-Schams nappes and Avers Bündnerschiefer, which were not in contact before D2, indicate this SE movement.

e) Isolated slivers of basement and Triassic cover rocks occur amidst the Avers Bündnerschiefer. The petrographic composition of the basement slivers is identical to the Rofna Gneiss. One of these slivers (profile 3b in fig. 5) is situated S of the most southernly occurrence of Rofna Gneiss within the Suretta nappe and indicates a relative displacement to the south due to backthrusting.

f) Structural analysis of the south end of the east-Schams nappes [Pauli, 1988], indicates that the Schams nappes do not continue further south but are folded by a S-closing second phase fold (inset in profile 3b of fig. 5). Therefore a connection, albeit severely disrupted, with the Falknis-Sulzfluh elements much further north is possible, as already proposed by Streiff [1962]. The southern end of the east-Schams nappes is close to the overlying S-Penninic Platta and Austroalpine units, which show a northward movement direction during the Tertiary [Ring *et al.*, 1988]. Shear bands with top to NNW movements are observed at the southern termination of the east-Schams nappes and are thought to be related to this northward movement. As will be argued in a later chapter these NNW movement directions are thought to be more or less coeval and by no means in contradiction with the backfolding and backthrusting event.

We thus firmly conclude that the solution "infra" with NW to NNW D1 nappe transport followed by backfolding and backthrusting during D2 above the Niemet-Beverin axial trace offers the most plausible interpretation of the present day geometry of the Schams nappes and surrounding units.

3) Concluding remarks

Summarizing, we can conclude from the structural data that top to the NW-NNW thrusting and folding with SW to NNW facing directions takes place during a first Alpine deformation event as the Schams sediments are detached from their basement. Associated with this deformation event is the development of a penetrative schistosity and a generally NNW-SSE trending stretching lineation. The present-day west-Schams nappe sequence represents the original pre-D2 stack of fold and thrust nappes (solution "infra"). Therefore, going from approximately north to south, the distal sediments of Gelbhorn unit 1b represent the most external unit, followed by the proximal sediments of Gelbhorn unit 1a, followed by the Tschera-Kalkberg unit, with the Weissberg unit 2c occupying the most internal, southern, position (fig. 3b). The Martegnas mélange (3e in fig. 1) is folded around the Niemet-Beverin fold and corresponds to the Areua-Bruschghorn mélange (3d in fig. 1) in the foottwall of the west-Schams nappes. The mélange is thought to have formed during the detachment of the Schams sediments from its substratum during the first deformation phase. This would place the rocks constituting the mélange in an original external position in respect to the Schams units.

Large-scale backflow during D2 produces a huge N-closing recumbent fold with elements of the Schams nappes on both limbs. Martegnas mélange and Arblatsch Flysch sediments (N-Penninic Tertiary Flysch, fig. 1 & 2) are now brought in the hanging-wall of the Schams nappes and the Avers Bündnerschiefer.

A last deformation phase, producing NW-NNW vergent folds with steep S to SE dipping axial planes is of minor importance.

IV. – Stratigraphy and sedimentology of the Schams nappes

A first section will briefly describe the complete sedimentary record found in the Schams nappes and summarize the basin evolution. Two subsequent chapters are devoted to the detailed discussion of the breccias found in Gelbhorn subunit 1a. In contrast to the other, more finegrained sediments depositional geometries can still be observed in the Vizan Breccia Formation. This formation plays a key role in the understanding of the paleotectonic environment discussed in a concluding section.

Since the sediments are very strongly deformed and metamorphosed under lower greenschist facies conditions the nature of the protoliths is sometimes interpretative. In the following we will use an inferred or observed sedimentological nomenclature and we will only additionally indicate metamorphic aspects if there are substantial differences between original and metamorphic lithology.

1) Basin evolution of the Schams paleogeographical realm

Detailed stratigraphical and sedimentological investigations, combined with the structural analysis outlined in the previous chapter, demonstrate that the now tectonically separated subunits within the Schams nappes once formed a single coherent paleogeographical realm. On the one hand this middle Penninic realm exhibits phases of discrete paleogeographical and paleotectonic differentiation resulting in contrasting sedimentary record found within the different subunits. On the other hand there are transitional domains and, additionally, certain time periods with a similar sedimentary record common in all tectonic subunits, supporting the notion of a coherent Schams paleogeographical realm.

The Gelbhorn unit represents a region which during the Mesozoic evolved into a basin which was to be filled mainly by resediments, including breccias. A proximal part of the basin with coarse clastics corresponds to the tectonic subunit 1a, whereas a distal finer clastic part corresponds to subunit 1b (fig. 3a and b). Both subunits of the Gelbhorn unit are linked together by large scale F1 hinge zones which preferentially formed at the distal termination of thick breccia fans, hence at the transition from 1a to 1b (fig. 3c). Since decollement occurred within the Carnian evaporites the Lower and Middle Triassic substratum was generally left behind during D1 folding and thrusting. In subunit 1a this decollement horizon is locally missing due to Jurassic erosion. As a result Lower and Middle Triassic carbonates and/or basement slivers, lithologically identical to the same formations found in unit 2 (Tschera-Kalkberg), have also been detached.

The Tschera-Kalkberg unit comprises a sedimentary sequence of platform carbonates. The individualization into the three tectonic subunits (fig. 3c) is controlled by the presence of Upper Triassic evaporites which often have been removed by erosion during the Jurassic (fig. 3b).

The evolution of the Schams paleogeographic realm can be divided into four episodes (fig. 3a): A: early stages of moderate subsidence and rifting (Permian – late Liassic); B: the main rifting and/or transcurrent faulting stage (late Liassic – early Cretaceous); C: the convergence stage (Mid-Cretaceous); and D: the collision stage (late Cretaceous ? and/or Tertiary ?). These stages cannot always be separated clearly in the rock record, but they roughly represent discrete stages during basin evolution.

A: early stages of subsidence and moderate rifting

The sediments, documenting the early stage of moderate rifting, have been partly removed by Jurassic erosion, partly they were left behind during detachment. Where preserved they exhibit common characteristics in all the Schams units and subunits.

A thick (max. 600 m) Lower to Middle Triassic carbonate platform evolved above an older, weathered surface of porphyritic igneous rocks (so-called "Taspinit", lithologically identical to parts of the "Rofna Gneiss" of the Suretta nappe). Limestones and dolomites alternate and intercalations of volcanic tuffs are characteristic. Fossils date these sediments as Anisian and Ladinian [Neher, *in* Streiff *et al.*, 1976]. At least parts of this Middle Triassic sequence are always preserved within the Tschera-Kalkberg unit, either as a separate tectonic subunit (2b, Kalkberg) or in stratigraphic contact with younger sediments (2c, Weissberg).

Above the evaporites of Carnian age yellow Upper Triassic dolomites exhibit a "Carpathic" facies (reduced thickness with intercalations of clay horizons, differing from the very thick Hauptdolomite formation characteristic for the Austroalpine facies). The age of these two sequences is inferred from their identical stratigraphic position when compared to other Middle or North Penninic domains.

The Liassic limestones of the Gelbhorn unit consist of echinodermal and spiculitic limestones and represent a continuous transition from neritic to open marine hemipelagic conditions. Ammonites indicate their minimum age as late Liassic [Jäckli, 1941]. Within the Tschera-Kalkberg unit the Liassic section is generally missing. However, in some places a dark belemnite-bearing limestone horizon, similar to the Liassic section of the Gelbhorn unit, is found between Upper Triassic dolomites and white marbles (Malm). Therefore the absence of the Liassic limestones in the Tschera-Kalkberg unit is not due to nondeposition but to erosional processes during the following stage B.

The evolution during this stage (A) is strikingly similar to that of the Prealps in western Switzerland (Briançonnais). Slow subsidence is possibly associated with moderate early rifting.

B: the main rifting and/or transcurrent faulting stage

During the main rifting stage two distinctly different paleotectonic environments evolved within the Schams realm: a basin (today preserved in the Gelbhorn unit) is rather abruptly separated from a platform (Tschera-Kalkberg unit). The kinematic inversion of the complex deformation history allows the reconstruction as described below, and going from N to S.

In the Gelbhorn subunit 1b the Liassic limestones are first overlain by shales and marls which contain intercalations of thin bedded breccias and sands, representing the distal parts of turbidites shed to the north and away from Gelbhorn subunit 1a. This formation is virtually undistinguishable from parts of the N-Penninic Bündnerschiefer. This formation (mapped as Nisellas series by Streiff *et al.* [1976]) is followed by impure, slightly marly limestones (sericite marble).

The coeval section within the Gelbhorn subunit 1a consists of basement bearing resediments, predominantly in the form of breccias (Vizan Breccias), which will be discussed in more detail in a later chapter. It is important to emphasize that the sedimentary structures of these resediments will give us the main arguments for the reconstruction of the paleotectonic setting during this stage.

Within the Tschera-Kalkberg unit a sequence of platform carbonates is found. In subunit 2a (Tschera) massive pure limestone (white marble) is overlain by the similar impure limestone (sericite marble) found in the Gelbhorn unit. These sediments are still undated but transitions and intercalations indicate that they were deposited contemporaneously with the Vizan Breccia.

In the most internal platform (subunit 2c, Weissberg) breccias locally occur again. However, these breccias do not contain basement clasts and they are paleogeographically completely separated from the Vizan breccias by subunit 2a (Kruysse [1967], erroneously mapped them as Vizan Breccia). Upwards and laterally they grade into pure limestones (white marble), whereas the sericite marble is mostly missing. In this most internal domain the evaporite horizon is always missing and Jurassic erosion down to the Lower and Middle Triassic is common. This deep erosion in subunit 2c exhibits a very close affinity to the same situation found in the Medianes Rigides of the Prealps, the most internal domain of the Briançonnais in western Switzerland [Baud and Septfontaine, 1979]. Only further to the north are the Carnian evaporites preserved and this then leads to the individualization into subunits 2a (Tschera) and 2b (Kalkberg).

Due to the absence of fossils the age of this episode can only be bracketed between the Liassic and the inferred Mid-Cretaceous age of the following stage.

C: the convergence stage

The lithology of sediments deposited during this stage is identical in all the subunits of the Schams nappes. Quartzites, sandy limestones and black shales characterize this sequence. A Middle Cretaceous age is inferred from the strong lithological affinities to the co-called "Gault" of the Falknis nappe [Allemann, 1957]. The same is also suggested by the chemical analysis of the black shales, deposited in an anoxic environment. The content in organic carbon is significantly higher than in other shale or marl horizons in the Schams nappes and comparable to that of the black shales associated with the Falknis "Gault". Anoxic events are characteristic for the entire Tethys realm during the Middle Cretaceous and are therefore good correlation horizons [Jenkyns, 1980]

The similar character of the sediments of this episode within the entire Schams area suggests that the Jurassic relief has been largely smoothed by erosion and/or sedimentation. This time period is considered to mark important changes in the plate motions [Dercourt *et al.*, 1986]. Convergence between Europe and Apulia is indicated by the onset of collision, deformation and metamorphism in the eastern Alps [Ring *et al.*, 1988], but no direct evidence for convergence is indicated for the Schams area.

D: the accretionary and/or collision stage

The youngest sediments consist of thin bedded limestones, intercalated with shales, calcareous and siliciclastic turbidites, and marly limestones. These sediments exhibit a flysch-type appearance and they have been mapped as "Gelbhorn Flysch" by Streiff *et al.* [1971/1976]. Unfortunately, it is not clear if sedimentation in the Schams area continues into the Tertiary (as expected from a close similarity with dated flysch of Tertiary age in the Falknis nappe) due to the lack of fossils.

It is important to mention that these sediments lay locally with an unconformity on the Middle Triassic in the most internal subunit 2c [Weissberg and Pauli, 1988]. There bicarinate *Globotruncana* [Pauli, 1988] date the matrix of pebbly mudstones as late Cretaceous. It is possible that this unconformity documents the onset of the first orogenic events in the Schams area. This same subunit 2c also contains ophiolitic slivers within a mélange found in the neighbourhood of the above mentionned transgressive contact in the region of the Avers Weissberg near the S termination of the E-Schams nappes [Pauli, 1988]. Both the above mentioned unconformity and the emplacement of the ophiolitic slivers suggest the onset of accretion and/or collision in the southernmost subunit 2c.

2) The Vizan Breccia in the west-Schams area

The following description of the Muttolta area will give important constraints for the reconstruction of the 3-dimensional depositional geometry in the Vizan Breccia Formation and its relationship with older formations (fig. 6a).

In this region, the Vizan Breccia Formation forms the normal limb of a large scale F1 fold, remaining normal during F2 folding. Hence the locality is particularly suited for deriving Jurassic depositional geometries.

The Vizan Breccia Formation at Muttolta mountain can be divided into 6 mappable members (fig. 6). Figure 7 synthesizes the depositional geometry in a scaled block diagram and also exhibits lithological sequences representative for each of these members.

The subdivision in six members is based on sedimentary and petrographical criteria. The bigger part of the Vizan Breccia Formation (Member 1, 3, 4 & 6) consists of poorly graded, mostly gravel sized breccias and well graded sandstones. Intercalations of silty horizons are common. This kind of sequence is interpreted as a turbidite deposition. Some rare isolated, up to 15 m long blocks (Liassic limestone) appear in the sequence (Member 3). They indicate a near escarpment as source region. The non-graded thick breccia horizons of Member 2 are interpreted as debris flows. Member 5 is very chaotic in appearance and shows all transitional stages from semi-coherent Triassic sequences to isolated blocks and finally into well mixed sands. This member is interpreted to represent one singular catastrophic event, a submarine landslide.

Members 1-3 exclusively contain Triassic and Liassic carbonate clasts. Basement clasts appear in Member 4 ($< 10\%$) and become important in Member 6 ($> 10\%$) while Member 5 exclusively contains Middle Triassic carbonate clasts.

The depositional geometry (fig. 7) of these breccia members is characterized by a basal contact which is concordant to the frequently slumped Liassic limestones in an E-W direction. However, the thickness of the Vizan Breccia decreases towards the west. This change in thickness indicates an apparent tilting of the base by some 8° (angle β in fig. 7) if the turbidites of member 6 are assumed to approximately represent a former horizontal level.

In a N-S direction angular unconformities are far more pronounced. Over a short distance of 600 m the base of the Vizan Breccia Formation cuts through the Liassic and Upper Triassic sediments. In addition, younger breccia members are seen to cut off older breccia members until member 4 forms the stratigraphic basis of the breccias at the southernmost exposures. In this direction an apparent tilt of 24° is inferred (angle α in fig. 7).

In three dimensions the Upper Triassic and Liassic bedrock appears to have been tilted by some 25° towards the NNE. In view of the tectonic flattening in a direction perpendicular to bedding (F1 schistosity is subparallel to bedding) this angle represents a minimum estimate.

The direction of sediment transport was roughly from S to N as inferred from three sources of information. Firstly the distal termination of some of the turbidites are found in the Gelbhorn subunit 1b which comes to lie to the north of the Muttolta region (Gelbhorn subunit 1a) after unfolding the major F1 closure between these subunits. Secondly, the few transport indicators (bottom marks, ripples) do at least not contradict a transport direction to the north. Thirdly, the contacts between individual breccia members become more conformable going from S to N (especially the contact at the base of member 4) indicating a transition from a southerly proximal region characterized by erosion and resedimentation into a more conformable northerly distal region.

Combining the evidence for the direction of tilting of the bedrocks with the inferred direction of sediment transport, it appears that the bedrock was tilted away from the source area. Such a geometry is incompatible with the classical situation of a domino-type extensional basin, where the turbidites are shed away from the fault scarp and unconformably onto bedrock dipping towards the fault, i.e. in a direction opposite to sediment transport [Eberli, 1987]. A transpressional scenario, as discussed in the final section, explains the observed geometry much better.

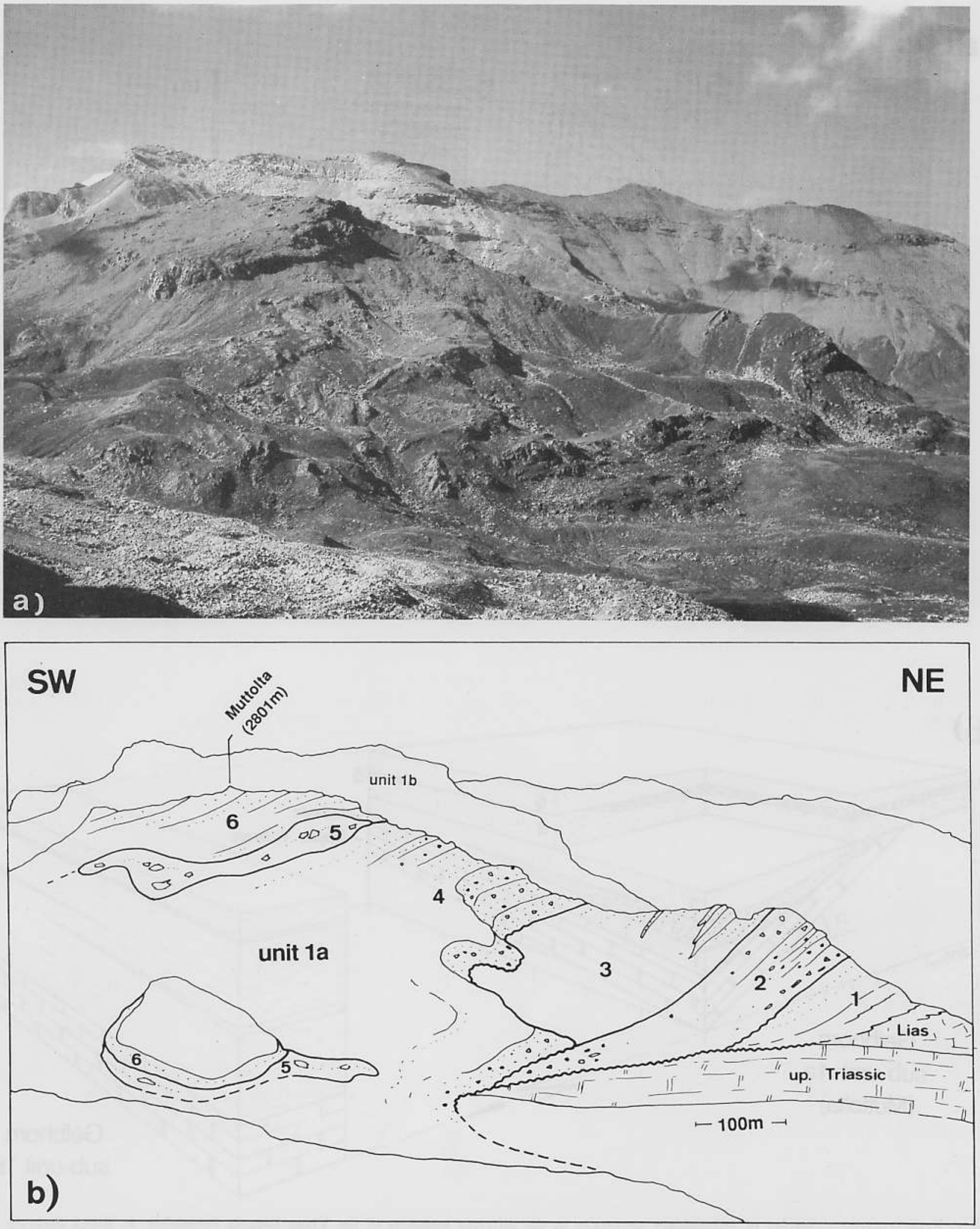

FIG. 6. – a) View of the Muttolta area in the west-Schams showing the Vizan Breccia Formation. b) Drawing after photograph, displaying the geometric relation between the different breccia members (1-6) and the underlying formations.

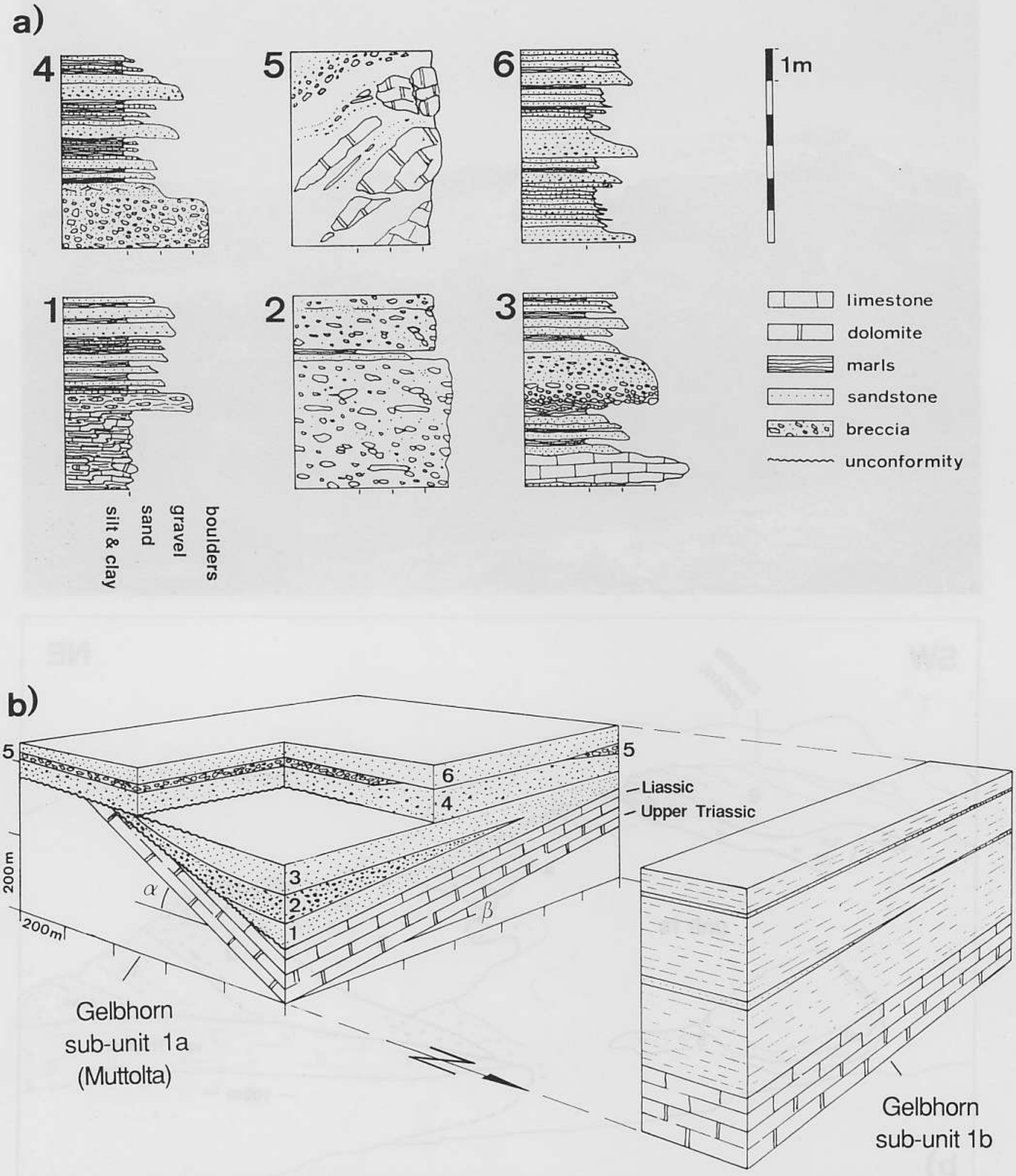

FIG. 7. – a) Representative examples of sedimentary sequences in the different members of the Vizan Breccia Formation. b) Block diagram of the Muttolta area, showing the tectono-sedimentary geometry of the area (block to the left) and the relation to the distal resediments (mainly sandstones) in the subunit 1b (block to the right).

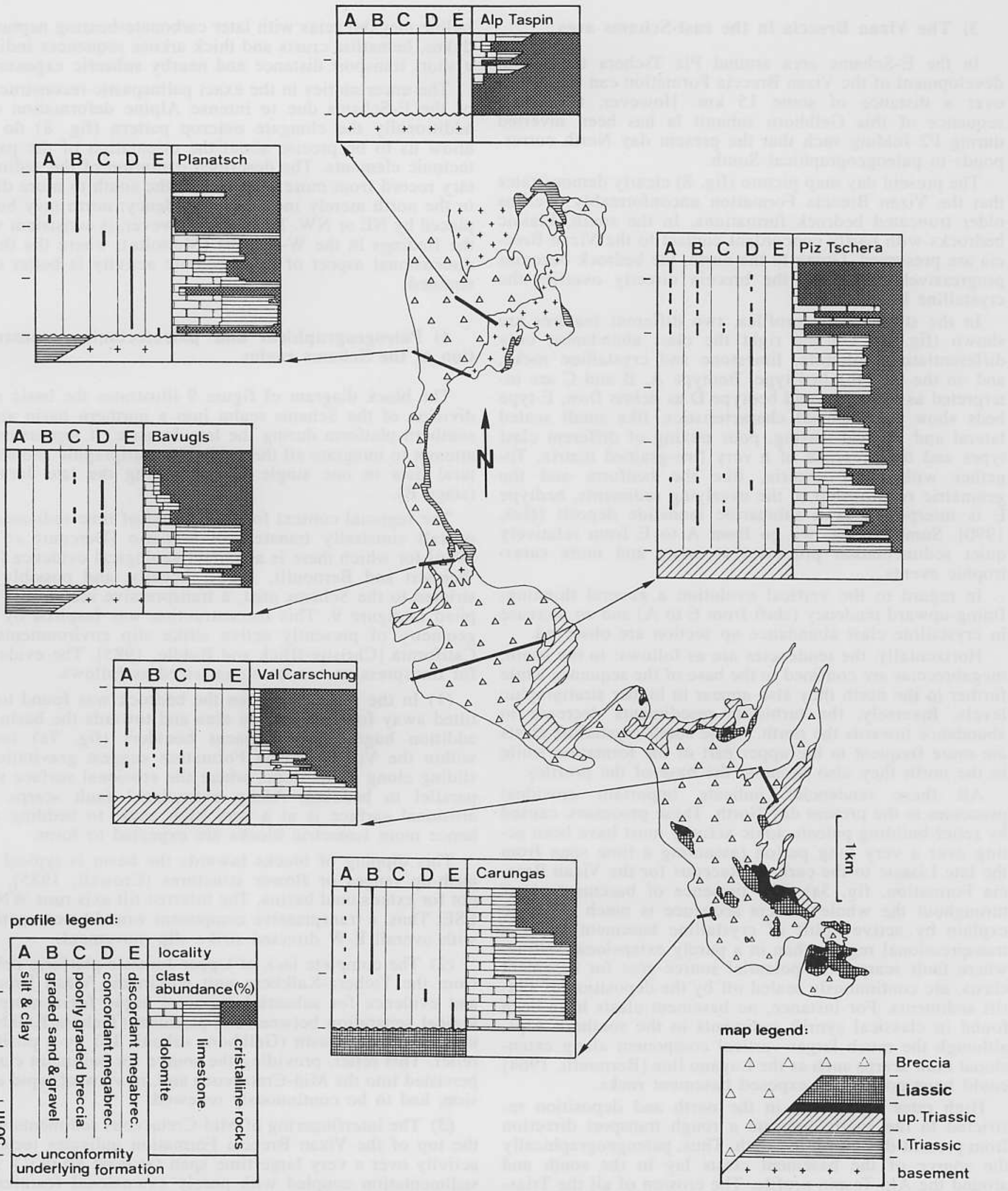

FIG. 8. – Map view of the Vizan Breccia Formation in the east-Schams, which lies on crystalline basement in the northern part and on Liassic sediments in the southern part. Stratigraphic profiles through the formation show the evolution of sediment type and clast type.

3) The Vizan Breccia in the east-Schams area

In the E-Schams area around Piz Tschera the lateral development of the Vizan Breccia Formation can be studied over a distance of some 15 km. However, the entire sequence of this Gelbhorn subunit la has been inverted during F2 folding such that the present day North corresponds to paleogeographical South.

The present day map picture (fig. 8) clearly demonstrates that the Vizan Breccia Formation unconformably overlies older truncated bedrock formations. In the south, Liassic bedrocks with partly concordant contact to the Vizan Breccia are preserved. Going to the north, the bedrock becomes progressively older till the breccia directly overlies the crystalline basement.

In the stratigraphic profiles, two different features are shown (fig. 8). On the right the clast abundance, only differentiating dolomite, limestone and crystalline rocks, and on the left, the bed type. Bedtype A, B and C are interpreted as turbidites and bedtype D as debris flow. E-type beds show very special characteristics, like small scaled lateral and vertical sorting, poor mixing of different clast types and the presence of a very fine-grained matrix. Together with other criteria, like the bedform and the geometric relationship to the overlying sediments, bedtype E is interpreted as a submarine landslide deposit [Hsü, 1990]. Summarizing, we go from A to E from relatively quiet sedimentation processes to more and more catastrophic events.

In regard to the vertical evolution a general thinning-fining-upward tendency (shift from E to A) and an increase in crystalline clast abundance up section are observed.

Horizontally, the tendencies are as follows: in the south, megabreccias are confined to the base of the sequence while further to the north they also appear in higher stratigraphic levels. Inversely, the turbiditic resediments decrease in abundance towards the north. In the south crystalline clasts are more frequent in the upper part of the formation while in the north they also occur at the base of the profiles.

All these tendencies indicate important erosional processes in the present day North. These processes, caused by relief-building paleotectonic activity must have been acting over a very long period (assuming a time span from the late Liassic to the early Cretaceous for the Vizan Breccia Formation, fig. 3a). The presence of basement clasts throughout the whole breccia sequence is much easier to explain by active uplift of crystalline basement under a transpressional regime than in a purely extensional setting, where fault scarps, the potential source area for basement clasts, are continuously sealed off by the deposition of synrift sediments. For instance, no basement clasts have been found in classical synrift sediments in the southern Alps, although the much larger vertical component along extensional fault scarps such as the Lugano line [Bernoulli, 1964] could have potentially exposed basement rocks.

High rates of erosion in the north and deposition restricted to the south, indicate a rough transport direction from present-day North to South. Thus, paleogeographically the source of the basement clasts lay in the south and around the Alp Taspin profile. The erosion of all the Triassic and Liassic cover (600-800 m) can only be explained by substantial uplift in this southern area. Exclusively crystalline megabreccias with later carbonate-bearing neptunian dykes, hematitic crusts and thick arkose sequences indicate a short transport distance and nearby subaeric exposure.

The uncertainties in the exact palinspastic reconstruction of the E-Schams due to intense Alpine deformation and, additionally the elongate outcrop pattern (fig. 8) do not allow us to be precise about the orientation of the paleotectonic elements. The described evolution of the sedimentary record from more proximal in the south to more distal in the north merely indicates a tendency; north may be replaced by NE or NW. The trend, however, is consistent with the findings in the W-Schams (Muttolta), where the three-dimensional aspect of paleotectonic activity is better constrained.

4) Paleogeographical and paleotectonic reconstruction of the Schams realm

The block diagram of figure 9 illustrates the basic subdivision of the Schams realm into a northern basin and a southern platform during the late Jurassic. It represents an attempt to integrate all the available stratigraphic and structural data in one single picture during the late Jurassic (stage B).

The regional context for that period of time indicates an overall sinistrally transtensive scenario [Dercourt *et al.*, 1986] for which there is abundant geological evidence [e.g. Weissert and Bernoulli, 1985]. Locally, and possibly restricted to the Schams area, a transpressive scenario is implied in figure 9. This reconstruction was inspired by the geometry of presently active strike slip environments in California [Christie-Blick and Biddle, 1985]. The evidence for transpression can be summarized as follows.

(1) In the Muttolta region the bedrock was found to be tilted away from the source area and towards the basin. In addition huge platy sediment boulders (fig. 7a) found within the Vizan Breccia Formation suggest gravitational sliding along a dip slope, where the erosional surface runs parallel to bedding. Along extensional fault scarps the erosional surface is at a very high angle to bedding and hence more isometric blocks are expected to form.

This dipping of blocks towards the basin is typical for push-up ranges or flower structures [Crowell, 1985], but not for extensional basins. The inferred tilt axis runs WNW-ESE. Thus, a transpressive component would be compatible with overall E-W directed strike slip movement.

(2) The complete lack of Upper Jurassic platform debris from the Tschera-Kalkberg unit within the Vizan Breccia and evidence for subaerial exposure argue for a morphological separation between the platform (Tschera-Kalkberg unit 2) and the basin (Gelbhorn subunit 1b) by a positive relief. This relief, providing the source for basement clasts, persisted into the Mid-Cretaceous and, in view of rapid erosion, had to be continuously renewed.

(3) The interfingering of Mid-Cretaceous sediments with the top of the Vizan Breccia Formation indicates tectonic activity over a very large time span (at least 40 m.y.). Resedimentation coupled with purely extensional features is confined to the rifting period and terminates with the onset of ocean floor spreading. Only strike-slip-movements, in

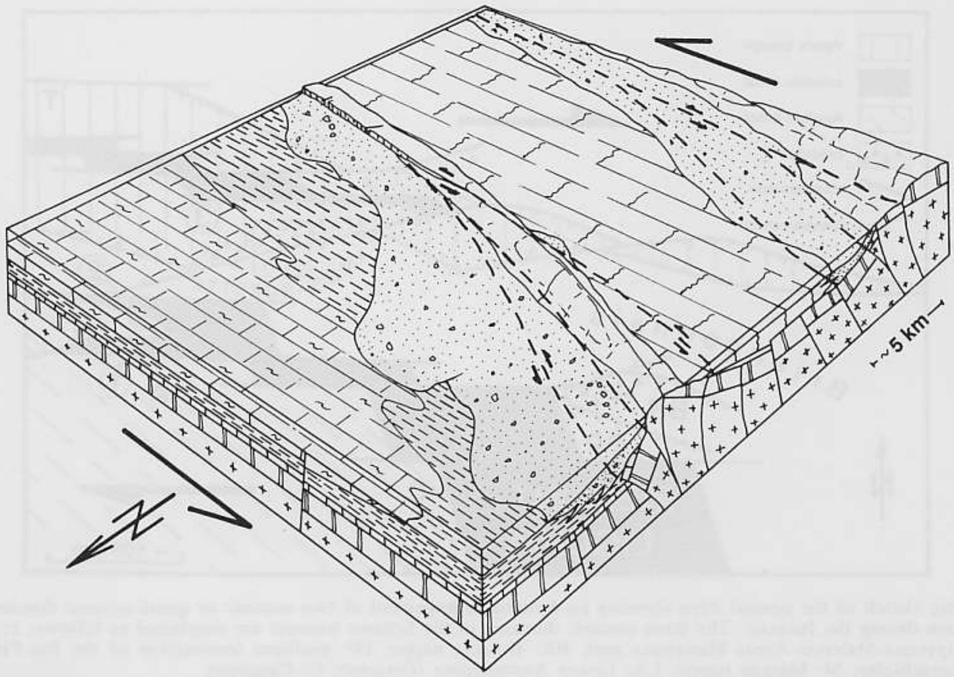

FIG. 9. – Reconstruction of the Schams sedimentary area in a transpressive regime during the late Jurassic epoch (for the legend of the lithologies see fig. 3).

our case with a transpressional component, can explain the continuous activity.

(4) The reduced thickness of syn-rift sediments and the absence of the classical deep sea post-rift association (radiolarites and pelagic limestones) indicate moderate subsidence for the Schams area. But small scale pronounced paleogeographical differentiation, deep reaching erosion and high-energy resedimentation indicate strong paleotectonic activity. Low subsidence combined with strong tectonic activity is hard to explain in an extensional context; a transpressional context fits better.

It is very likely that the reconstruction in figure 9 oversimplifies a more complex reality. The constraints in N-S direction are quite good, in E-W direction they are rather poor. A final chapter will present an attempt to integrate the local transpressive paleotectonic activity (fig. 9) into a larger scale synthesis (fig. 11).

V. – Synthesis and discussion

1) Paleogeographical and paleotectonic configuration

In view of the considerable complexities of Alpine deformation the paleotectonic sketch map of the situation during the late Jurassic (fig. 10) must only be regarded as a first approximation. Caution is particularly indicated with regard to the strike of the postulated paleotectonic fault zones and the width of the domains of oceanic crust. The picture presented is led by the following principal results of our combined structural and sedimentological approach and, additionally, by previously published reconstructions [in particular: Kelts, 1981; Weissert and Bernoulli, 1985; Trümpy, 1988].

a) According to our reconstruction the Gelbhorn unit represents the proximal and distal parts of a basin situated to the north of the Tschera-Kalkberg unit which is considered to represent the eastern equivalent of the Briançonnais platform. Both these two units of the Schams nappes correspond to the Falknis and Sulzfluh units which have been transported further to the north during Tertiary thrusting. The breccias of the Gelbhorn and Falknis nappes occupy a different paleogeographic position when compared to the Breccia nappe of W-Switzerland. While the latter mark the transition into the more internal Pre-Piemontais and the Piemont-Liguria oceanic domain the former is interpreted to mark the transition into the Gelbhorn basin and the still more external ophiolite zone 3 and the N-Penninic Bündnerschiefer and Flysch.

b) Based on sedimentological and paleotectonic arguments the breccias of Gelbhorn subunit 1b are interpreted to have formed in a locally transpressive regime. Hence a WNW-ESE trending strike was chosen for tracing this major transpressive lineament within a regime of overall sinistral transtension, indicated by overall plate tectonic constraints [Dercourt *et al.*, 1986] and previous tentative reconstructions [Weissert and Bernoulli, 1985]. Local transpression in the Schams area indicates that on a much larger scale the transcurrent component of transtension was by far more substantial than the tensional component in E-Switzerland and probably the eastern Alps in general. Also the paleotectonic evolution within the Schams area is characterized

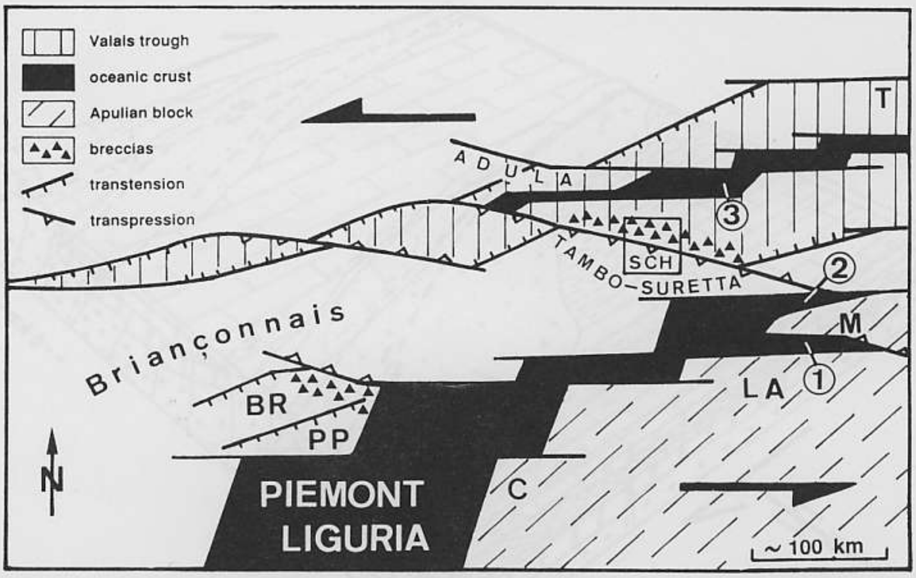

FIG. 10. – Paleogeographic sketch of the central Alps showing en-échelon arrangement of two oceanic or quasi-oceanic domains forming in an overall sinistral transtension system during the Jurassic. The three oceanic domains in the Schams transect are numbered as follows: 1: Platta unit; 2: Malenco-Lizun-Avers unit; 3: Chiavenna-Malenco-Areua-Martegnas unit; BR: Breccia nappe; PP: northern termination of the Pre-Piemontais; SCH: Schams nappes; T: Tauern Bündnerschiefer; M: Margna nappe; LA: Lower Austroalpine (Grisons); C: Canavese.

by ongoing rifting and/or transcurrent faulting until Mid-Cretaceous times, in contrast to the neighbouring S-Penninic and Austroalpine domains.

c) The Margna nappe is only tentatively interpreted to represent a ribbon continent with Austroalpine affinities [Liniger and Guntli, 1988], between ophiolite zones 1 and 2 (fig. 1) and near the E-termination of the Piemont-Liguria oceanic crust [following arguments of Trümpy, 1988]. However, Cretaceous backthrusting could also be responsible for this duplication into ophiolite zones 1 and 2.

d) The ophiolites of the Areua-Martegnas ophiolitic zone 3 are considered to have originally formed to the north of the Schams area and hence somewhere within or at the S-margin of the Valais trough. In spite of the considerable lithological similarities between Martegnas and Platta ophiolites we are forced to place the Martegnas ophiolites to the north of the Schams area on the basis of our kinematic inversion of F2 folding and contrary to previous interpretations [Streiff, 1962; Eiermann, 1988]. It is by no means certain that all the ophiolitic remains of ophiolitic zone 3 (fig. 1) formed near one and the same oceanic spreading center (as depicted for simplicity in figure 11). Alternatively, some of them could mark sites of predominantly transcurrent motions (oceanic fracture zones) within severely thinned continental crust.

e) The overall geometry of the eastwards broadening N-Penninic Valais trough [Trümpy, 1980, 1988], characterized by pull-apart basins separated by locally transpressive fault zones is inspired by the model of Kelts [1981] who stressed the analogy of the Valais trough to the situation in the gulf of California. We also think that this paleotectonic setting is particularly favourable for massive erosion and redeposition leading to a very thick pile of Bündnerschiefer.

Thus, it appears that the Piemont-Liguria ocean cannot be traced as a continuous spreading center into the area of the Tauern window. Instead we propose en-échelon spreading during sinistral transtension between the Apulian block and the European foreland. The Schams area and their former crystalline substratum (Tambo-Suretta) represent a continental fragment caught between the eastwards terminating Piemont-Liguria and the westwards terminating Valais oceanic spreading centers and/or oceanic fracture zones. An interesting consequence of this en-echelon spreading geometry is that the eastern continuation of the Schams paleogeographic realm will eventually come to lay near the northern margin of Apulia. Strong similarities during the Triassic to early Jurassic evolution between the Tasna nappe (easternmost part of the Briançonnais *s.l.* outcropping in the Engadine window, Gruner [1981], Trümpy [1972]) and Austroalpine elements additionally support this view.

2) Consequences of the paleotectonic configuration for the orogenic evolution

The strong influence of the paleotectonic features on local Alpine tectonic features within the Schams area have already been mentioned: e.g. detachment of thin basement slivers at the sites of unconformities where the Triassic décollement horizons were eroded; pre-determination of F1 fold hinges at the sites of extremely rapid facies changes.

On a regional scale the en-échelon reconstruction presented in figure 10 could help to explain the following major structural and metamorphic differences in the Alpine evolution of eastern and western Switzerland.

a) The Briançonnais domain forms part of the foreland thrust belt in W-Switzerland (Prealps) and largely escaped penetrative tectonic overprint and associated metamorphism. In E-Switzerland the continuation of the Briançonnais is found in a more internal position (i.e. nearer to the Apulian margin). Consequently it was more penetratively deformed and metamorphosed, and additionally, later overridden by the Tambo and Suretta basement nappes.

(b) Another striking difference concerns the tectonometamorphic evolution of the neighbouring Austroalpine domains. The Sesia-Dent Blanche units adjacent to a Piemont-Liguria ocean of considerable width underwent subduction-related HP metamorphism [e.g. Compagnoni *et al.*, 1977]. The Austroalpine units of Switzerland and Austria, however, situated adjacent to a narrow or non-existing Piemont-Liguria ocean largely escaped such a HP overprint because no immediately neighbouring ocean wide enough was available for subduction. They generally exhibit no metamorphism or normal greenschist to amphibolite facies metamorphism in the Cretaceous [e.g. Frank, 1987]. According to Frank *et al.*, [1987] HP metamorphism, and consequently subduction, in Austria is restricted to the paleogeographically northernmost part of the Pennine basin (Valais trough ?) outcropping in the Tauern window. This would be in agreement with our scheme depicted in figure 10, suggesting that a truly oceanic domain is expected in a more external position (Valais trough) for the Tauern cross section.

3) The Cretaceous orogenic evolution

Within the Schams nappes only the southernmost subunit 2c of the Tschera-Kalkberg unit was marginally affected by Eoalpine tectonism. However, the onset of convergence associated with the formation of an accretionary wedge is well documented for the suture between the Platta-Arosa ophiolitic unit and the Austroalpine nappes [Ring *et al.*, 1988], including the Margna nappe [Liniger and Guntli, 1988]. We tentatively attribute deformation within the S-Penninic Bündnerschiefer and imbrication within the Lizun-Forno-Malenco ophiolitic units (ophiolite zone 2 in fig. 1 and 10) to such an accretionary process. Internal deformation within the Austroalpine (Apulian plate), and, locally metamorphism up to amphibolite grade [Schmid and Haas, 1989] are also of Cretaceous age. This suggests that further east (eastern Alps) collision of the Apulian plate with the European plate (flakes of continental crust represented by the Pennine units of the Tauern window) was already under way at the same time. All authors cited above record top to the W to NW movement during this Eoalpine orogeny. This is hardly compatible with the classical pictures of subduction and associated accretionary prism formation in a direction perpendicular to the former oceanic domains carried over from recent analogues. A dextral transpressive regime is far more realistic, as pointed out by Ratschbacher [1986]. There is strong geochronological evidence that Cretaceous deformation and metamorphism were followed by rapid cooling before 70 Ma ago [Thöni, 1986 and references cited therein].

Cretaceous deformations and metamorphism have also been postulated for the Adula basement nappe which would occupy a much more external position in our figure 10. If the yet unpublished and debatable age dates (Hunziker *et al.*, [1989] quote a time span between 76 and 180 Ma!) from the Adula nappe represent real events and turn out to be Eoalpine indeed major modifications in either the paleogeographic reconstruction or the kinematics of Alpine orogeny are necessary. However, in the absence of reliable and published geochronological data it is too early to speculate on this problem. It has to be mentioned, however, that there is no need at all to regard the Adula basement as the crystalline basis for the Valais Bündnerschiefer (as depicted in figure 10) since all contacts of this basement and surrounding sediments are of tectonic nature.

As a consequence of these uncertainties and, of course, severe Tertiary orogeny described in the next sections, a reconstruction of the Cretaceous suture between Austroalpine units, ophiolite zones 1 and 2 and possibly also parts of the European continental margin is very difficult.

4) The main phase of nappe emplacement in the Tertiary

The main phase of detachment of the Schams cover rocks, associated with top to the NW-NNW thrusting and D1 isoclinal folding very probably falls into the Middle to late Eocene based on the following arguments: (1) sedimentation in the Briançonnais *s.l.* of the Falknis and Sulzfluh units and in the Prealps of W-Switzerland continued into the Eocene; (2) the transport direction during F1 was inferred to be NW to NNW directed, while Ring *et al.*, [1988], Schmid and Haas [1989] and Liniger and Guntli [1988] report W-directed movements during the Cretaceous for the Austroalpine and Platta units, (3) the Arblatsch Flysch is additionally affected by a first deformational event which may well correspond to the Schams F1 event. Furthermore, preliminary radiometric K-Ar age determinations on white mica, lying within the S1 schistosity affecting Triassic sediments of the Schams nappes, give early Oligocene ages (pers. comm. Hunziker and Húon).

However, the notion of two strictly separated Cretaceous and Tertiary orogenic cycles (Eoalpine and Mesoalpine in the sense of Trümpy, [1973]) may be misleading. The data of Ring *et al.*, [1988] suggest a rather continuous change in thrusting direction from top to the west into top to the north and across the Cretaceous-Tertiary boundary associated with successive accretion of Penninic elements during foreland propagation of deformation.

D1 deformation in the Schams and surrounding tectonic units led to the pre-F2 stacking of units in the following stacking order (from structurally lower to structurally higher): (1) Adula basement and detached N-Penninic Bündnerschiefer, (2) ophiolite zone 3 (Chiavenna-Areua-Martegnas), (3) Schams cover nappes, detached and in front of their original crystalline substratum (Suretta-Tambo), (4) a S-Penninic accretionary wedge of Avers Bündnerschiefer and ophiolite zone 2 (Lizun-Forno-Malenco) and (5) the Austroalpine nappes, ophiolite zone 1 (Arosa-Platta), and the Margna nappe.

At this stage it is impossible to be very specific about the question as to from which part of the present day Tambo and Suretta basement the Schams nappes have been detached, although the petrographic composition of detached basement slivers within the Schams nappes and of basement components in the Vizan Breccia is identical to the Rofna Porphyry also found in the Suretta nappe. At least part of the Schams nappes (Gelbhorn unit) must have been derived from the Tambo basement containing similar lithologies (e.g. Truzzo Granite) since they can be traced along the front of the Tambo nappe (fig. 1) and into the northernmost part of the Misox "synclinal" zone. However, we cannot exclude the possibility that more internal Schams units were originally detached in an area now occupied by the Splügen "synclinal" zone, situated between Suretta and Tambo basement nappes.

5) Post-nappe folding during the late Oligocene to Miocene

The structural analysis provides evidence for large scale post-nappe folding, including backthrusting and backfolding within the flat lying part of this transect, north of the southern steep belt near the Insubric line and south of the northern steep belt forming the "root zone" of the Helvetic nappes. Manifestations of backfolding and backthrusting are widespread within the northern and southern steep belts [Milnes, 1974] and their formation is generally believed to be due to post-collisional shortening during the late Tertiary [Schmid *et al.*, 1987, 1989]. The importance of post-nappe refolding in the Schams area has been recognized early by Haug [1925], Streiff [1939, 1962] and Milnes and Schmutz [1978] but age and kinematic significance remained enigmatic. In this section we attempt to place this F2 folding into a kinematic context within the overall orogenic evolution along this transect.

It is clear that F2 refolding must be of late or post Eocene age since it also affects the Lower Eocene sediments of the N-Pennine Arblatsch Flysch. During this event the structurally higher previously cooled [Hurford *et al.*, 1989] Austroalpine units and the Platta unit can be considered as a relatively rigid orogenic lid in the sense of Laubscher [1983], whose rheology is governed by frictional strength. While the units below this orogenic lid were affected by viscous F2 refolding this orogenic lid remained in an upright position, together with the Arosa-Platta ophiolitic suture (ophiolite zone 1 in figs. 1 and 10).

However, as was argued in an earlier chapter this orogenic lid, including the Margna nappe and ophiolitic zones 1 and 2, was transported by at least 50 km to the north and over the N-Penninic sediments including the Arblatsch Flysch during the Tertiary, reworking the earlier Cretaceous suture.

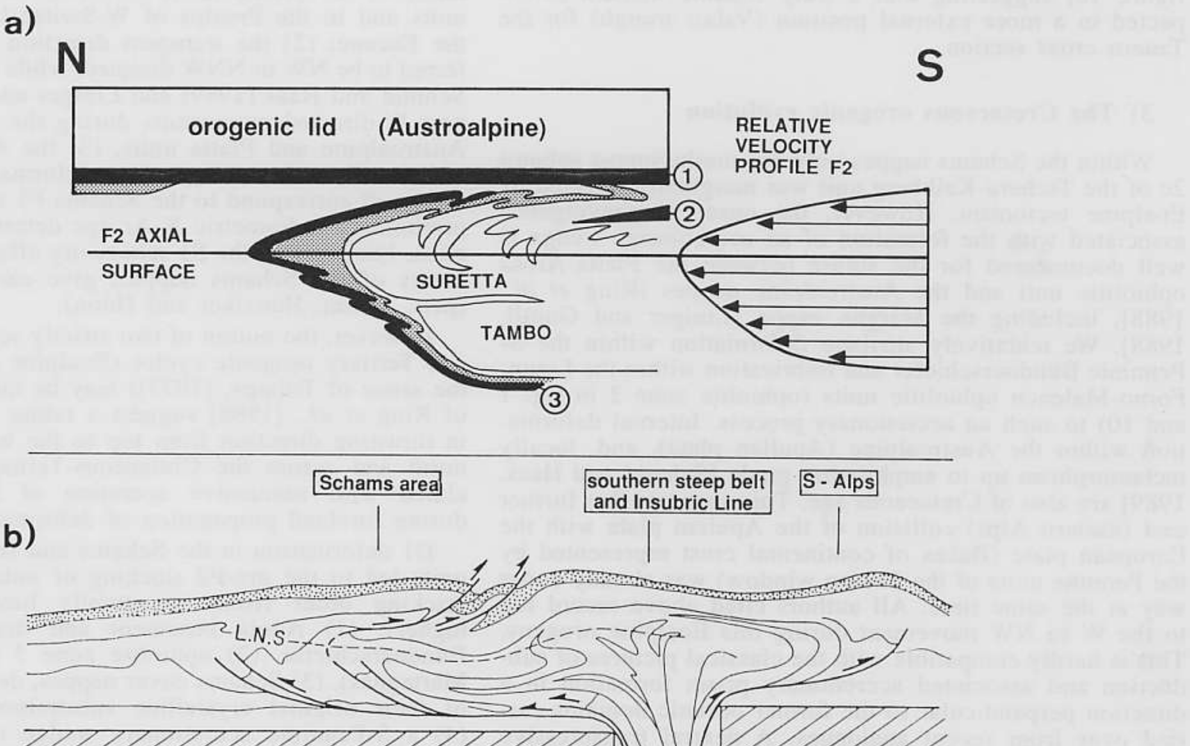

FIG. 11. – a) Qualitative relative velocity profile leading to F2 refolding within the Schams nappes (stippled) together with the enveloping ophiolite unit 3 (Areua-Martegnas) and the N-Penninic Bündnerschiefer and Flysch. The F2 axial surface of the Niemet-Beverin fold is considered to mark the site of a line of no shear strain (LNS) as outlined in figure 10b.
b) Synthetic section through the model of Merle and Guillier [1989]. Note refolding and reverse sense of shear to both sides of the LNS and within silicone putty below the sand layer (stippled) representing the orogenic lid. Horizontal intrusion is linked to vertical extrusion of silicone putty between two metal indenters (cross-ruled).

A kinematic model of F2 deformation and large scale refolding of the Schams units, including ophiolite zone 3 and parts of the N-Penninic Bündnerschiefer and Flysch must explain the following features: (1) a mechanism for the inversion of this F1 stack of tectonic units over a distance of some 30 km (length of the upper inverted limb of the Niemet-Beverin fold) has to be found; (2) the orogenic lid (Austroalpine units and Arosa-Platta Ophiolites) remains largely unaffected by this F2 refolding; (3) the spectacular flatlying backfolds and backthrusts affecting the upper interface between Suretta basement and its authochthonous cover, and additionally, the E-Schams nappes and the frontal part of the Avers Bündnerschiefer.

Recent modelling work by Merle and Guillier [1989] resulted in a geometrically and kinematically very similar velocity profile as suggested for F2 (fig. 11) within a viscous medium (silicone putty) underlying an orogenic lid governed by Navier-Coulomb frictional strength (sand). This modelling produced a relative velocity profile resulting in a line of no shear strain (LNS, corresponding to the axial trace of the Niemet-Beverin fold, fig. 11) bounded by top to the N-shear below and top to the S-shear above the LNS, i.e. the axial trace of the Niemet-Beverin fold. This situation essentially arises from intense post-collisional shortening between two rigid pistons, simulating shortening across the southern steep belt and the associated Insubric line, leading to rapid uplift of the Bregaglia (Bergell) and Gruf units (fig. 2). As viscous crustal material protrudes in a vertical direction it has to escape laterally (to the north and south below the orogenic lid (sand layer). The experimental configuration was choosen such as to produce indentation of part of the Apulian plate which in turn results in a N-directed viscous horizontal intrusion of a large part of this material (corresponding to the flat-lying Penninic nappes north of the southern steep belt). At the same time some of this material is backthrusted and backfolded to the south (along the Insubric line and within the southern Alps). This viscous horizontal intrusion mechanism offers a viable kinematic model because it satisfactorilly explains the above mentioned major features associated with F2 deformation. Additionally, it is based on modern concepts of rheological stratification [Ranalli and Murphy, 1987].

The inversion of the F1 stack would be the result of top to the south simple shear in the hangingwall of the Niemet-Beverin axial trace, affecting (1) originally S-dipping isoclinal F1 folds at the basement-cover interface of the Suretta nappe (fig. 2) and (2) a S-dipping F1 stack of N-Penninic sediments, ophiolite zone 3, Schams nappes and frontal parts of the Avers Bündnerschiefer. The orogenic lid remains unaffected by this refolding. It may even be simultaneously thrusted to the north, in which case the velocity profile indicated in figure 11 may merely represent deviatoric components of a larger scale subhorizontal top to the N-velocity profile. The intense backthrusting and backfolding above the Niement-Beverin axial trace indicates an asymmetry in width of the relative velocity profile to both sides of the LNS, and consequently higher amounts of deviatoric shear strains above the LNS, as compared to the region below the LNS (see fig. 11).

This asymmetry could be responsible for the observation that the F2 minor folds below the Niemet-Beverin axial trace, schematically shown in figure 11, exhibit a vergence which is consistent with the N-closing major fold hinge, while the vergence of F2 minor folds above the Niemet-Beverin axial trace are inconsistent with a folding mechanism in the strict sense. It has to be noted however that the F2 minor folds are almost parallel (NW-SE, fig. 4a) to the F2 movement direction in the E-Schams whereas they are generally more perpendicular to the F2 movement direction in the W-Schams area (WSW-ENE to WNW-ESE, fig. 4a). This change in orientation of F2 fold axes is consistent with the observed difference in intensity of F2 shearing. More intense top to the S-shearing above the Niemet-Beverin axial trace probably led to the rotation of F2 fold axes into near-parallelism with the overall movement direction during F2 (N-S or NNW-SSE).

We thus propose large scale F2 refolding to be caused by a complex flow pattern within the still viscous Pennine units below the orogenic lid of Austroalpine and Platta units. Strain intensity during F2 deformation and within the sedimentary units may be additionally enhanced by the indentation of the relatively more flow resistant Suretta-Tambo basement cores (they typically only exhibit crenulation folding during F2) into the softer cover rocks. If F2 is indeed seen in conjunction with the formation of the southern steep belt its age would have to be placed into the late Oligocene to Miocene, i.e. the time of backthrusting motions in the vicinity of and along the Insubric line further to the south [Schmid *et al.*, 1987, 1989].

It thus appears that post-collisional Neogene deformation substantially reworked the entire Penninic stack of nappes below the Austroalpine orogenic lid. This imposes severe restrictions to the interpretation of the southern part of the NFP-20 East seismic profile which lies entirely within this zone of postcollisional reworking. The traces of earlier (Cretaceous and Eocene) collisional events have been severely modified. Also, the astonishingly high degree of ductility of the crust, even at lower greenschist facies conditions, argues against oversimplifying interpretations of seismic reflection profiles in terms of ramp and flat geometries.

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References

ALLEMANN F. (1957). – Geologie des Fürstentums Liechtenstein (Südwestlicher Teil) unter besonderer Berücksichtigung des Flyschproblems. – *Jb. Hist. Ver. Liechtenstein.*

BAUD A. & SEPTFONTAINE M. (1980). – Présentation d'un profil palinspastique de la nappe des Préalpes médianes en Suisse occidentale. – *Eclogae. Geol. Helv.*, Basel, 73, pp. 651-660.

BERNOULLI D. (1964). – Zur Geologie des Monte Generoso (Lombardische Alpen). – *Beitr. Geol. Karte Schweiz [N.F.]*, Bern, 118, 135 p.

CHRISTIE-BLICK N. & BIDDLE K. (1985). – Deformation and basin formation along strike-slip faults. – *Spec. Publ. Soc. Econ. Paleont. Mineral.*, Tulsa, 37, pp. 1-37.

COMPAGNONI R., DAL PIAZ G.V., HUNZIKER J.C., GOSSO G., LOMBARDO B. & WILLIAMS P.F. (1977). – The Sesia-Lanzo zone, a slice of subducted continental crust with the Alpine high pressure low temperature assemblages in the western Italian Alps. – *Rend. Soc. Ital. Mineral. Petrol.*, Milano, 33, 281-334.

CROWELL J.C. (1985). – The recognition of transform terrane dispersion within mobile belts. *In:* HOWELL D.G. Ed., Tectonostratigraphic terranes of the Circum-Pacific region. – Circum-Pacific Council on Energy and Mineral Resources. – *Earth Science Series*, 1, pp. 51-61.

DERCOURT J. & 18 others. (1986). – Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias. *In:* AUBOUIN J., LE PICHON X. & MONIN A.S. Eds., Evolution of the Tethys. – *Tectonophysics*, Amsterdam, 123, pp. 241-315.

DEUTSCH A. (1983). – Alkaliamphibole und Stilpnomelan aus der südlichen Platta-Decke (Graubünden). – *Eclogae Geol. Helv.*, Basel, 76, pp. 295-308.

DIETRICH V., VUAGNAT M. & BERTRAND J. (1974). – Alpine metamorphism of mafic rocks. – *Schweiz. Mineral. Petrogr. Mitt.*, Zürich, 54, pp. 247-290.

EBERLI G.P. (1987). – Carbonate turbidite sequences deposited in rift-basins of the Jurassic Tethys Ocean (eastern Alps, Switzerland). – *Sedimentology*, Oxford, 34, pp. 363-388.

EIERMANN D. (1988). – Zur Stellung des Martegnas-Zuges. – *Eclogae. Geol. Helv.*, Basel, 81, pp. 259-272.

FRANK W. (1987). – Evolution of the Austroalpine elements in the Cretaceous. *In:* FLÜGEL H.W. & FAUPL P. Eds., Geodynamics of the eastern Alps. – Deuticke, Vienna, pp. 379-406.

FRANK W., HÖCK V. & MILLER Ch. (1987). – Metamorphic and tectonic history of the central Tauern window. *In:* FLÜGEL H.W. & FAUPL P. Eds., Geodynamics of the eastern Alps. – Deuticke, Vienna, pp. 34-54.

GANSSER A. (1937). – Der Nordrand der Tambodecke. – *Schweiz. Mineral. Petrogr. Mitt.*, Zürich, 17, pp. 291-523.

GRUNER U. (1981). – Die jurassischen Breccien der Falknis-Decke und altersäquivalente Einheiten in Graubünden. – *Beitr. Geol. Karte Schweiz*, Bern, N.F. 154, 136 p.

GULSON B. (1973). – Age relations in the Bergell region of the south-east Swiss Alps: with some geochemical comparisons. – *Eclogae Geol. Helv.*, Basel, 66, pp. 293-313.

HAUG (1925). – Contribution à une thèse stratigraphique des Alpes occidentales. – *Bull. Soc. géol. Fr.*, Paris, 28, pp. 97-244.

HSÜ K. (1990). – Physical principles in sedimentology, Heidelberg.

HUNZIKER J.C., DESMONS J. & MARTINOTTI G. (1989). – Alpine thermal evolution in the central and the western Alps. *In:* COWARD, M., DIETRICH D. & PARK R., Eds., Alpine tectonics. – *Geol. Soc. Spec. Publ.*, London, 45, pp. 353-367.

HURFORD A., FLISCH M. & JÄGER E. (1989). – Unravelling the thermo-tectonic evolution of the Alps: a contribution from fission track analysis and mica dating. *In:* COWARD M., DIETRICH D. & PARK R., Eds., Alpine tectonics. – *Geol. Soc. Spec. Publ.*, London, 45, pp. 369-398.

JÄCKLI H. (1941). – Geologische Untersuchungen im nördlichen Westschams (Graubünden). – *Eclogae Geol. Helv.*, Basel, 34, pp. 17-105.

JENKYNS H. (1980). – Cretaceous anoxic events: from continents to oceans. – *J. Geol. Soc.*, London, 137, pp. 171-188.

KELTS K. (1981). – A comparison of some aspects of sedimentation and translational tectonics from the Gulf of California and the Mesozoic Tethys, northern Penninic Margin. – *Eclogae Geol. Helv.*, Basel, 74, 2, pp. 317-338.

KRUYSSE H. (1967). – Geologie der Schamser Decken zwischen Avers und Oberhalbstein (Graubünden). – *Eclogae Geol. Helv.*, Basel, 49, pp. 1-78.

LAUBSCHER H. (1971). – The large-scale kinematics of the western Alps and the northern Appenines and its palinspastic implications. – *Am. J. Sci.*, New Haven, 271, pp. 193-226.

LAUBSCHER H. (1983). – Detachment, shear, and compression in the central Alps. – *Geol. Soc. Amer.*, Boulder, *Mem.* 158, pp. 191-211.

LEMOINE M., BAS T., ARNAUD-VANNEAU A., ARNAUD H., DUMONT T., GIDON M., BOURBON M., GRACIANSKY P.C. de, RUDKIEWICZ J.L., MÉGARD-GALLI J. & TRICART P. (1986). – The continental margin of the Mesozoic Tethys in the western Alps. – *Mar. Petrol. Geol.*, Amsterdam, 3, pp. 179-199.

LINIGER M. & GUNTLI P. (1988). – Bau und Geschichte des zentralen Teils der Margna Decke. – *Schweiz. Mineral. Petrogr. Mitt.*, Zürich, 68, pp. 41-54.

LÜDIN P. (1987). – Flysch und Mélangebildungen in der südpenninisch/unterostalpinen Arosa-Zone (Mittelbünden und Rätikon, Schweiz). – Diss. Univ. Basel.

MARTHALER M. & STAMPFLI G.M. (1989). – Les Schistes lustrés à ophiolites de la nappe du Tsaté: un ancien prisme d'accrétion issu de la marge apulienne? – *Schweiz. Mineral. Petrogr. Mitt.*, Zürich, 69/2, pp. 211-216.

MAYERAT A.-M. (1989). – Analyse structurale et tectonique du socle et de la couverture des nappes penniques du Rheinwald (Grisons). – These Univ. Neuchâtel.

MERLE O., COBBOLD P. & SCHMID S. (1989). – Tertiary kinematics in the Lepontine Dome. *In:* COWARD M., DIETRICH D. & PARKS R., Eds, Alpine tectonics. – *Geol. Soc. Spec. Publ.*, London, 45, pp. 153-171.

MERLE O. & GUILLIER B. (1989). – The building of the central Swiss Alps: an experimental approach. – *Tectonophysics*, Amsterdam, 165, pp. 41-56.

MILNES A. (1974). – Structure of the Pennine zone (Central Alps): a new working hypothesis. – *Geol. Soc. Amer. Bull.*, Boulder, 85, pp. 1727-1732.

MILNES A. & SCHMUTZ H. (1978). – Structure and history of the Suretta nappe (Pennine zone, Central Alps), a field study. – *Eclogae Geol. Helv.*, Basel, 71, 1, pp. 19-33.

MONTRASIO A. & TROMMSDORF V. (1983). – Guida all'excursione del massicco di Val Masino-Bregaglia Val Malenco occidentale, Sondrio. – *Mem. Soc. Geol. It.*, Padova, 26, pp. 421-434.

NABHOLZ W. (1945). – Geologie der Bündnerschiefergebirge zwischen Rheinwald, Valser- und Safiental. – *Eclogae Geol. Helv.*, Basel, 38, 1, pp. 1-119.

PANTIC N. & GANSSER A. (1977). – Palynologische Untersuchungen in Bündnerschiefern (vorläufige Mitteilung). – *Eclogae Geol. Helv.*, Basel, 70, pp. 59-82.

PAULI C. (1988). – Geologie des Averser Wissberg. – Unpubl. Diplomarbeit, ETH Zürich.

PERETTI A. (1985). – Der Monte-del-Forno-Komplex am Bergell-Ostrand: Seine Lithostratigraphie, alpine Tektonik und Metamorphose. – *Eclogae Geol. Helv.*, Basel, 78, pp. 23-48.

PFIFFNER O.A. (1977). – Tektonische Untersuchungen im Infrahelvetikum der Ostschweiz. – *Mitt. Geol. Inst. ETH u. Univ. Zürich (N.F.)*, 217, 432 p.

PFIFFNER O.A., FREI W., FINCKH P. & VALASEK P. (1988). – Deep seismic reflection profiling in the Swiss Alps: Explosion seismology results for line NFP-20 East. – *Geology*, Boulder, 16, pp. 987-990.

PFIFFNER O.A., KLAPER E., MAYERAT A.-M. & HEITZMANN P. (1990). – Structure of the basement-cover contact in the Swiss Alps. *In:* ROURE F., HEITZMANN P. & POLINO R., Eds., Deep structure of the Alps. – *Mém. Soc. géol. Fr.*, Paris, 156; *Mém. Soc. géol. suisse*, Zürich, 1; *Vol. spec. Soc. Geol. It.*, Roma, 1, pp. 247-262.

POLINO R., DAL PIAZ G.V. & GOSSO G. (1990). – Tectonic erosion at the Adria margin and accretionary processes for the Cretaceous orogeny of the Alps. *In:* ROURE F., HEITZMANN P. & POLINO R., Eds., Deep structure of the Alps. – *Mém. Soc. géol. Fr.*, Paris, 156; *Mém. Soc. géol. suisse, Zürich, 1; Vol. spec. Soc. Geol. It.*, Roma, 1, pp. 345-367.

RANALLI G. & MURPHY D. (1987). – Rheological stratification of the lithosphere. – *Tectonophysics*, Amsterdam, 132, pp. 281-295.

RATSCHBACHER L. (1986). – Kinematics of Austro-Alpine cover nappes: changing translation path due to transpression. – *Tectonophysics*, Amsterdam, 125, pp. 335-356.

RING U., RATSCHBACHER L. & FRISCH W. (1988). – Plate-boundary kinematics in the Alps: motion in the Arosa suture zone. – *Geology*, Boulder, 16, pp. 696-698.

SCHMID S.M., AEBLI H.R., HELLER F. & ZINGG A. (1989). – The role of the Periadriatic line in the tectonic evolution of the Alps. *In:* COWARD M., DIETRICH D. & PARK R., Eds., Alpine tectonics. – *Geol. Soc. Spec. Publ.*, London, 45, pp. 153-171.

SCHMID S.M. & HAAS R. (1989). – Transition from near-surface thrusting to intra-basement décollement; Schlinig thrust; eastern Alps. – *Tectonics*, Washington, 8, pp. 697-718.

SCHMID S.M., ZINGG A. & HANDY M. (1987). – The kinematics of movements along the Insubric line and the emplacement of the Ivrea zone. – *Tectonophysics*, Amsterdam, 135, pp. 47-66.

SCHMUTZ H.-U. (1976). – Der Mafit-Ultramafit Komplex zwischen Chiavenna und Val Bondasca (Prov. Sondrio, Italien; Kt. Graubuenden, Schweiz). – *Beitr. Geol. Karte Schweiz [N.F.]*, Bern, 149.

STAUB R. (1958). – Klippendecke und Zentralalpenbau; Beziehungen und Probleme. – *Beitr. Geol. Karte Schweiz [N.F.]*, Bern, 103, 184 p.

STREIFF V. (1939). – Geologische Untersuchungen im Ostschams (Graubünden). – Diss. Univ. Zürich, 235 p.

STREIFF V. (1962). – Zur östlichen Beheimatung der Klippendecken. – *Eclogae. Geol. Helv.*, Basel, 55, pp. 77-134.

STREIFF V., JÄCKLI H. & NEHER J. (1971/1976). – Geologischer Atlas der Schweiz 1:25 000: Blatt 1235 Andeer, mit Erläuterungen. – *Schweiz. Geol. Komm.*, Bern.

THÖNI M. (1986). – The Rb-Sr thin slab isochron method – an unreliable geochronologic method for dating geologic events in polymetamorphic terrains? – *Mem. Sci. Geol. Padova*, 38, pp. 283-352.

TRÜMPY R. (1960). – Paleotectonic evolution of the central and western Alps. – *Geol. Soc. Amer. Bull.*, Boulder, 71, 6, pp. 843-908.

TRÜMPY R. (1972). – Zur Geologie des Unterengadins. *In:* Ökologische Untersuchungen im Unterengadin, Lieferung I/4: Ergebnisse der wissenschaftlichen Untersuchungen im Schweizer Nationalpark. – *Komm. schweiz. natf. Ges. z. wiss. Erforschung des Nationalparks*, 12, pp. 71-87.

TRÜMPY R. (1973). – The timing of orogenic events in the central Alps. *In:* DE JONG & SCHOLTEN Eds., Gravity tectonics. – Wiley, London, pp. 229-251.

TRÜMPY R. (1980). – An outline of the geology of Switzerland. – Schweiz. Geol. Komm., Wepf, Basel, 104p.

TRÜMPY R. (1988). – A possible Jurassic-Cretaceous transform system in the Alps and the Carpathians. – *Geol. Soc. Amer., Spec. Paper* 218, Boulder, pp. 93-109.

TRÜMPY R. & HACCARD D. (1969). – Réunion extraordinaire de la Société géologique de France: Les Grisons. – *C.R. somm. Séan. Soc. géol. France*, Paris, 9, pp. 329-396.

WEISSERT H. & BERNOULLI D. (1985). – A transform margin in the Mesozoic Tethys: evidence from the Swiss Alps. – *Geol. Rundsch.*, Stuttgart, 74, pp. 665-679.

ZIEGLER W. (1956). – Geologische Studien in den Flyschgebieten des Oberhalbsteins (Graubünden). – *Eclogae. Geol. Helv.*, Basel, 49, pp. 1-78.