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Penninic cover nappes in the Prättigau half-window (Eastern Switzerland): Structure and tectonic evolution

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Key words: Alps, Penninic, Bündnerschiefer, Falknis nappe, Prättigau half-window, structural geology, Alpine tectonics

ZUSAMMENFASSUNG

Die Sedimentabfolge der zum Valaisan gehörenden Grava-Decke im Prättigau-Halbfenster der Ostschweiz besteht aus kretazischen Schiefern (Bündnerschiefer) und spätkretazisch/alttertiärem Flysch. Diese Gesteine wurden durch die folgenden alpinen Deformationsvorgänge überprägt: (D1a) Abscherung der Sedimentbedeckung einer südwärts abtauchenden Lithosphärenplatte und Akkretion der abgescherten Serien als Duplex an der Basis des Orogenkeils, ab etwa 50 Ma; (D1b) lokale Verfaltung der D1a-Strukturen; (D2) top-SE-Scherung und "Rückfaltung" in einem extensionalen Regime, zwischen 35 und 30 Ma; (D3) erneute kompressive Verformung im Zusammenhang mit interner Verkürzung der unterschobenen europäischen Kruste; dadurch Bildung von nordvergenten Falten (Lunschania-Antiform, Valzeina-Synform), kinematisch verbunden mit einer NNE-gerichteten Überschiebung am Kontakt zwischen der Grava-Decke und dem unterlagernden Infrahelvetischen Komplex, wobei diese Überschiebung eine östliche Fortsetzung der Glarner Hauptüberschiebung darstellt (nach 30 Ma); (D4) Bildung offener Falten mit südostfallenden Achsenebenen durch zusätzliche, SE-NW-gerichtete Verkürzung. Die Falknis-Decke (Briançonnais) im Gürgaletsch-Gebiet erfuhr eine ähnliche tektonische Prägung. Sie bildet einen eigenen Duplex aus zwei Schuppen (D1a), wurde lokal verfaltet (D1b), und schliesslich von top-SE-gerichteter extensionaler Scherung und damit verbundener "Rückfaltung" erfasst (D2), wobei sich die hier erstmals beschriebene Gürgaletsch-Scherzone bildete, welche als Nordfortsetzung und -ende der Turba-Mylonitzone aufgefasst wird.

ABSTRACT

The sedimentary sequence of the Grava nappe (Valaisan) in the Prättigau half-window of eastern Switzerland consists of Cretaceous calcschists ("Bündnerschiefer") and Late Cretaceous/Early Tertiary flysch. It records the following stages of Alpine deformation: (D1a) décollement of the sediment cover of a southward-subducted lithospheric slab and accretion of this cover as a hinterland-dipping duplex at the base of the orogenic wedge, beginning around 50 Ma; (D1b) local refolding of D1a structures; (D2) top-SE shearing and "backfolding" in an extensional regime, between 35 and 30 Ma; (D3) renewed contractional deformation related to internal shortening of the underthrust European crust and formation of north-vergent folds (Lunschania antiform, Valzeina synform) which are kinematically linked to a top-north-northeast shear zone at the base of the Grava nappe against the Infrahelvetic complex, representing the eastern, along-strike continuation of the Glarus overthrust (after 30 Ma); (D4) SE-NW-directed additional shortening leading to open folds with southeast-dipping axial surfaces. The Falknis nappe (Briançonnais) in the Gürgaletsch area, at the southern border of the Prättigau half-window, suffered a similar tectonic evolution. It formed its own small duplex consisting of two imbricates (D1a), was locally folded (D1b), and affected by top-SE extensional shearing and related "backfolding" (D2), kinematically linked to the newly identified Gürgaletsch shear zone which forms the northern continuation and termination of the well-known, D2 Turba mylonite zone.

1. Introduction

The aim of this study, which was carried out as a PhD thesis at the Geology-Paleontology Institute of Basel University, was to investigate the tectonic evolution from oceanic subduction to continent-continent collision in the boundary region between Eastern and Central Alps in Eastern Switzerland. This was done by analyzing the structures of Bündnerschiefer and Flysch sediments. These sediments formed an accretionary prism in front of the alpine subduction zone and were affected by polyphase deformation during subduction, collision, and post-collisional shortening.

The study area is located in the Prättigau half-window of Eastern Switzerland (Figs. 1, 2). The study is mainly focussed on the Grava nappe, a tectonic unit derived from the Valais paleogeographic domain (Steinmann 1994), made up by Cretaceous to Tertiary Bündnerschiefer and Flysch sediments, and exposed in the interior of the half-window. These sediments, being incompetent and anisotropic, are highly susceptible to folding on all scales. In many outcrops, three to four generations of folding can be clearly distinguished. On the other hand, it is difficult and time-consuming to correlate these structures over a larger area. Therefore, previous to this study,

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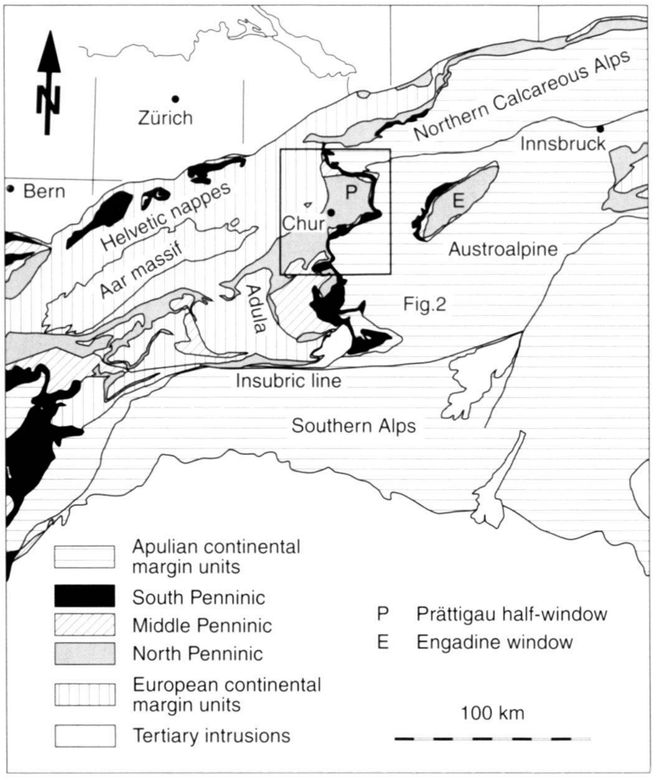

Fig. 1. Tectonic map of the Central and Eastern Alps with location of study area.

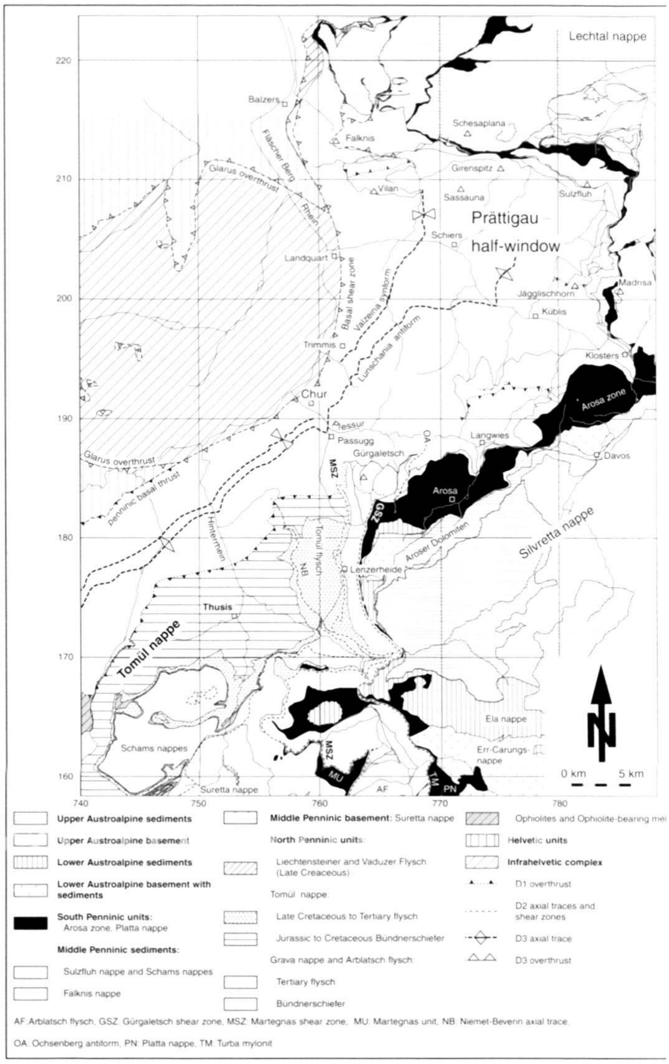

Fig. 2. Tectonic map of the Prättigau half window and surrounding area.

no serious attempts have been made to decipher this valuable archive of Alpine deformation.

Except for minor uncertainties, it was possible to correlate small-scale with large-scale deformation structures, to correlate these structures throughout the study area, and to assign them to four major stages of deformation (D1 to D4), one of which is further subdivided into substages (D1a, b). The structural evolution of the Grava nappe reflects two shear-sense reversals during the Tertiary, from top-north "pro-shear" to top-southeast "retro-shear", and back to "pro-shear".

Many additional details of the regional structural geology may be found in Weh (1998). This PhD thesis is available on request from the Geology-Paleontology Institute of Basel University.

2. Overview of the regional geology

The Prättigau half-window is a westward-opening, 25 km x 25 km embayment of the Austroalpine-Penninic boundary in Eastern Switzerland (Figs. 1, 2). The half-window is framed by the overlying Austroalpine nappes on its northern, eastern, and southern margins. These represent the former continental margin of the Apulian (Adriatic) microcontinent. They were stacked during the Late Cretaceous (Froitzheim et al. 1994, 1996). The Apulian continental margin was, in Cretaceous time, divided from Europe by the two oceanic basins of the Penninic zone (South Penninic or Piemont-Liguria ocean, North Penninic or Valais ocean) and an intervening continental terrane, the Briançonnais fragment. The Penninic nappes exposed within the half-window include, from top to bottom, the Arosa zone (ophiolites and ophiolite-bearing mélanges from the Piemont-Liguria ocean and the distal Apulian margin; Ring et al. 1989), the Sulzfluh nappe (sedimentary rocks derived from the Briançonnais fragment, dominated by Late Jurassic shallow-water limestone), the Falknis nappe (Jurassic to Early Tertiary sequence of sedimentary rocks, probably derived from the northern margin of the Briançonnais fragment against the Valais basin; Gruner 1981, Weh 1998), and the thick Bündnerschiefer-Flysch sequence of the Grava nappe (derived from the Valais basin; Steinmann 1994). Sulzfluh and Falknis nappes do not form continuous sheets but are rather made up by lenses which reach important thicknesses in some

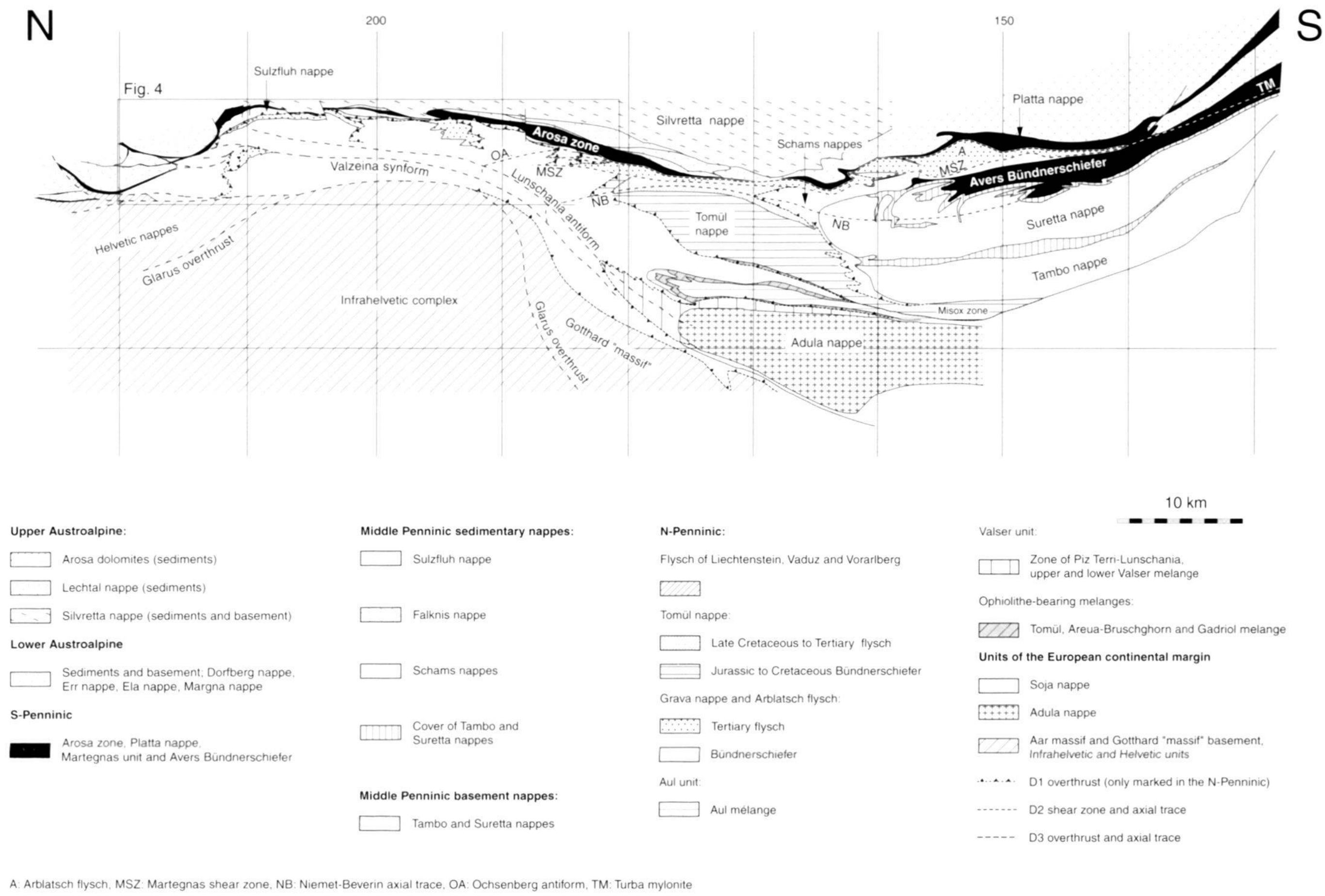

Fig. 3. N-S cross section through eastern Swiss Alps (after Schmid et al., 1996, modified according to results of this study).

areas and completely pinch out in others. Towards the west, the Penninic units of the half-window mostly border against the underlying Infrahelvetic complex, that is, the Aar massif and auto- and allochthonous sediment units covering it (Pfiffner 1977). This Infrahelvetic complex is overlain to the North by the Helvetic nappes along the Glarus overthrust (Schmid 1975). The Helvetic nappes border against the Grava nappe only in the northwest corner of the Prättigau half-window (Fig. 2). Infrahelvetic complex and Helvetic nappes are derived from the European margin of the Valais ocean.

As follows from the preceding, the structurally highest and deepest units occur in the East and in the West of the study area, respectively. This situation results from a general eastward dip of the tectonic boundaries and main structural elements in the eastern Central Alps, and makes it possible to construct cross-sections of the nappe stack by projection over relatively short distances (Figs. 3, 4). The cross-section in Fig. 4 was produced by east-west-projection of about 50 detailed cross-sections which had been recorded mostly along N-S oriented stream valleys and mountain ridges. Different angles of projection between 0° and 30° were chosen for different parts of the study area, dependent on the dip angles of the main structures in these parts. The exact procedure is described in Weh (1998). Minor uncertainties and incorrectnesses of this method arise from the lensoid shape of some tectonic units, e.g., the Falknis and Sulzfluh nappes, and from the strike of some major folds deviating from E-W.

3. Structural analysis of the Grava nappe

3.1. Stratigraphic and structural outline; previous work

The Bündnerschiefer and flysch sediments of the Prättigau half-window are part of the Grava nappe (Steinmann 1994, Schmid et al. 1996). This is the lower of two major Bündnerschiefer/Flysch tectonic units rooted to the South in the Misox zone between the Adula and Tambo basement nappes (Fig. 3). The other one is the Tomül nappe which overlies the Grava nappe to the South but does not reach as far north as the Prättigau half window, being restricted to the area south of Chur (Fig. 2). Within the study area the Grava nappe consists entirely of basin sediments from the Valais basin which was partly

GSZ: Gürgaletsch shear zone, MSZ: Martgnas shear zone, NB: Niemet-Beverin axial trace, OA: Ochsenberg antiform

Fig. 4. N-S cross-section of the Prättigau half window.

floored by oceanic crust (Dürr et al. 1993, Florineth & Froitzheim 1994, Steinmann & Stille 1999). Their metamorphic grade as determined from illite crystallinity and vitrinite reflectance is anchizonal in the North to epizonal in the Southwest (Thum & Nabholz 1972, Ferreiro Mählmann et al. 1992). Fe-Mg carpholite indicating an earlier metamorphism with high P/T ratio occurs in the Southwest near Chur (Oberhänsli et al. 1995). The age of the sediments in the Grava nappe is Lower Cretaceous to Eocene (Nänny 1948, Steinmann 1994). The lower part (Lower Cretaceous) is dominated by marl and sandy limestone, whereas higher up, calcareous and siliciclastic turbidites and breccia layers, intercalated with shale, become increasingly more important. The term "Bündnerschiefer" is often used for the lower part of the series, "Flysch" for the upper. There is, however, no agreement about the exact boundary. The stratigraphy of the Grava nappe in the Prättigau half-window was studied by Nänny (1948). He distinguished and partly dated biostratigraphically eight series (from older to younger: Klus, Valzeina, Sassauna, Pfävigrat, Fadura, Gyrenspitz, Eggberg, Ruchberg). Klus to Eggberg series are Cretaceous in age, the Ruchberg series is Paleocene to Eocene (Nänny 1948). On the tectonic map of Switzerland (Spicher 1980), Klus, Valzeina, and Sassauna series are termed "Bündnerschiefer", Pfävigrat, Fadura, Gyrenspitz, Eggberg, and Ruchberg series are termed "Flysch". Trümpy (1980) subdivides the "Flysch" in the sense of Spicher (1980) into what he calls "preflysch" (Turonian to Maastrichtian, that is, Pfävigrat to Eggberg series) and a "flysch" sensu strictu, which is Tertiary in age and encompasses only the Ruchberg series.

During our study we found that the boundaries drawn by Nänny on his map and profile (Nänny 1948, tables 2.3) are incorrect in some areas. This is because Nänny interpreted the structure of the half-window in terms of simple, north-facing and overall north-vergent folds. In fact, we found that in the entire southeastern half of the half-window, the main folding phase (D2) is everywhere south- to east-facing, and more often south-vergent than north-vergent. The simple style of Nänny's profiles has little similarity with the actual situation. Therefore, we did not adopt his stratigraphic boundaries in our map and profiles, except for the Cretaceous-Tertiary boundary which is lithologically well-defined and could be adopted from Nänny (1948) with only minor corrections. We will use "Tertiary Flysch" in this paper for the Ruchberg series, and "Cretaceous schists" for the Cretaceous part, that is, the "Bündnerschiefer" and "Pre-Flysch" in the sense of Trümpy (1980).

The Grava nappe is not a nappe in the strict sense (actually, even not in a rather wide sense), but originally represents, as our reconstruction will show, a duplex consisting of "horses" that were imbricated by N-directed D1 thrust faults emplacing Cretaceous schists over Tertiary Flysch. At present, the most

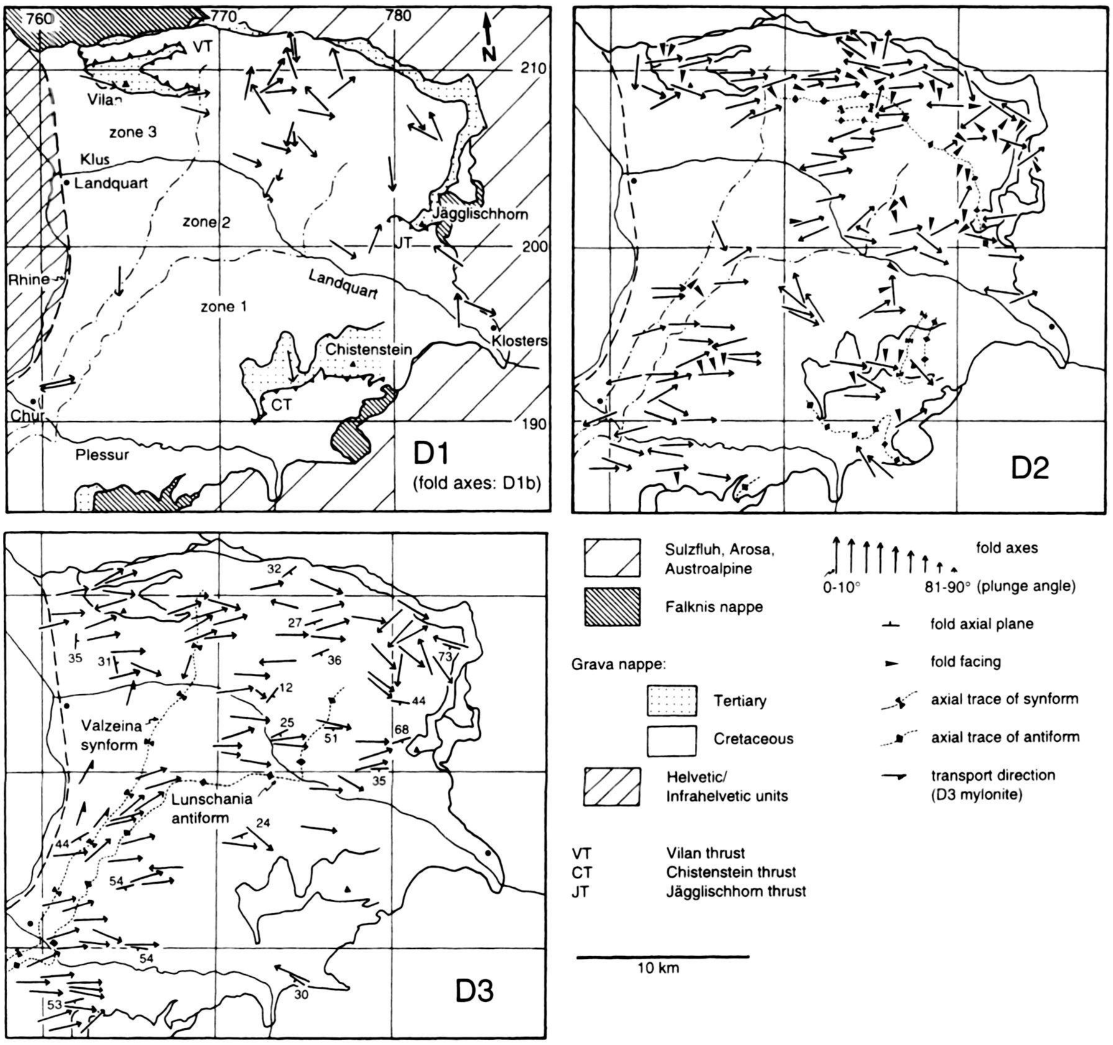

Fig. 5. Orientation of structural elements in the Prättigau half-window.

prominent regional structures of the Prättigau half-window are two large-scale D3 folds, the Lunschania antiform and the Valzeina synform (Figs. 2, 3, 4). The Lunschania antiform was described by Voll (1976) and Probst (1980) far away from the half window, in the area north of the front of the Adula nappe. Voll (1976) and Steinmann (1994) traced it from there northeastward to the vicinity of Chur, and we traced it from Chur to the northeastern corner of the Prättigau half window. This axial trace is thus exposed over a length of 75 km. The newly named Valzeina synform accompanies the Lunschania antiform to the NW and can be traced over the same distance. Using the axial traces of these D3 folds, three structural zones can be defined (Fig. 5): (zone 1) southeast of and above the axial trace of the Lunschania antiform, (zone 2) between the axial traces of the Lunschania antiform and the Valzeina synform, and (zone 3) northwest of and below the Valzeina synform. The latter zone includes the basal shear zone of the Grava nappe.

Before starting the detailed structural description, we have to explain why we split the first deformation phase, D1, into subphases D1a and D1b instead of introducing an additional phase. D2 structures can be clearly correlated across the study area and represent a strain field clearly different from initial, top-N thrust sheet imbrication. Therefore we can assume that D2 structures are approximately of the same age across the study area. In contrast, correlation is more difficult for structures predating D2. In places, the D2 folds are predated by two sets of structures. In lower structural levels of the Grava nappe, these structures encompass a cleavage (our D1a) and folds that deformed this cleavage (our D1b). In higher structural levels and in the Falknis nappe, D2 is locally preceded by thrusts (our D1a) and by folds (our D1b) which do not deform a D1a cleavage (because no such cleavage exists there) but are occasionally seen to deform the thrusts (e.g., Fig. 9). It is not possible, at the present state of knowledge, to temporally correlate these sets of structures between higher and lower structural levels. It may well be, for example, that D1b structures in higher levels developed contemporaneously with D1a structures in lower levels, since higher thrust sheets are often folded when lower thrust sheets are accreted (Boyer & Elliott 1982). Therefore, we do not intend to assign an age to the individual pre-D2 structures, but we take the local occurrence of two sets of such structures into account by using D1a for the older and D1b for the younger set in any location.

3.2. Structural zone 1 southeast of the Lunschania antiform

This zone is characterized by post-nappe D2 folds with shallowly dipping axial planes. These represent the dominant fold phase and are generally associated with a well-developed axial planar cleavage. The facing directions of the D2 folds are predominantly south but vary from E over S to SW (Fig. 5). Their vergence is variable and depends on the position with respect to major D2 folds. Two such major folds are identified in zone 1 near the southern termination of the half-window: The N-closing Niemet-Beverin fold (Schmid et al. 1990), representing a synform in the study area, and the S-closing Ochsenberg fold, representing an antiform (Figs. 2, 3, 4). The axial surfaces of D2 folds dip gently southeast (in the southernmost part of structural zone 1) to northeast (in the northern part of zone 1). Thus they are warped into a large, open dome (Fig. 4). From north to south, the axial trace of the Ochsenberg antiform passes from the Grava nappe into the structurally higher Falknis nappe. In a similar way, the axial trace of the Niemet-Beverin synform passes from north to south up into progressively higher tectonic units. In this sense, both major D2 folds may be described as backfolds.

In the upper, northern limb of the Ochsenberg antiform, the predominant vergence of D2 folds is towards south (Fig. 4). The Cretaceous schists are here in an overall upright position (except for the inverted limbs of several medium-scale D2 folds with amplitudes of ca. 1 to 2 km). In its lower, southern limb, which is also the upper limb of the Niemet-Beverin synform, the Cretaceous schists are upside-down and the D2 fold vergence is towards north (Fig. 4). Finally, below the axial surface of the Niemet-Beverin synform, in the area southwest of the half-window, the nappe stack is in an upright position (Grava nappe below, Tomül nappe above) and the D2 fold vergence is towards south again (see Schmid et al. 1990). Our field work has shown that the entire volume of Cretaceous schists and Tertiary flysch cropping out in the Prättigau half-window is structurally above the axial surface of the Niemet-Beverin synform, in contrast to the profile depicted in Schmid et al. (1996) where it was assumed to lie almost entirely below this D2 axial surface.

The Ochsenberg antiform deforms the D1 thrust contact of the Falknis over the Grava nappe (Fig. 4). The Niemet-Beverin synform deforms the D1 thrust of the Tomül over the Grava nappe and other thrust contacts further south (see also Fig. 3). Hence, these D2 folds are clearly post-nappe structures. Northeast of and above the trace of the Ochsenberg antiform, the above-mentioned medium-scale D2 folds of 1 to 2 km amplitude deform minor D1 thrust contacts within the Grava nappe, along which Cretaceous schists had been transported northward over Tertiary flysch. The Tertiary rocks form two wedges tapering downward into the Cretaceous schists, a southern one at Chistenstein and a northern one at Jägglischhorn (Figs. 4, 5). The Tertiary rocks in both wedges rest with stratigraphic contacts on the Cretaceous schists at their base but are overthrust by Cretaceous schists at their top. After their formation the D1 wedges were deformed by cross-cutting D2 folds as shown on Figure 4. The original geometry of these wedges is interpreted to result from D1 south-over north imbrication of "horses" forming a duplex. The roof thrust of this duplex is located along the contact between the Grava nappe and the overlying Sulzfluh and Falknis nappes, since these higher nappes are not incorporated into the Tertiary flysch wedges. The floor thrust of the Grava nappe D1 duplex is not preserved in the Prättigau half window due to the pervasive D3 deformation in its structurally lowest part where a shear zone formed during D3 (see below). The Sulzfluh nappe at the northeastern corner of the half window forms another duplex overlying the one of the Grava nappe (Fig. 4, near coordinate 210).

Where the polarity of the strata could be determined from graded bedding and turbidite bottom marks, the facing direction of D2 folds in structural zone 1 is predominantly south to east (Fig. 5). This implies that the strata were in an upright position before D2 backfolding. If major isoclinal D1 folds had been present previous to D2, this would have led to opposite D2 facing directions within former upright and inverted D1 limbs, which is not observed. However, small-scale isoclinal D1 folds, termed D1b, do occur in the southernmost part of structural zone 1. In this strongly deformed area it was not possible to determine the younging direction of the sediments, and hence, the isoclinal D1b folding is not monitored by changes in the facing direction of D2 folds shown in Figure 5. Open D1b folds were identified in the northern part of zone 1 (Fig. 5). Such open folds may be responsible for the variability in strike of D2 axes from E-W over NE-SW to N-S (Fig. 5). The only other large-scale D1 structures that can be unambiguously identified in structural zone 1 are the thrusts related to duplex formation. These thrusts did not produce inverted limbs, which points to duplex formation during an early, brittle deformation stage.

In the northeastern part of structural zone 1, no D1 cleavage can be detected, and the first cleavage formed during D2 (Fig. 6a). In contrast, in the southwesternmost part of zone 1 near Passugg (Fig. 2), D2 folds deform an earlier cleavage (D1) and quartz-calcite veins oriented parallel to this cleavage. These veins bear a stretching lineation formed by quartz fibres oriented predominantly North-South (Fig. 6b, c, d). Fibres of the high-P-low-T mineral Mg-Fe-carpholite grew parallel to and together with the quartz fibres forming the lineation, showing that high-pressure conditions were reached during D1

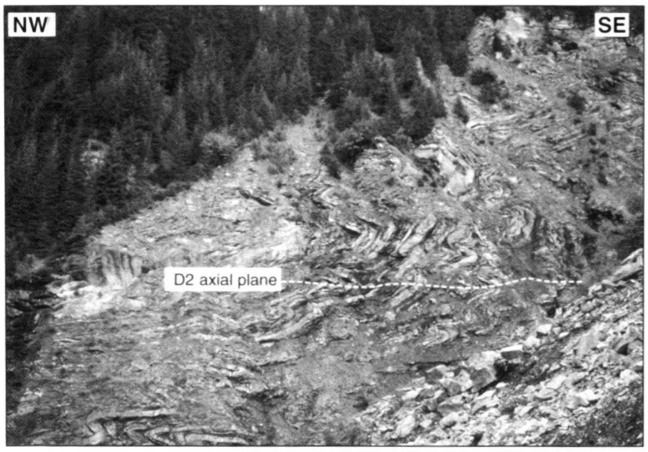

Fig. 6a

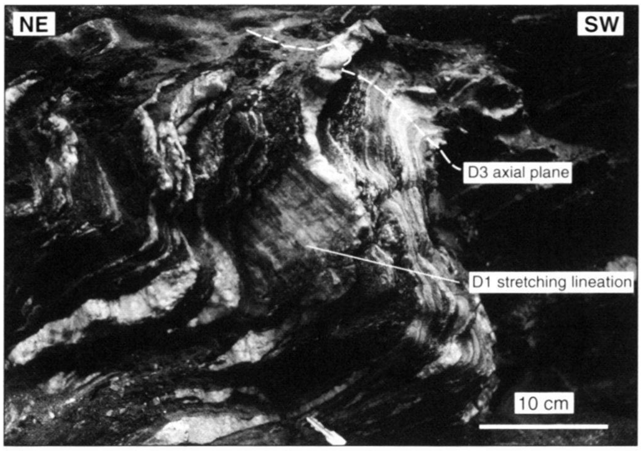

Fig. 6b

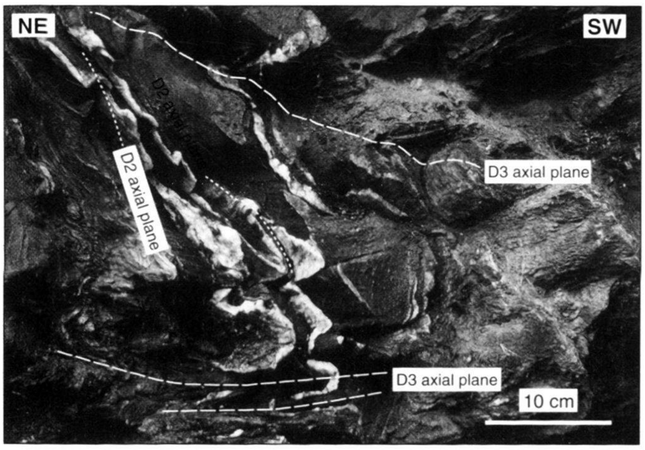

Fig. 6c

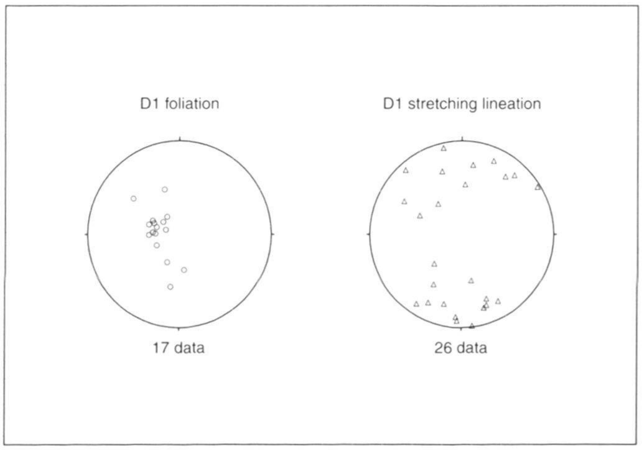

Fig. 6d

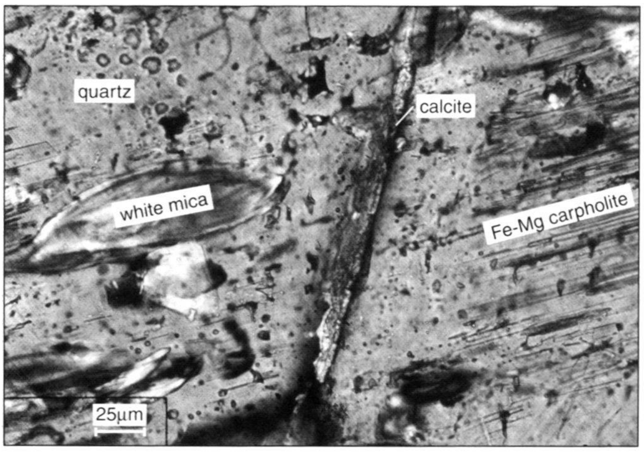

Fig. 6e

Fig. 6f

Fig. 6. Structural elements of the Grava nappe in the Prättigau half-window. a) Recumbent, SE-facing D2 folds in structural zone 1.West side of Jägglischhorn NE of Küblis, Prättigau (see Fig. 2). b) Fibre lineation on Fe-Mg-carpholite-bearing quartz-calcite vein. Rabiusa gorge, ca. 100 m south of P.736, Passugg near Chur (Fig. 2). c) D2 and D3 folds deforming D1 veins ; same locality as (b). d) Orientation of D1 foliation and stretching (=fibre) lineation in the Rabiusa gorge near Passugg, same locality as (b). Lower hemisphere Schmidt projection. e) Fe-Mg-carpholite included in quartz of a D1a vein, crosscut by a later calcite vein. Same locality as (b). f) Upright D2 fold in structural zone 2. Schraubach valley NE of Schiers, Prättigau (Fig. 2).

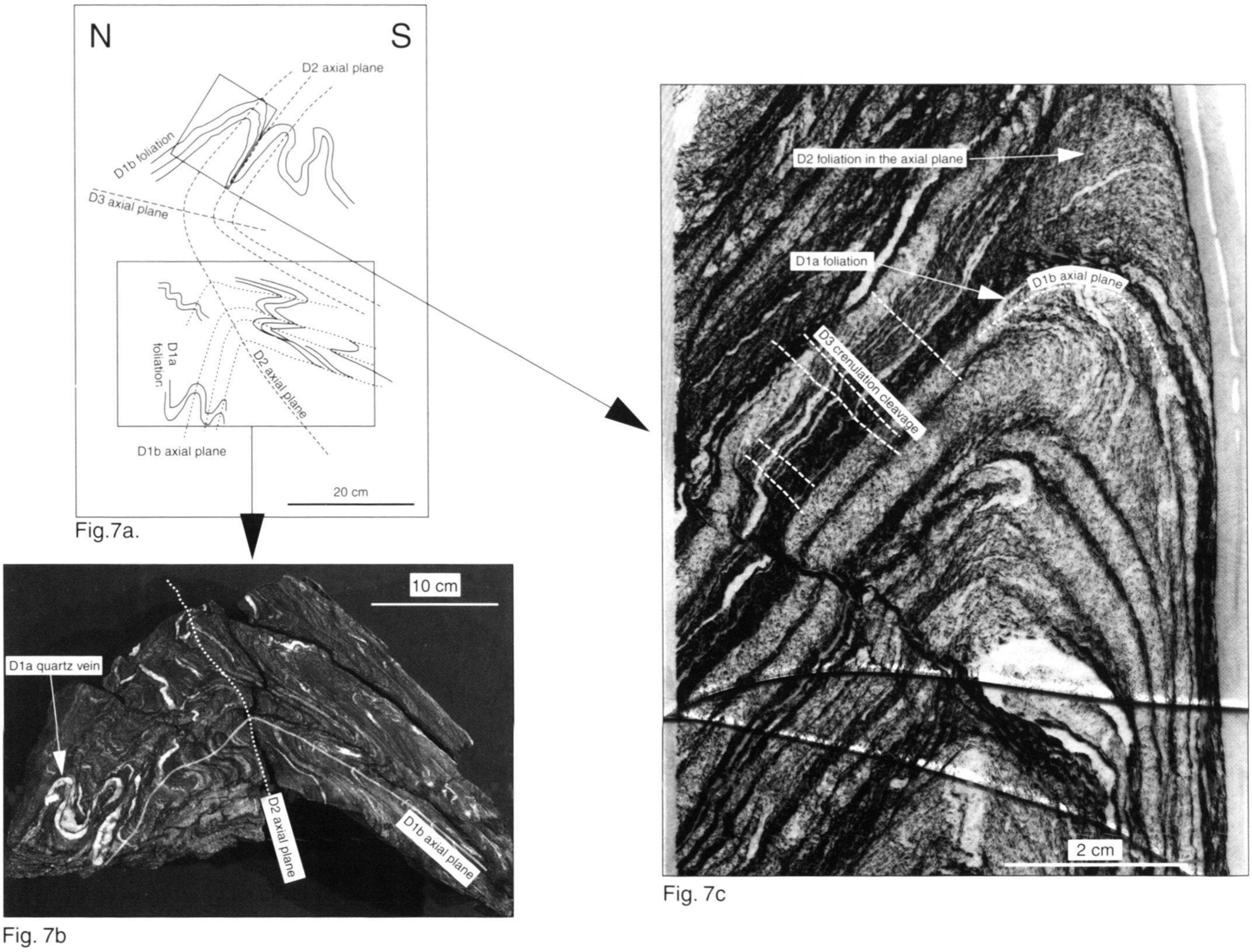

Fig. 7. Overprinting relations in structural zone 2 . Locality: P. 622, Plessur river gorge, 1 km SE of Chur (Fig. 2). a) Overview of the outcrop. b) Polished sample from lower limb of D3 antiform. c) Thin section photograph from upper limb of D3 antiform, showing structures of four deformation phases (D1a: veins and foliation; D1b: first folding; D2: upright, main fold; D3 weak crenulation cleavage dipping to the right).

(see Goffé & Oberhänsli 1992). We assign the veins at Passugg to subphase D1a because the veins are similar to other veins at Chur which are in fact D1a because they were deformed by D1b folds (see below and Fig. 7).

Throughout structural zone 1, the D2 folds and older structures are overprinted by open D3 folds with steeply to moderately southeast-dipping axial planes and east- to southeast-plunging axes. The D3 folds are north-vergent, that is, they have long limbs with shallow D2 cleavage and short limbs in which the axial planes and cleavage of D2 folds are reoriented into a steeply dipping attitude. D3 folds in structural zone 1 are associated with a crenulation cleavage and represent parasitic folds on the upper limb of the Lunschania antiform. The intensity of these folds increases from NE to SW within structural zone 1. At the Passugg locality, D3 folding is quite pronounced (Fig. 6b, c).

3.3. Structural zone 2 between Lunschania antiform and Valzeina synform

This zone occupies the central part of the half-window. It widens towards NE due to the fact that the structural thickness between the Lunschania and Valzeina axial surfaces increases in this direction (Fig. 2). The D2 folds which are shallowly oriented in structural zone 1, change their attitude quite abruptly across the axial surface of the Lunschania antiform in order to become subvertical in structural zone 2. Structural zone 2 is thus characterized by upright D2 folds.

An example of an upright D2 fold on the thin section scale, from the SW part of zone 2 near Chur, is shown in Fig. 7. The D2 fold in this example is a similar fold with thickened hinges and an axial plane crenulation cleavage (visible in the upper part of the thin section in Fig. 7). This D2 fold refolds two older cleavages. The younger one of these, related to D1b, represents the axial planar cleavage of isoclinal folds with a smaller amplitude than D2. These D1b folds deform a first, penetrative cleavage as well as quartz veins oriented parallel to this cleavage. Cleavage and quartz veins thus represent the oldest deformation stage, D1a. Note that the D1a and D1b cleavages can be clearly distinguished only in the hinge zone of the D2 fold, but not on the limbs. The D1a quartz veins are of the same type as the ones that contain fibrous Fe-Mg carpholite at the Passugg locality (see above). Therefore, we attribute the formation of this high-P-low-T mineral to D1a.

The D1a, D1b, and D2 structures are all overprinted by D3 folds and associated crenulation cleavage S3 (Fig.7a, c). This crenulation cleavage dips shallowly to moderately east to southeast. The D3 folds are parasitic folds of the Lunschania antiform. The structural evolution of the Chur outcrop (Fig. 7) can thus be summarized as follows: D1a - penetrative cleavage and quartz veins; D1b - isoclinal folding; D2 - open to tight folding and crenulation cleavage; D3 - open folding and crenulation cleavage.

In the northern part of structural zone 2, the same structural phases can be identified, but the associated deformation is generally weaker and less penetrative than in the South. The main folds are upright, open to tight D2 folds (Fig. 6f). Most of these are upward facing, a minority is downward facing. These opposite facing directions result from earlier folding: Upward D2 folding is observed on upright D1b limbs, downward facing on inverted D1b limbs. The upward-facing D2 folds are the equivalent of the southward-facing D2 folds in structural zone 1, verticalized by folding around the hinge of the Lunschania antiform. Tight D1b folds are observed in some outcrops, and these deform a penetrative cleavage, quartz-calcite veins, and mullion structures, all belonging to D1a. The steeply dipping axial-plane cleavage of the D2 folds is crenulated by weak D3 folds with subhorizontal to shallowly southeast-dipping axial surfaces. These are parasitic folds of the Lunschania antiform. They are in turn locally overprinted by a younger crenulation (D4) with moderately southeast-dipping axial surfaces. D4 is very weak and rarely observed in structural zone 2, absent in structural zone 1, but becomes more ubiquitous in structural zone 3, i.e. below the axial surface of the Valzeina synform.

3.4. Structural zone 3 northwest of the Valzeina synform

This zone is situated between the quaternary fill of the Rhine valley to the West and the axial trace of the Valzeina synform to the East. Like zone 2, it widens towards north (Fig. 5). Across the Valzeina synform, an abrupt change occurs from steeply oriented layering (folded by upright D2 folds) in zone 2, to a dominantly shallow orientation of the layering in zone 3.

The dominant folds in zone 3 are tight D3 folds with NE- to E-plunging axes, shallowly to moderately SE-dipping axial surfaces and axial-plane cleavage, well exposed in the Klus gorge east of Landquart (Fig. 5). In the northern part of zone 3, NE of Landquart, these folds overprint south- to east-facing earlier folds correlated with D2 of structural zones 1 and 2. Toward south and towards west within zone 3, the intensity of D3 deformation increases and no older folds or cleavages are preserved. D3 folds are locally overprinted by open, north-vergent, weak D4 folds with moderately to steeply southeast-dipping axial surfaces and without a new cleavage. Associated with the small-scale D4 structures are large, open anti- and synforms north of Landquart.

In a downward direction, towards the base of the Bündnerschiefer complex (which is not exposed but covered by the qaternary fill of the Rhine valley), D3 folds become more and more isoclinal and finally disappear due to the complete transposition of the layering into parallelism with the D3 foliation. The D3 axial plane cleavage thus becomes a mylonitic foliation which bears a NNE-SSW oriented stretching lineation ("transport direction" in Fig. 5). Viewed perpendicular to the lineation, asymmetric structures (σ clasts, shear bands, S-C structures) indicate a top-NNE shear-sense (Fig. 8a). The mylonites are overprinted by minor, open D4 folds with steeply SE-dipping axial planes (Fig. 8b).

This mylonite zone formed during north-directed thrusting of the Bündnerschiefer over the Infrahelvetic complex exposed on the other, western side of the Rhine valley. This tectonic contact, which represents the Penninic basal thrust in the study area, is therefore a D3 structure. It is probable, however, that the floor thrust of the D1 duplex was already located in the same zone but was completely overprinted by later D3 mylonitization.

At Vilan in the northernmost part of zone 1, a wedge of Tertiary flysch, including the Ruchberg type locality, occurs between Cretaceous schists below and above (Figs. 2, 3, 4). This flysch rests with a depositional contact on the Cretaceous schists below and is overthrust by the ones above, along the Vilan thrust. We interpret this thrust as a D1 structure, like similar thrusts at Jägglischhorn and at Chistenstein.

3.5. Structure of the Grava nappe: Summary

Large-scale D1 structures are, from S to N, the Chistenstein, Jägglischhorn and Vilan thrusts that subdivide the Bündnerschiefer/Flysch complex of the Prättigau half-window into four "horses". The thrusts are brittle and the orientations of cut-off lines defined by the intersection of the thrust surfaces with the Cretaceous-Tertiary boundary constrain thrusting to be north-directed. The roof thrust of the Bündnerschiefer/Flysch duplex was below the Falknis nappe, and the floor thrust was at the base of the Bündnerschiefer complex but has later been completely overprinted by D3 mylonitisation. Small-scale D1a structures include a penetrative foliation, mullion structures, and quartz-calcite veins in which Fe-Mg carpholite has grown in the southernmost part of the half-window. D1b structures are isoclinal folds deforming the veins and the foliation. Such small-scale structures are found in structural zones 2 and 3 and in the southwesternmost part of zone 1. Open D1b folds occur in the northern part of zone 1 (Fig. 5). Here, however, they do

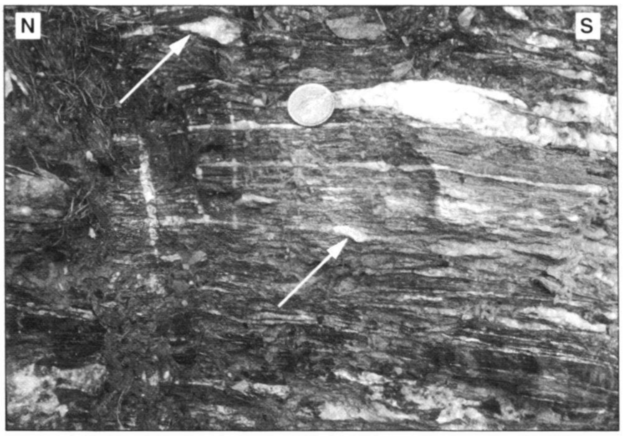

Fig. 8a

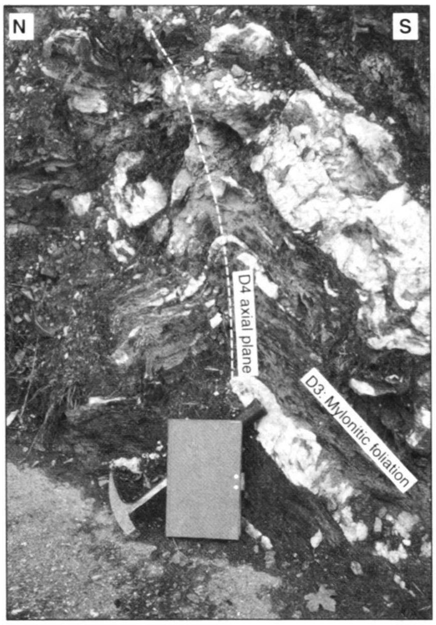

Fig. 8b

Fig. 8c

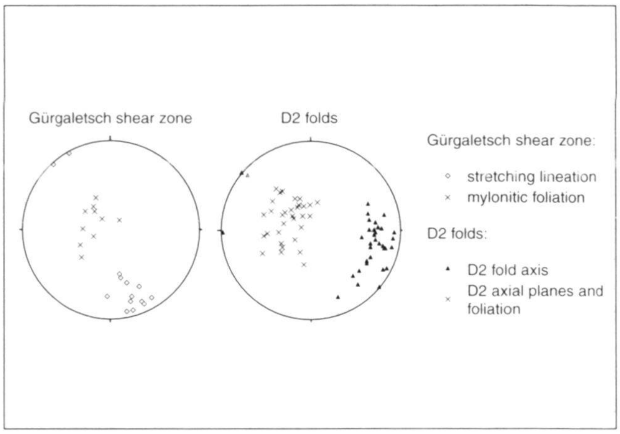

Fig. 8d

Fig. 8. Structures from the basal shear zone of the Grava nappe and from the Falknis nappe at Gürgaletsch. a) Mylonitic calcschist in the basal shear zone (D3) of the Grava nappe. Asymmetric, sheared fragments of quartz-calcite veins (arrow) indicate top-NNE shear sense. Road from Trimmis to Says, near Trimmis (see Fig. 2). b) D4 fold overprinting basal shear zone. Same locality as (a). c) σ clast (sheared fragment of earlier vein?) in mylonitic calcschist of the Upper Cretaceous Couches Rouges formation in the Gürgaletsch shear zone, indicating top-SE normal shearing during D2. Falknis nappe at Gürgaletsch; outcrop is near P. 2447 south of Gürgaletsch (Fig. 2), west of Parpaner Schwarzhorn. d) Orientation of D2 structural elements in the Gürgaletsch area. Lower hemisphere Schmidt projection. D2 fold axial planes are parallel to mylonitic foliation of Gürgaletsch shear zone. D2 fold axis distribution shows progressive rotation towards the shear direction of the Gürgaletsch shear zone (as represented by stretching lineations).

not deform a D1a foliation because no such cleavage is present. We tentatively assume that D1a small-scale structures formed together with the large-scale D1 thrusts, during duplex stacking, and that D1b folding overprinted the horses of the duplex after their formation. Duplex stacking must have been diachronous, starting in the south and ending in the north (Boyer & Elliott 1980), and D1b folding may have been diachronous, too.

During D2 the D1 thrusts were shortened by folding around recumbent "backfolds", including the Ochsenberg antiform and, southwest of the half window, the Niemet-Beverin synform. In the inverted limbs of these folds, the originally south-dipping thrusts were rotated into a northward-dipping orientation. The entire Grava nappe of the Prättigau half-window is structurally above the axial surface of the Niemet-Beverin synform. As will be shown below, D2 structures resulted from top-southeast extensional shearing.

During D3, a top-N mylonite zone overprinted the base of the Grava nappe. The nort-vergent Lunschania and Valzeina folds formed contemporaneously in the hangingwall of the mylonite zone. In the steep limb between the Lunschania and Valzeina axial surfaces, the originally recumbent D2 folds were verticalized by D3. When shearing in the basal shear zone had ceased, open, N-vergent D4 folds accommodated some further shortening.

4. Structure of the Falknis nappe in the Gürgaletsch area

4.1. Field relations

The Falknis nappe is a cover nappe without basement, comprising a sedimentary sequence from Jurassic to Eocene with rare slivers of Triassic rocks at the base (Allemann 1957, Gruner 1981). Polymict breccias and conglomerates (Falknis breccia) are interlayered with Upper Kimmeridgian to Lower Tithonian carbonates in the Falknis nappe. These were shed from a partly subaeric high to the Southeast (Gruner 1981). Most authors assume that this source area was part of the Briançonnais swell, and, therefore, that the Falknis nappe originates from the northern margin of this swell (Stampfli 1993, Steinmann 1994; for a different view, see Gruner 1981). Two major outcrop areas of the Falknis nappe exist: the Falknis area at the N margin of the half-window, and the Gürgaletsch area to the south. The metamorphic grade is anchizonal in both areas (Ferreiro Mählmann et al. 1992). Only the Gürgaletsch area will be discussed in the present paper (see Weh 1998 for details concerning the Falknis area).

The profile through the Gürgaletsch area (Fig. 9) shows recumbent D2 folds that are characteristic for this area. They have shallowly east- to southeast-dipping axial surfaces, E-W to SE-NW axes (Fig. 8d), and face towards south (Fig. 9). Late Jurassic Falknis breccia is exposed in the North of the profile (northern part of Gürgaletsch schuppe). Towards south, we encounter progressively younger formations up to the Upper Cretaceous Couches Rouges Formation and the Paleocene Globorotalien-Schichten (Lichtsteiner 1992). Along the contact marked "D1 overthrust" in Fig. 9, these Couches Rouges border against Jurassic rocks which form the base of a second sequence (Malakoff schuppe), again younging towards south and deformed by south-facing, recumbent D2 folds. The D1 overthrust between Couches Rouges and Jurassic rocks is folded by the same D2 folds. During D1, the southern sequence (Malakoff schuppe) was thrust towards north over the northern one (Gürgaletsch schuppe). The overthrust was subsequently, during D2, rotated clockwise (looking east), shortened, and folded. These relations were in principle already recognized by Gruner (1981).

A syncline-anticline pair occurs in the structurally higher part of the Gürgaletsch Schuppe (Alpstein anticline, Urden syncline). These folds are attributed to D1 because they are overprinted by recumbent D2 folds and their axial surfaces

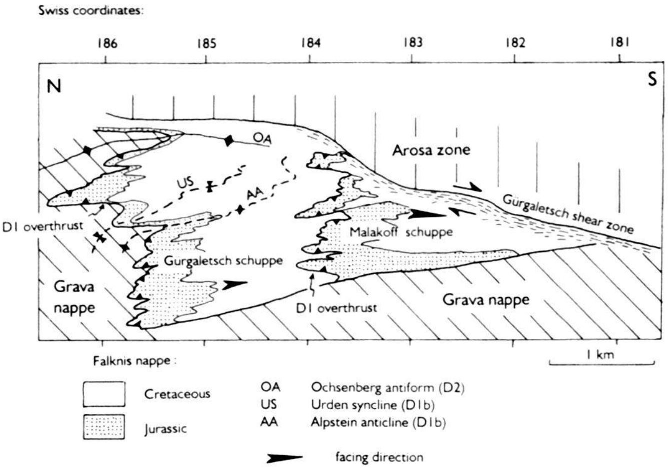

Fig. 9. Simplified cross section of the Falknis nappe in the Gürgaletsch area, showing dominant recumbent D2 folds kinematically linked with the Gürgaletsch shear zone and overprinting earlier D1 thrusts and folds.

presently dip north. The Alpstein anticline and Urden syncline also deform the basal thrust of the Gürgaletsch Schuppe over the Grava nappe. Hence these two folds may be assigned to D1b, and the thrust to D1a.

Further towards south in the profile (Fig. 9), close to the base of the overlying Arosa zone, a tectonic mélange develops. The incompetent Couches Rouges marls form the matrix while disrupted hinges of D2 anticlines, consisting of older formations, form the components. The D2 axial-plane foliation develops into a mylonitic foliation in the Couches rouges, dipping shallowly SE, parallel to the contact with the overlying Arosa zone. This foliation bears a SE-plunging stretching lineation. Viewed perpendicular to the lineation, asymmetric structures (σ clasts, shear bands) consistently indicate top-SE directed transport (Fig. 8c). This mylonitic structure stops abruptly at the base of the Arosa zone which is marked by a brittle fault.

The recumbent D2 folds observed within the Gürgaletsch Schuppe also deform the thrust contact between Falknis nappe and Bündnerschiefer at the northern end of the profile (Fig. 9). These folds can be traced across the thrust contact into the southeast-facing D2 folds of the Bündnerschiefer in the lower limb of the Ochsenberg antiform (Fig. 9). The Gürgaletsch and Malakoff schuppen are underlain by Tertiary flysch and Cretaceous Bündnerschiefer along a gently N-dipping contact that is entirely covered by Quaternary deposits. This contact probably represents the D1 floor thrust of the Gürgaletsch-Malakoff duplex. It may, however, have been strongly overprinted by D2 extensional shearing, because the northern continuation of the Martegnas shear zone, another D2 top-SE shear zone comparable to the Turba mylonite zone (Figs. 2, 3, 4), probably runs very close to or directly at the base of the Gürgaletsch-Malakoff duplex.

4.2. Structural interpretation of the Gürgaletsch area

The newly discovered zone of intense, mylonitic top-SE shearing along the top of the Falknis nappe at Gürgaletsch is termed "Gürgaletsch shear zone". We assume that it is syngenetic with D2 folding for the following reasons: (1) the D2 axial plane foliation develops into the mylonitic foliation of the shear zone; (2) the shortening and clockwise rotation (looking E) of the D1 overthrust between the Gürgaletsch schuppe and Malakoff schuppe requires a large, top-S directed component of shearing during D2, consistent with the shear sense of the Gürgaletsch shear zone.

The following structural history is envisaged for the Gürgaletsch area: In a regime of south-over-north imbrication during D1, two schuppen of Falknis-type sediments, Gürgaletsch Schuppe and Malakoff Schuppe, were accreted at the base of the Arosa zone to form a small, hinterland-dipping duplex (Fig. 10). As a result of this duplex geometry, the basal thrust of the Falknis nappe dipped south in the northernmost part and became subhorizontal farther south. The Gürgaletsch Schuppe and its basal thrust were subsequently deformed by two north-vergent folds, Alpstein antiform and Urden syncline (D1b). This must have happened after the Grava nappe had become accreted because the basal thrust of the Gürgaletsch schuppe is at the same time the roof thrust of the Grava nappe duplex. During D2, the overall shear sense changed to top-SE, that is, the Arosa zone and overlying Austroalpine nappes moved down towards SE relative to the Falknis and Grava nappes, and a broad shear zone developed below the Arosa zone. Now the south-dipping sedimentary layering of the two schuppen, the thrust of the Malakoff over the Gürgaletsch Schuppe, and the basal thrust of the Gürgaletsch Schuppe in the North, all had a component of dip in the direction of shearing that was greater than the dip angle of the shear zone itself, and therefore were in an orientation for shortening and folding.

The Gürgaletsch shear zone can be followed towards south to Tiefencastel and the Oberhalbstein area, where it continues under the name of Turba mylonite zone (Nievergelt et al. 1996). Northeast of the Gürgaletsch area, on the other hand, the mylonite zone disappears. There, the deformation is no longer localized in a shear zone but distributed over a larger volume of rock. More specifically, this volume is the zone of important D2 folding in the upper Grava nappe (Ochsenberg antiform and minor backfolds further north, see Fig. 4).

5. Summary, discussion, and correlation with adjacent areas

5.1. Early Tertiary accretion of sediment nappes (D1)

In the Grava nappe, D1 structures include three north-directed thrusts emplacing Cretaceous schist on Tertiary flysch (Chistenstein, Jägglischhorn, and Vilan thrusts). These thrusts are part of a duplex whose roof thrust was located at the base of the Falknis nappe and whose floor thrust is not preserved due to intense D3 overprint. In the deeper parts of the nappe (structural zones 2 and 3), small- to mesoscale structures formed during D1 indicate a two-stage evolution. D1a comprises mullion structures, a penetrative cleavage and, parallel to this cleavage, quartz veins bearing the mineral Fe-Mg carpholite which formed at 7.0 ± 1.0 kbar and less than 300°C (Weh 1998). D1b comprises isoclinal folds deforming the cleavage and the veins. We were not able to reconstruct the geometry of D1b folds in the deeper part of the Grava nappe due to strong D2/D3 overprint. In the Falknis nappe at Gürgaletsch, a north-directed D1a thrust emplaced the Malakoff schuppe over the Gürgaletsch schuppe. A D1b synform-antiform pair deformed the Gürgaletsch schuppe and its basal thrust over the Grava nappe. The pre-D2 reconstruction of these folds suggest that they were north-vergent but had rather steep axial surfaces (Fig. 10).

During D1 the Penninic sediment nappes were sheared off from their southward subducted basement and accreted to the base of the orogenic wedge. The latter consisted of the Austroalpine nappes and, at their base, the Arosa mélange zone. These higher tectonic units had been stacked already during the Late Cretaceous, whereas accretion of the Penninic nappes discussed here only began in the Early Tertiary, as indicated by the age of the youngest sediments in these units. These represent Paleocene to possibly Eocene in the Falknis nappe (Allemann 1957) and the "lower part of the Lower Eocene" in the Grava nappe (Ruchberg series; Nänny 1948). There is no evidence for pre-Tertiary deformation of the Grava nappe. On the contrary, the oldest structures of the higher Grava nappe, the D1 thrusts, buried the Ruchberg series and must hence be Tertiary in age. Our field data thus suggest that accretion of the Grava nappe did not begin before the Eocene (see also Schmid et al. 1996). The possibility still exists, however, that deformation of the lower parts of the Grava nappe, that is, the southern parts of structural zones 2 and 3, began already earlier. No Tertiary sediments were identified here, and hence, a late Cretaceous age of D1a deformation and concomitant carpholite formation in this part of the Grava nappe cannot be excluded.

In the Falknis nappe, which is of more southerly origin than the Grava nappe, the youngest sediments, of Paleocene to possibly Early Eocene age, rest unconformably on older formations, indicating pre-Paleocene tectonic movements. These movements began already in the Upper Campanian to Lower Maastrichtian (Allemann 1957). No thrusts or folds related to this pre-Tertiary deformation can be identified. In the absence of such structures, we assume that erosion was either caused by uplift related to block tilting, e.g., in a strike-slip regime, or by arching related to a flexural forebulge of the Piemont-Ligurian subduction zone located farther to the South.

5.2. Backfolding and top-SE extensional shearing (D2)

The D2 folds are backfolds in the sense that their axial surfaces climb into progressively higher structural units towards south, that is, into more southerly-derived nappes. This is ex-

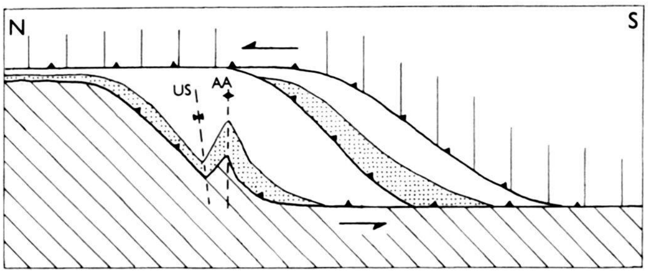

Fig. 10. Reconstructed pre-D2 geometry of the Falknis nappe in the Gürgaletsch area.

emplified by the Niemet-Beverin fold whose axial surface climbs from north to south through the following nappes: Grava nappe (Valais) - Tomül nappe (Valais) - Schams nappes (Briançonnais) - Suretta nappe (Briançonnais) - Avers Bündnerschiefer (Liguria) (Fig. 3). In the lower limb of the Niemet-Beverin synform, the nappe stack remained in an upright position whereas it became overturned in the upper limb (Schmid et al. 1990, Schreurs 1993). Our study has shown that the entire volume of the Grava nappe in the Prättigau half-window lies above the axial surface of the Niemet-Beverin synform, and that a whole series of comparable D2 folds, only of smaller scale, developed above and to the north of the Niemet-Beverin fold. The Ochsenberg antiform follows above the Niemet-Beverin synform; it brings the inverted nappe stack of the upper limb of the Niemet-Beverin fold back into an upright position. The even higher synforms again locally invert the nappe stack for short distances, as is shown by the locally overturned, internal D1 thrusts of the Grava nappe (Fig. 4).

The D2 folds are kinematically linked to top-SE shear zones, as was shown above for the case of the Gürgaletsch-Turba shear zone. Another newly identified shear zone (Martegnas shear zone), also with a top-SE transport direction, occurs at a slightly deeper tectonic level (Figs. 2,3,4). The Turba shear zone coincides with a metamorphic discontinuity, that is, it has lower-grade rocks in the hanging wall resting on higher-grade rocks in the footwall, a certain temperature range being omitted in between (Ferreiro Mählmann 1995, Nievergelt et al. 1996). It is for this reason that we interpret the Gürgaletsch-Turba shear zone as a post-nappe extensional fault, and the entire D2 stage as an extensional event during the Tertiary orogenic evolution. The change from D1 accretion to D2 extension coincided with a reversal of the shear sense from top-N to top-SE (to E in the case of the Turba zone further south, Nievergelt et al. 1996). In this new kinematic frame, the sedimentary layering and many of the nappe boundaries were in an orientation for shortening. This led to widespread D2 backfolding. In our view, these folds did not develop in a contractional but rather in an extensional setting (as was demonstrated by Marquer 1991 and Marquer et al. 1996 for the same deformational phase in the Tambo and Suretta nappes). "Extensional setting" in this context means that the Penninic nappes of Graubünden were thinned and extended in a SE-NW direction at that time. We do not imply, however, that N-S convergence across the Alps ceased, which is in fact rather improbable (Schmid et al. 1996), nor do we exclude synchronous shortening at deeper structural levels.

D2 backfolding, the Niemet-Beverin phase, occurred between about 35 and 30 Ma, that is, in the Oligocene. The minimum age is constrained by the 30 Ma Bergell granodiorite intrusion that truncates the Turba mylonite zone (Nievergelt et al. 1996). The upper age bracket, 35 Ma, comes from the observation that the Niemet-Beverin phase postdates a considerable part of the exhumation of the Adula eclogites which had suffered peak pressures around 40 Ma (see discussion in Schmid et al. 1996).

It is important to note that the D2 extensional shearing is not responsible for the bulk of the exhumation of the Adula high pressure rocks but that a large part of this exhumation and the juxtaposition of the high-pressure rocks against the overlying lower-pressure rocks of the Tambo nappe occurred already before D2 extensional shearing (Schmid et al. 1996, Partzsch 1997). The same holds for the Fe-Mg-carpholite-bearing rocks of the Grava nappe in our study area: high-P/low-T conditions were present during D1a, and during D1b the carpholite was already replaced by chlorite (Weh 1998). In the Bündnerschiefer of the Engadine window, representing the eastward continuation of the Grava nappe of the Prättigau half-window, Bousquet et al. (1999) identified a top-NW detachment fault, formed during the local D1. This fault accommodated the exhumation of carpholite-bearing high-pressure rocks located in its footwall. We did not observe such a detachment in the Prättigau area. It may have been present, however, in the southwestern part of the half-window near Passugg, i.e., above the carpholite-bearing rocks. If it existed, it was obliterated by the intense D2 and D3 deformation in this area.

5.3 "Out of sequence" N-directed thrusting and the wedging-out of the Helvetic nappes (D3)

N-S shortening within the Penninic sediment nappes of the study area resumed during D3. Structures belonging to this phase dominate the lower part of the Grava nappe (structural zone 3). In contrast, D2 is the dominant folding phase in the upper part of the Grava nappe (zone 1) and the Falknis nappe at Gürgaletsch. Large, north-vergent D3 folds like the Lunschania and Valzeina structures are kinematically linked to the basal, syn-D3, mylonitic shear zone of the Grava nappe (section 3.4). D4 folds accommodated some further shortening after theD3 mylonite zone became blocked.

The structural relations in the basal shear zone are very similar to the ones observed in the basal part of the Glarus Verrucano (Helvetic nappes) above the Glarus overthrust, exposed west of the Rhine valley (Fig. 2). In both areas, a pene-

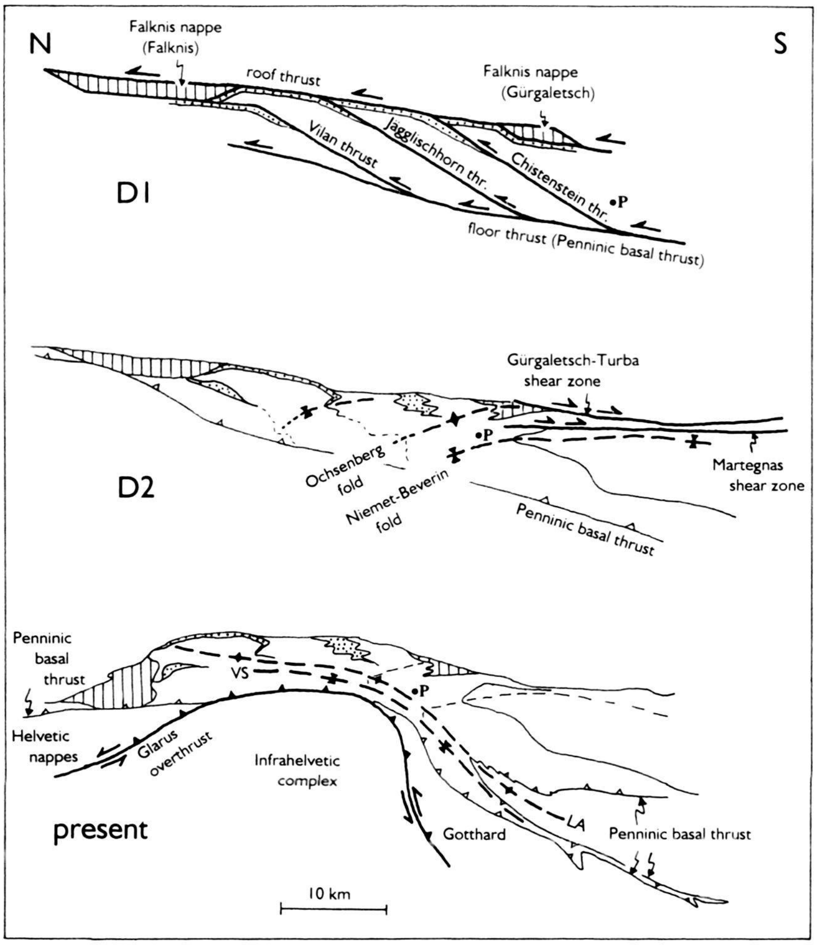

Fig.11. Structural evolution of the Prättigau half-window. Upper panel: D1 duplex geometry. Middle panel: Overprint by top-SE shearing during the Niemet-Beverin phase (D2). Lower panel: Present-day profile, showing main D3 structures - the Glarus thrust, the Valzeina synform and the Lunschania antiform. Note that the older Penninic basal thrust (the floor thrust of the D1 duplex) id folded around the Lunschania and Valzeina folds to the South. Stippled: Tertiary flysch of the Grava nappe; vertical ruling: Falknis nappe. Other units may be identified by comparison with Fig. 3. "P" indicates Passugg carpholite locality.

trative foliation (Calanda phase along the Glarus thrust, D3 in our study area), axial-planar with respect to N-vergent folds, curves downward into parallelism with the thrust contact. This foliation is associated with a stretching lineation trending N-S in the Verrucano above the Glarus thrust (Siddans 1979), and NNE-SSW in the Cretaceous schists at the bottom of the Grava nappe (Fig.5). The penetrative foliation is in both areas overprinted by small-scale open folds and a crenulation cleavage dipping steeply SSE (Ruchi phase along the Glarus thrust, D4 in our case). It is for these reasons that we equate the D3 basal shear zone between Chur and Landquart with the Glarus thrust at the base of the Helvetic nappes, that is to say, the amount of northward thrusting that occurred along the Glarus thrust west of the study area (Helvetic nappes over the Infrahelvetic complex), is accommodated by the basal shear zone in our study area. The Helvetic nappes laterally wedge out towards the East, i.e., the Chur Rhine valley (Fig. 2). The apex of the Helvetic nappes in the northern part of the Rhine valley is at Fläscher Berg (Fig. 2). Another, similar apex exists to the Southwest, in the Vorderrhein valley SW of Chur (Fig. 2). Therefore, within the study area, the Grava nappe was transported directly over the Infrahelvetic complex. However, it is not necessary that the Helvetic nappes wedge out completely because thin remnants of Helvetic Verrucano may still be hidden below the quaternary Rhine valley fill.

We assume that this wedging-out (or at least extreme thinning) of the Helvetic nappes results from the "out-of-sequence" nature of the D3 thrust, interfering with older structures. In contrast, Trümpy (1992) proposed that the omission of Helvetic nappes in the Rhine Valley between Chur and Landquart is the result of a late Alpine N-S oriented normal fault, the "Churer Störung". We did not find any structural evidence for such a fault and, in addition, zircon fission track data of Fügenschuh and Weh (data in Weh 1998) argue against its existence.

Equating the D3 basal shear zone of the Grava nappe with the Glarus thrust implies that this shear zone is rooted, together with the Glarus thrust, between the Aar and Gotthard massifs. It follows that the "Penninic basal thrust" (Schmid et al. 1996) south of the Gotthard massif, that is, the thrust which emplaces Penninic Bündnerschiefer onto the cover of the Gotthard massif (a cover that is itself allochthonous, Etter 1987), is not identical with the D3 basal shear zone of our study area. In fact, the Penninic basal thrust south of the Gotthard massif must be older than our D3 deformation because it is folded around the Valzeina synform and the Lunschania antiform (Fig. 11). Our basal shear zone, in contrast, is cogenetic with these folds.

The age of the Glarus thrust and the Calanda phase in its footwall is constrained by the youngest sediments affected, i.e.Lower Oligocene (ca. 35 Ma) flysch of the Aar massif cover. Deposition of these sediments, however, also predates the older Pizol phase, that is, the emplacement of "exotic sheets" of South Helvetic origin on the Aar massif cover, which were later buried "out of sequence" by the Glarus thrust. This Pizol phase may be time-equivalent to our D2. This would then imply that thrust-sheet emplacement took place in the Helvetic realm while the Penninic nappes were extended, favouring a "gravity spreading" model as envisaged by Milnes & Pfiffner (1977, 1980) for the same time interval. A tentative correlation and estimated ages of the deformation phases are given in Table 1.

Tab. 1. Correlation of deformation phases between the study area and adjacent areas. Phases in the Schams and Suretta nappes after Schreurs (1993) and Schmid et al. (1996), phases in the Helvetic nappes after Milnes & Pfiffner (1977).

Helvetic	Grava, Falknis (this study)	Schams, Suretta	age
Ruchi	D4		
Calanda	D3	D3 (Domleschg)	Post 30 Ma
Pizol?	D2	D2 (Niemet-Beverin)	35-30 Ma
	D1a, b	D1 (Ferrera), pre-D1 thrusts	50 (?)-35 Ma

6. Conclusions

The Grava and Falknis nappes formed hinterland-dipping (south-dipping) duplexes when they were detached in the Early Tertiary from the southward-subducting lithosphere and accreted to the base of the orogenic wedge. Burial of the Grava nappe led to a pressure-dominated metamorphism with formation of Fe-Mg carpholite in the southermost part of the Prättigau half-window. The accretion stage (D1) is locally subdivided in two subphases: thrusts, cleavage, and veins formed during D1a and were tightly to isoclinally folded during D1b.

The kinematic picture changed abruptly around 35 Ma when the Penninic nappes were affected by top-SE extensional shearing. A series of backfolds, of which the Niemet-Beverin synform is the most important but by far not the only one, formed synchronously with a system of top-SE extensional shear zones (Turba-Gürgaletsch, Martegnas). Folds and shear zones are kinematically linked in the way that, going from north to south, the top-southeast displacement accommodated by the backfolds is more and more transferred to the shear zones. The Oligocene extensional episode may be related to gravity spreading (Milnes & Pfiffner 1977, 1980) during which the Helvetic realm was probably the locus of north-directed thrusting (Pizol phase).

After about 30 Ma, the underthrust European continental crust became shortened internally by Calanda-phase folding and cleavage formation, and by the evolving Glarus thrust. This deformation, D3 in the study area, affected also the lower part of the Grava nappe. The D3 basal shear zone of the Grava nappe between Chur and Landquart is identical with the Glarus thrust dipping eastward into the Rhine valley. There is no evidence and no necessity for a late Alpine "Churer Störung".

The present-day antiformal shape of the Prättigau half-window is a combined result of three processes: (1) The D1 duplex of the Grava nappe already had an antiformal geometry, as is suggested by the occurrence of Falknis nappe units north and south of the half-window (see Fig. 11, upper panel). (2) Formation of the Lunschania antiform and Valzeina synform (D3) contributed significantly to the shape of the half-window. The Lunschania antiform is responsible for the sharp bend of the Austroalpine basal thrust at the NE corner of the half-window. (3) Additional arching of the half-window occurred after D3, as is evidenced by fission-track work of Fügenschuh and Weh (in Weh 1998) and by the antiformal shape of the Glarus thrust and of the D3 fold axial traces (Fig. 11, lower panel) – although this antiformal shape may in part be a primary feature of the Glarus thrust (Schmid 1975).

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REFERENCES

ALLEMANN, F. 1957: Geologie des Fürstentums Liechtenstein (Südwestlicher Teil) unter besonderer Berücksichtigung des Flyschproblems. Jb. Hist. Ver. Fürstent. Liechtenstein 56, 1–244.

BOUSQUET, R., OBERHÄNSLI, R., GOFFÉ, B., JOLIVET, L. & VIDAL, O. 1999: High pressure-low temperature metamorphism and deformation in the "Bündnerschiefer" of the Engadine window: Implications for the regional evolution of the eastern Central Alps. J. metamorphic. Geol. 17, 657–674.

BOYER, S. E. & ELLIOTT, D. 1982: Thrust systems. AAPG Bull. 66, 1196–1230.

DÜRR, S.B., RING, U. & FRISCH, W. 1993: Geochemistry and geodynamic significance of North Penninic ophiolites from the Central Alps. Schweiz. mineral. petrogr. Mitt. 73, 407–419.

ETTER, U. 1987: Stratigraphische und strukturgeologische Untersuchungen im gotthardmassivischen Mesozoikum zwischen dem Lukmanierpass und der Gegend von Ilanz. Ph.D. thesis, Bern University, Bern.

FERREIRO MÄHLMANN, R. 1995: Das Diagenese-Metamorphose-Muster von Vitrinitreflexion und Illit-"Kristallinität" in Mittelbünden und im Oberhalbstein, Teil 1: Bezüge zur Stockwerkstektonik. Schweiz. mineral. petrogr. Mitt. 75, 85–122.

FERREIRO MÄHLMANN, R., PETSCHICK, R., ERDELBROCK, K., KRUMM, H., WOLF, M. & BERNOULLI, D. 1992: Coalification map of the Pennine-Austroalpine boundary (Switzerland, Liechtenstein and Austria). Terra Nova 4, Abstract Supplement 2, 21 (ALCAPA meeting, Graz).

FLORINETH, D. & FROITZHEIM, N. 1994: Transition from continental to oceanic basement in the Tasna nappe (Engadine window, Graubünden, Switzerland): evidence for Early Cretaceous opening of the Valais ocean. Schweiz. mineral. petrogr. Mitt. 74, 437–448.

FROITZHEIM, N., SCHMID, S. M. & CONTI, P. 1994: Repeated change from crustal shortening to orogen-parallel extension in the Austroalpine units of Graubünden. Eclogae geol. Helv. 87, 559–612.

FROITZHEIM, N., SCHMID, S. M. & FREY, M. 1996: Mesozoic paleogeography and the timing of eclogite-facies metamorphism in the Alps: A working hypothesis. Eclogae geol. Helv. 89, 81–110.

GOFFÉ, B. & OBERHÄNSLI, R. 1992: Ferro- and magnesiocarpholite in the "Bündnerschiefer" of the eastern Central Alps (Grisons and Enagdine window). Eur. J. Mineral. 4, 835–838.

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

LICHTSTEINER, F. 1992: Stratigraphie der Falknis-Decke im Gürgaletsch-Gebiet. Unpubl. diploma thesis, Zürich University.

MARQUER, D. 1991: Structures et cinématique des déformations alpines dans le granite de Truzzo (Nappe de Tambo: Alpes centrales suisses). Eclogae geol. Helv. 84, 107–123.

MARQUER, D., CHALLANDES, N., & BAUDIN, T. 1996: Shear zone patterns and strain distribution at the scale of a Penninic nappe: the Suretta nappe (Eastern Swiss Alps). J. struct. Geol. 18, 753–764.

MILNES, A. G. & PFIFFNER, O. A. 1977: Structural development of the Infrahelvetic complex, eastern Switzerland. Eclogae geol. Helv. 70, 83–95.

MILNES, A. G. & PFIFFNER, O. A. 1980: Tectonic evolution of the Central Alps in the cross section St.Gallen-Como. Eclogae geol. Helv. 73, 619–633.

NÄNNY, P. 1948: Zur Geologie der Prätigauschiefer zwischen Rhätikon und Plessur. Ph.D. thesis, Zürich University, Zürich.

NIEVERGELT, P., LINIGER, M., FROITZHEIM, N., & FERREIRO MÄHLMANN, R. 1996: Early to mid Tertiary extension in the Central Alps: The Turba mylonite zone (Eastern Switzerland). Tectonics 15, 329–340.

OBERHÄNSLI, R., GOFFÉ, B. & BOUSQUET, R. 1995: Record of a HP-LT metamorphic evolution in the Valais zone: Geodynamic implications. Boll. Museo Regionale Scienze Naturali Torino, 13, suppl. 2, 221–239.

PARTZSCH, J. 1997: The tectono-metamorphic evolution of the middle Adula nappe, Central Alps, Switzerland. Ph.D. thesis, Basel University, Basel.

PFIFFNER, O.A. 1977: Tektonische Untersuchungen im Infrahelvetikum der Ostschweiz. Mitt. Geol. Inst. ETH u. Univ. Zürich N.F. 217, 1–432.

PROBST, P. 1980: Die Bündnerschiefer des nördlichen Penninikums zwischen Valser Tal und Passo di San Giacomo. Beitr. Geol. Karte Schweiz N.F. 153, 63 p.

RING, U., RATSCHBACHER, L., FRISCH, W., BIEHLER, D. & KRALIK, M. 1989: Kinematics of the Alpine plate-margin: structural styles, strain and motion along the Penninic-Austroalpine boundary in the Swiss-Austrian Alps. J. geol. Soc. (London) 146, 835–849.

SCHMID, S.M. 1975: The Glarus overthrust: fiel evidence and mechanical model. Eclogae geol. Helv. 68, 247–280.

SCHMID, S. M., RÜCK, P. & SCHREURS, G. 1990: 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). Mém. Soc. géol. France 156, 263–287.

SCHMID, S. M., PFIFFNER, O. A., FROITZHEIM, N., SCHÖNBORN, G., & KISSLING, E. 1996: Geophysical-geological transect and tectonic evolution of the Swiss-Italian Alps. Tectonics 15, 1036–1064.

SCHREURS, G. 1993: Structural analysis of the Schams nappes and adjacent tectonic units: implications for the orogenic evolution of the Penninic zone in eastern Switzerland. Bull. Soc. géol. France 164, 415–435.

SIDDANS, A.W.B. 1979: Deformation, metamorphism and texture development in Permian mudstones of the Glarus Alps (Eastern Switzerland). Eclogae geol. Helv. 72, 601–621.

SPICHER, A. 1980: Tektonische Karte der Schweiz, 1: 500 000. Schweiz. Geol. Komm., Bern.

STAMPFLI, G.M. 1993: Le Briançonnais, terrain exotique dans les Alpes? Eclogae geol. Helv. 86, 1–45.

STEINMANN, M. 1994: Ein Beckenmodell für das Nordpenninikum der Ostschweiz. Jb. Geol. B.-A. (Wien) 137, 675–721.

STEINMANN, M. & STILLE, P. 1999: Geochemical evidence for the nature of the crust beneath the eastern North Penninic basin of the Mesozoic Tethys ocean. Geol. Rundsch. 87, 633–643.

THUM, I. & NABHOLZ, W. 1972: Zur Sedimentologie und Metamorphose der penninischen Flysch- und Schieferabfolgen im Gebiet Prättigau-Lenzerheide-Oberhalbstein. Beitr. Geol. Karte Schweiz N.F. 144, 1–55.

TRÜMPY, R. 1980: Geology of Switzerland: a guide-book. Part A: An outline of the geology of Switzerland. Wepf, Basel.

TRÜMPY, R. 1992: Ostalpen und Westalpen - Verbindendes und Trennendes. Jb. Geol. B.-A. (Wien) 135, 875–882.

VOLL, G. 1976: Structural studies of the Valser Rhine valley and Lukmanier region and their importance for the nappe structure of the central Swiss Alps. Schweiz. mineral. petrogr. Mitt. 56, 619–626.

WEH, M. 1998: Tektonische Entwicklung der penninischen Sediment-Decken in Graubünden (Prättigau bis Oberhalbstein). Dissertation aus dem Geol.-Paläont. Institut der Universität Basel, Nr. 15.

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Erratum

Penninic cover nappes in the Prättigau half-window (Eastern Switzerland): Structure and tectonic evolution

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The figures 2, 3 and 4 of the article "Penninic cover nappes in the Prättigau half-window (Eastern Switzerland): Structure and tectonic evolution" published in Volume 94/2 (2001), pp. 237–152 in the Eclogae geologicae Helvetiae were misprinted. These pages are considered as the erratum.

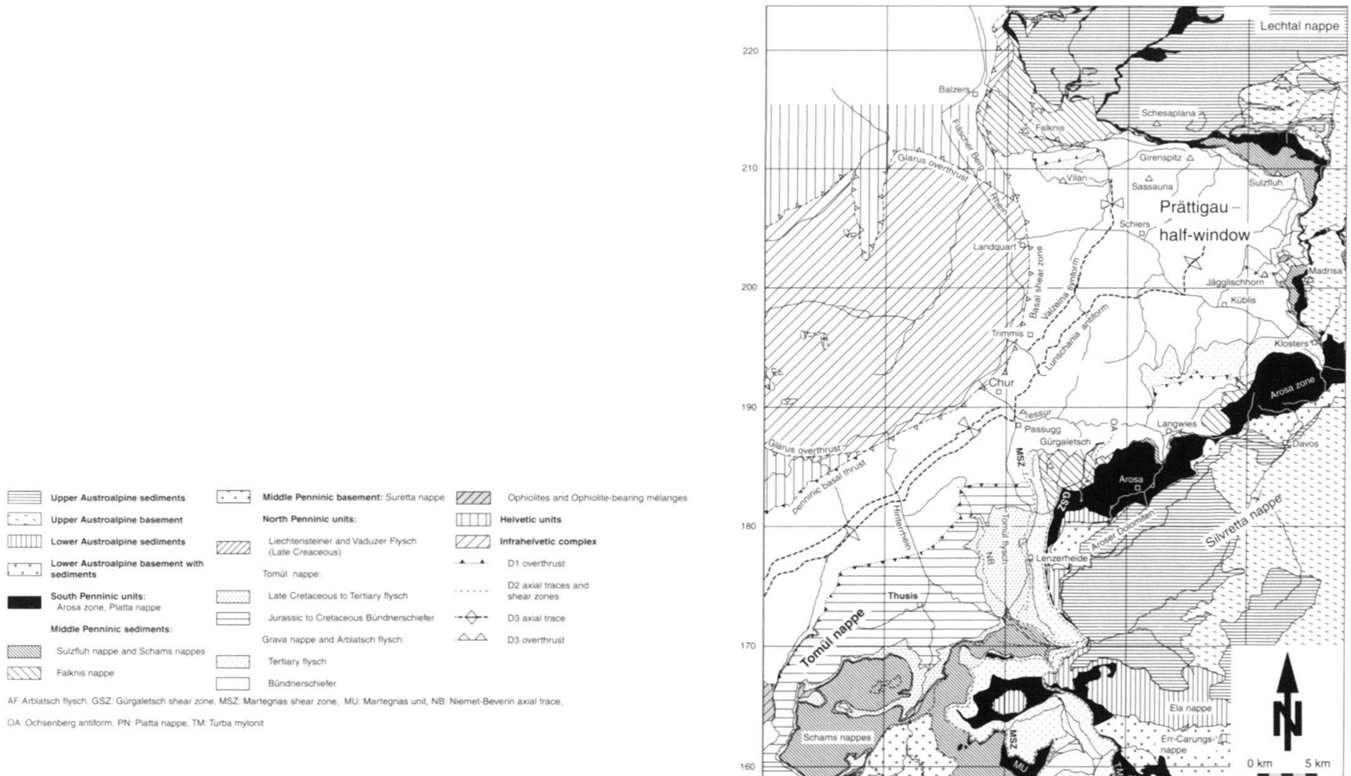

Fig. 2. Tectonic map of the Prättigau half window and surrounding area.

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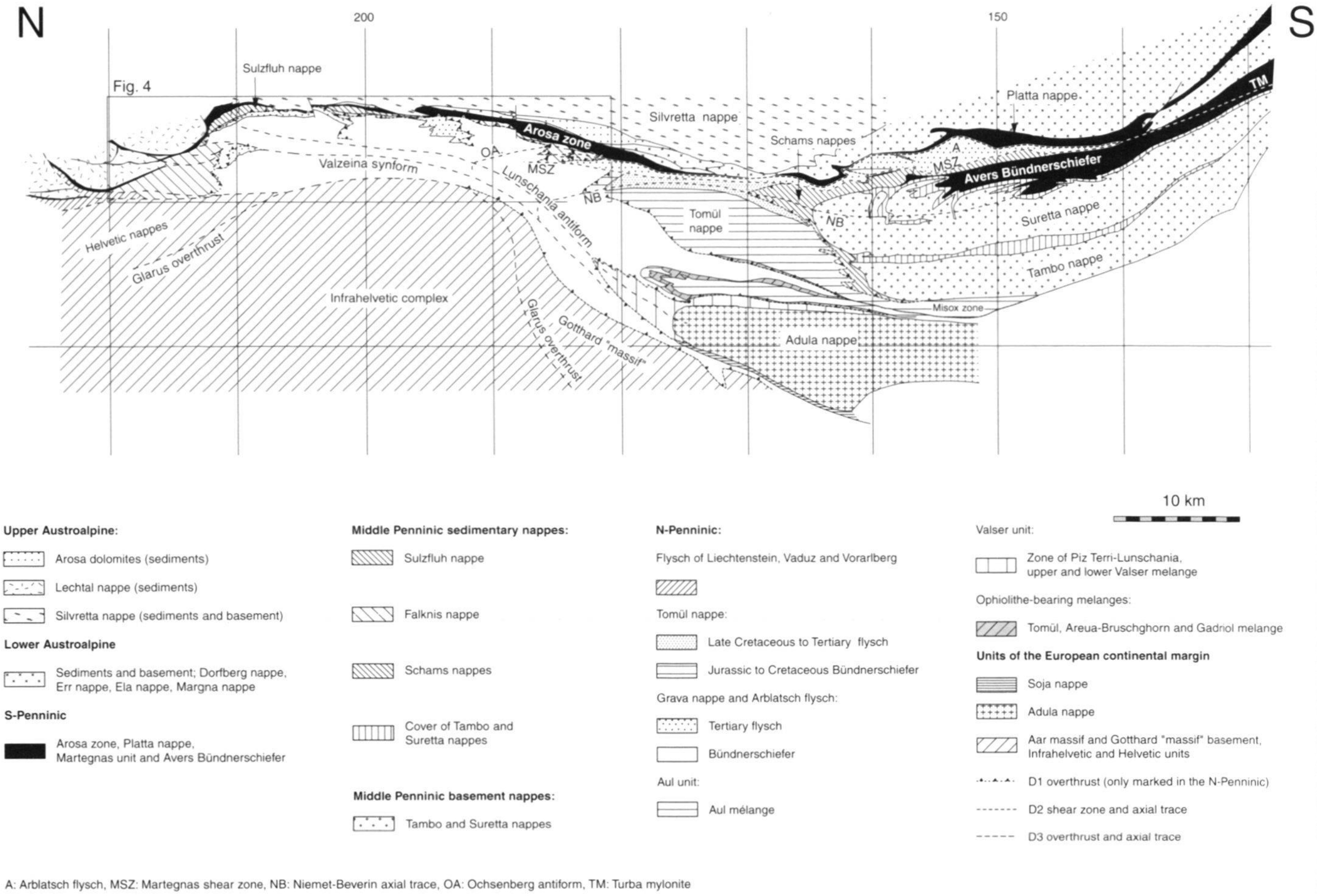

Fig. 3. N-S cross section through eastern Swiss Alps (after Schmid et al., 1996, modified according to results of this study).

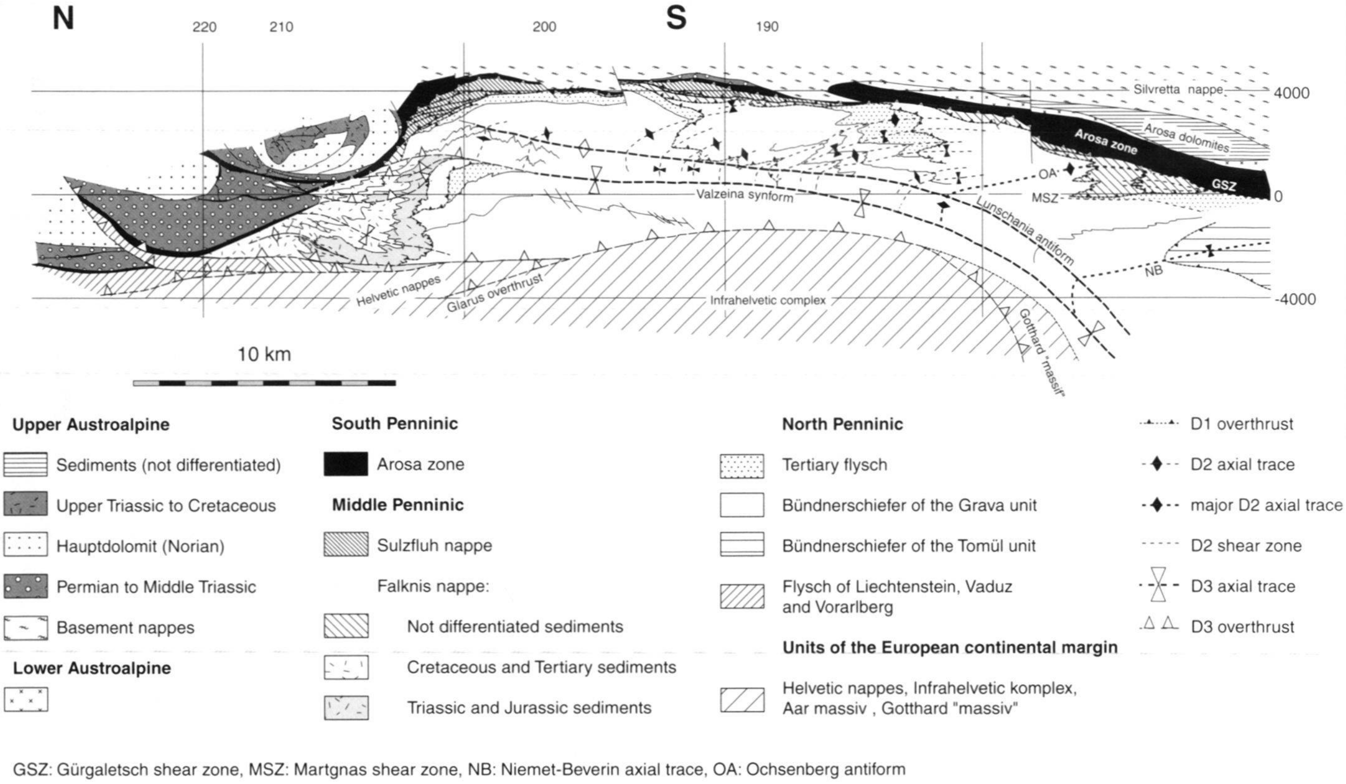

Fig. 4. N-S cross-section of the Prättigau half window.