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Structure of the eastern Klippen nappe (BE, FR): Implications for its Alpine tectonic evolution

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Key words: Préalpes, Klippen nappe, Préalpes Médianes, Briançonnais, fold-and-thrust structures, synsedimentary faults, detachment folds, imbricates, detachment, evaporites

ABSTRACT

We examine the structures of the biggest and best exposed unit of the Prealpine nappe stack, the Klippen nappe in the eastern Préalpes Romandes. During the Alpine orogeny, the Klippen nappe was incorporated into the accretionary wedge of the closing Piemont ocean, detached from the basement along a basal evaporite horizon and transported onto the foreland in a thin-skinned tectonic style.

The stratigraphy of this cover nappe changes significantly parallel and perpendicular to strike. These variations give rise to changes in structural style of the cover nappe, from mainly fold structures in the north to large imbricates in the south.

Results from our field study, previous work and seismic data permit the subdivision of the cover sequence into 5 sectors from north to south, which are separated by thrust faults. This subdivision is the basis for the reconstruction of the Klippen nappe paleobasin. This basin is crosscut by a number of synsedimentary paleofaults. Our model of emplacement and internal deformation of the Klippen nappe suggests that ramping and stacking of imbricates in the southern part of the nappe is controlled by the low thickness and insufficient continuity of the evaporite layers below the massive carbonate units. The fault-related fold structures in the northern part seem to be influenced by the larger thickness of these evaporites and the presence of heterogeneities which resulted from synsedimentary faults within the interlayered carbonate sequences.

ZUSAMMENFASSUNG

Die Klippendecke ist die grösste Einheit innerhalb des Präalpinen Deckenstapels und wurde im Bereich der östlichen Préalpes Romandes untersucht. Im Szenarium eines Akkretionskeils mit Sedimenten des Piemont-Ozeans wurde die Klippendecke im Verlauf der Alpinen Orogenese entlang eines basalen Evaporithorizonts von ihrem Unterlager abgeschert und als penninische Sedimentdecke weit in Richtung Vorland transportiert. Die stratigraphische Abfolge dieser Sedimentdecke zeigt deutliche Änderungen in Mächtigkeiten und Fazies senkrecht und parallel zum Streichen. Dies wird als wichtiger Schlüssel zum Verständnis der tektonischen Entwicklung und Platznahme der Decke angesehen. Im Zusammenhang mit den auffälligen stratigraphischen Unterschieden von N nach S sind deutliche Änderungen im tektonischen Stil der Decke zu beobachten. Im Norden herrschen Faltenstrukturen vor, im Süden hauptsächlich Schuppenbau.

In Kombination mit früheren Arbeiten und seismischen Daten erlauben die Ergebnisse unserer Feldstudie eine Unterteilung der Deckensedimente in 5 Sektoren von N nach S, die durch Überschiebungen voneinander getrennt sind. Diese Unterteilung ist die Grundlage für die Rekonstruktion der Beckengeometrie im Mesozoikum. Das Becken war offenbar von zahlreichen synsedimentären Brüchen durchsetzt. Unser Modell der Platznahme und internen Deformation der Klippendecke lässt vermuten, dass die Bildung von Rampen und Schuppen im südlichen Teil der Decke von der geringen Mächtigkeit und der fehlenden Kontinuität der Evaporitlagen unterhalb der massiven Karbonatabfolgen kontrolliert wird. Die Falten- und Überschiebungsstrukturen im Nordteil sind möglicherweise von der dort mächtigen Evaporitlage und Unregelmässigkeiten entlang der synsedimentären Brüchen innerhalb der Karbonatserien begünstigt worden.

1. Introduction

The Préalpes are a pile of different structural units located along the northern front of the present Alpine mountain belt. Two large lobes are formed by the Préalpes du Chablais south of Lake Geneva and the Préalpes Romandes east of Lake Geneva (Fig. 1). Smaller erosional remnants of the Prealpine nappes are found in the 'Klippen' in central and eastern Switzerland (Stanserhorn, Mythen, Grabs) as well as in France (Annes and Sulens) south of Lake Geneva. Between their original and present position, the Préalpes went through a complex history of paleo- and Alpine tectonics.

In general, the pile is subdivided into four different units from top to bottom: (1) Nappe Supérieure (with Gurnigel-, Dranse, Simmen-, Gets nappe; Caron 1972), (2) Breccia nappe (3) Klippen nappe (also known as 'Préalpes Médianes') and (4) Niesen nappe.

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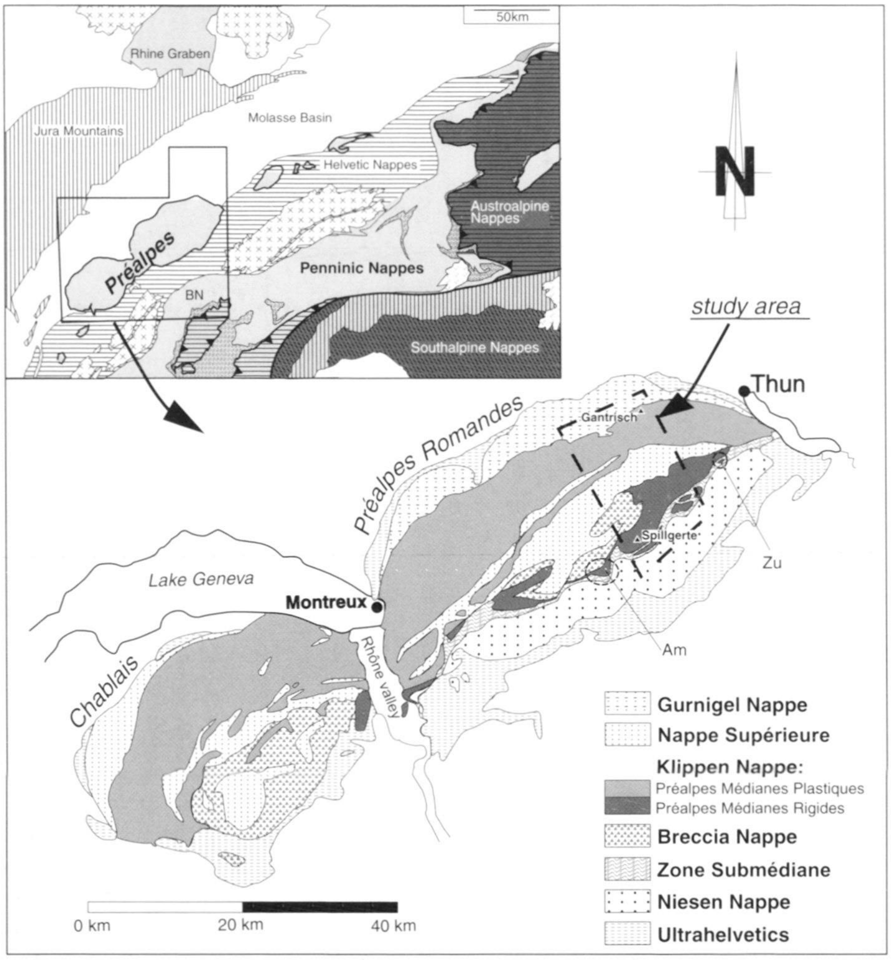

Fig. 1. Tectonic sketch map of the Klippen nappe (Swiss Préalpes Romandes and French Préalpes du Chablais) and its position within the Alps (inset). BN: Bernhard nappe, Am:Amselgrat, Zu: Zünegg lens.

In addition, two important mélange zones developed during nappe transport, the Ultrahelvetics and the Zone Submédiane (Weidmann et al. 1976).

During the Alpine orogeny, the sediments of the nappe stack (Valais, sub-Briançonnais, Briançonnais, Piemontais) were detached from their crystalline substratum and thrust on top of the Autochthonous and Subalpine Molasse to the north and the Helvetic nappes to the south. (Fig. 2)

In our field study, we examined the tectonic structures of the largest and best exposed member of the Préalpes, the Klippen nappe. Its Mesozoic carbonate sequences were deposited on the Briançonnais microcontinent and became detached along upper and middle Triassic evaporites (Baud 1972, Baud & Septfontaine 1980). Remnants of these Briançonnais deposits are found in the Bernhard nappe (Siviez-Mischabel and Pontis nappe; Escher et al. 1997, Sartori 1987b, 1990), which remained attached to the footwall and underwent pervasive deformation and greenshist metamorphism. In comparison, metamorphism of the Préalpes is very low grade: diagenesis in the north to lowermost greenschist facies (burial of about 10 km) in the extreme south (Mosar 1988a, Jaboyedoff & Thélin 1996). The Klippen nappe was transported over a distance exceeding 100 km (Masson 1976).

Thickness of the evaporites can reach 1000 m below the Préalpes (Mosar 1991), but their total thickness is not well constrained. The original thickness and stratigraphic levels of these sequences in the paleobasin probably changed with location, possibly controlling the evolution of detachment tectonics to a large extent.

Most previous studies in the eastern Préalpes focused on surface geology and surface structures. Detailed geological maps are available over small parts of the investigated area (Arbenz 1947, Bieri 1925, Furrer 1979, Genge 1949, Gisiger 1967, Isenschmid 1979, Keusch 1985, Page 1969, Thury 1971, Umiker 1952, Wegmüller 1956, Winkler 1977) but only a few interpretations of structures at depth (Mosar 1991, Pfiffner et al. 1997, Plancherel 1979) and the geodynamic evolution of the nappe stack (Mosar et al. 1996, Stampfli et al. 1998) have been made. We examined structures in an area between Gantrisch, Schwarzsee, St. Stephan (Simmen Valley) and Wierihorn (Diemtig Valley) to constrain data for a geometrical reconstruction of our cross sections (Figs. 1 and 3).

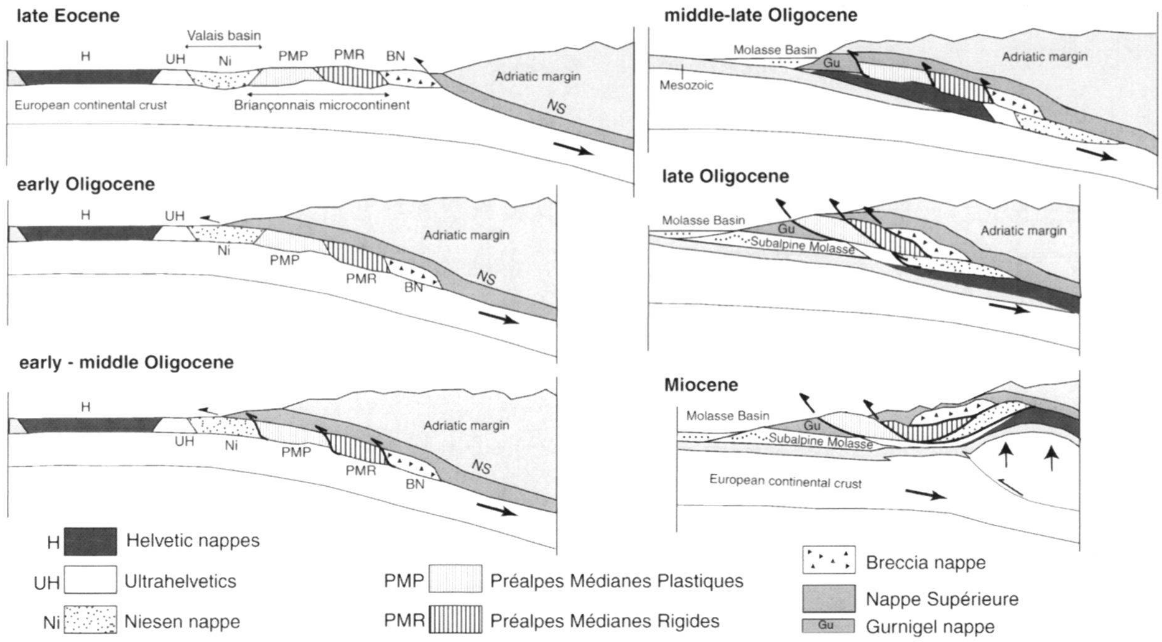

Fig. 2. Schematic profiles showing tectonic evolution of the Préalpes Romandes in time. Partly after Lemoine (1984).

The sedimentary deposits of the Préalpes detached in a rim-basin context, which was linked to rifting of the Alpine Tethys (Mosar et al. 1996). The basin reached its maximum extension in Liassic times (Borel & Mosar 2000). At that time, the Briançonnais microcontinent was located along the northern part of the Alpine Tethys and underwent moderate extension on a rift shoulder (Stampfli 1993, Stampfli & Marthaler 1990). Extensional synsedimentary faults influenced the distribution of sediments as well as the tectonic evolution of the nappe during Alpine deformation significantly (Borel 1997), and divided the Klippen nappe into different facies realms perpendicular to strike.

The geology of the Klippen nappe is crucial for the understanding of nappe formation and transport in the Préalpes. Its structural style and evaporitic base yield information about the former paleobasin as well as the timing and dynamics of nappe emplacement. The aim of this work is to provide an explanation for the main structures in the eastern Klippen nappe in relation to the geometry and location of important synsedimentary faults and facies realms in the Briançonnais paleobasin. In addition, we discuss the evolution of the eastern Klippen nappe paleobasin and its implications for the geodynamic evolution of the Prealpine nappe stack, especially the Klippen nappe.

2. The Klippen nappe: Geology and structure

The structural style of the Préalpes and the Klippen nappe and its geological framework has been discussed for more than 100 years in numerous works (Masson 1976). Schardt (1884, 1892, 1894, 1899) was the first to recognize and describe the allochthonous character of the Préalpes. He distinguished 3 different units (Klippen nappe, Breccia nappe and Ultrahelvetics), located the sedimentary origin in the 'intra Alpine Briançonnais' realm and postulated a horizontal transport of 80-100 km. Subsequent studies often lagged behind the comprehensive work of Schardt and the subdivision and origin of the different Prealpine rocks was debated for many years. Only at the beginning of the seventies did the studies of Baud (1972), Baud & Septfontaine (1980), Caron (1972), Caron et al. (1980), Homewood (1974), shed some light on the confusion about the origin of the different Flysch units and implications for the general Alpine context. The first ideas about the paleogeographic framework were also made by Schardt (1898, Fig. 1), who presented the first simple palinspastic reconstruction of the Klippen and Breccia nappe. Ellenberger (1952) noted the Briançonnais character of the Triassic rocks in the Klippen nappe and correlated it with the Penninic 'Grand Bernard Zone'.

The Klippen nappe is made up of Mesozoic carbonates associated with marls and shales deposited on the Briançonnais microcontinent. For macrotectonic reasons, Lugeon & Gagnebin (1941) divided the Klippen nappe in two parts : the '*Préalpes Médianes Rigides*' in the south and the '*Préalpes Médianes Plastiques*' in the north. This subdivision reflects the change in structural style from a fold-dominated northern part to large imbricate structures in the southern part. Because this subdivision is important for both stratigraphy and tectonics, we refer to this nomenclature in the following sections.

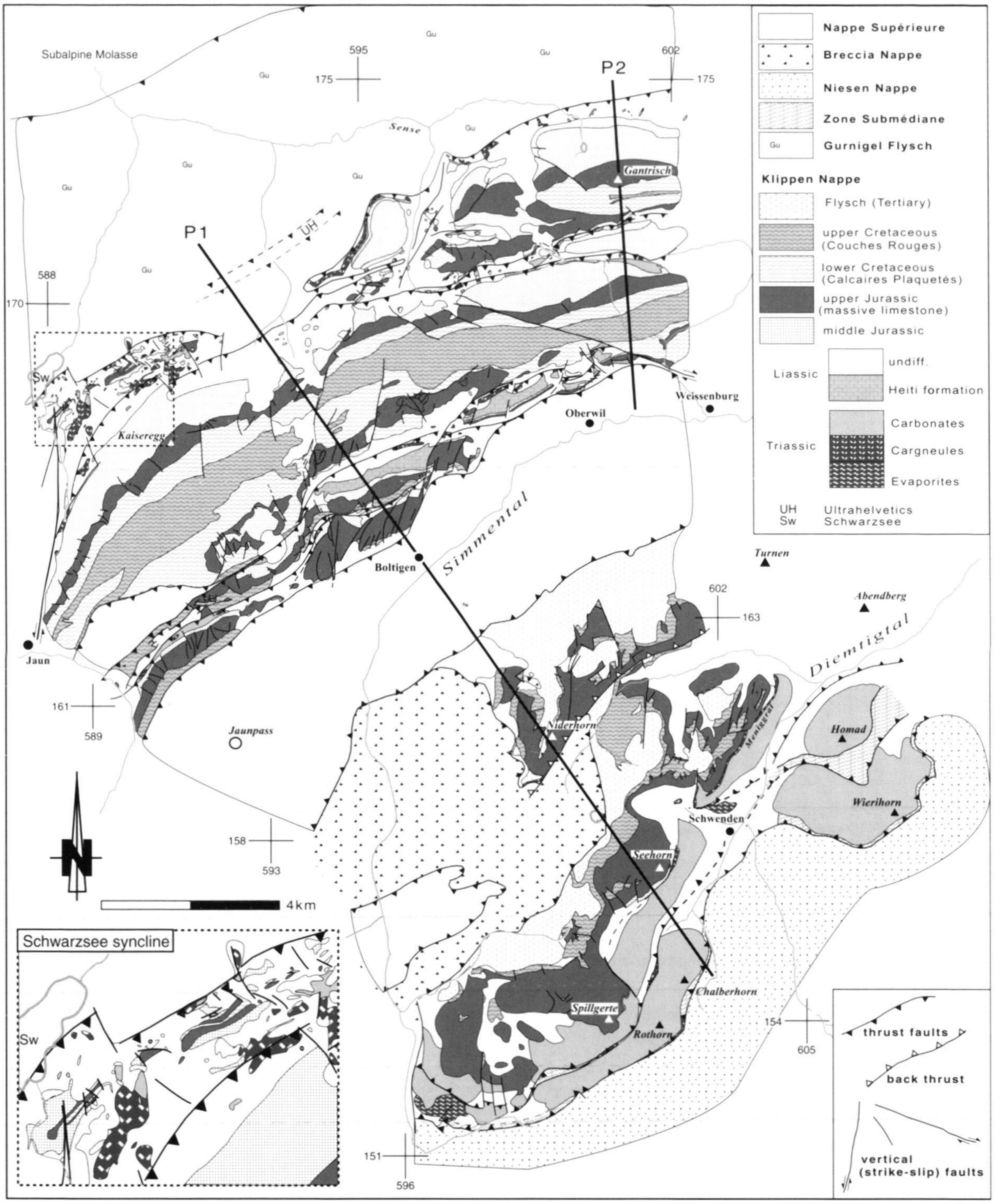

Fig. 3. Geological map of the Klippen nappe between Gantrisch, Schwarzsee, and Spillgerte with traces of cross sections P1 and P2, compiled by data from our field observations and map data from Bieri (1925), Arbenz (1947), Genge (1949), Umiker (1952), Wegmüller (1956), Gisiger (1967), Page (1969), Thury (1971), Winkler (1977), Furrer (1979), Isenschmid (1979), Keusch (1985). Inset shows an enlarged map of the region east of Schwarzsee (Schwarzsee syncline).

For a detailed discussion of geological and tectonic settings in the modern literature, the reader is referred to Baud & Septfontaine (1980), Borel (1997), Mosar (1988a, 1989, 1991, 1994, 1997), Mosar et al. (1996), Plancherel (1979) and references therein.

2.1 Structure and evolution of the Prealpine nappe stack

In Fig. 2 we give a schematic overview of the kinematic evolution and timing of deformation of the Prealpine nappe stack. Timing is constrained by transported metamorphism, which put greenshist facies sediments onto anchizonal (Mosar 1988b). This metamorphism has an incipient age of 27 Ma according to Jaboyedoff & Cosca (1999). Stratigraphic investigations show that a Flysch basin developed progressively in a northwestward direction from the Nappe Supérieure, to the Breccia nappe and finally to the Klippen nappe. The Nappe Supérieure (in the older literature also known as 'Simmen nappe' or 'Nappe Rhétique') has its origin in the Piemont ocean (Wegmüller 1953). The four subunits of the Nappe Supérieure, proposed by Caron (1972), contain flysch-type sediments from Triassic to Late Cretaceous times.

The Gurnigel nappe at the northern border of the Préalpes is currently regarded as a digitation of the lowermost unit of the Nappe Supérieure (Caron 1972, Lemoine 1984), i.e. of Piemont origin, thrust to the north in an early stage of nappe transport and subsequently overthrust by the Klippen nappe in a final stage of deformation (Middle-Late Oligocene, cf. Fig. 2).

The Breccia nappe (also known as 'Hornfluh nappe'), which is less voluminous in the Préalpes Romandes than in the Préalpes du Chablais, is positioned below the Nappe Supérieure and contains Jurassic breccias and shales. The top of the nappe is made up of green, grey or red marly pelagic limestones (Couches Rouges), corresponding to the upper Cretaceous rocks of the Klippen nappe. Its tectonic style is characterised by three isolated synclines plunging to the NW (Arbenz 1947, Jaccard 1904). The Nappe Supérieure was thrust on top of the Breccia- and Klippen nappes prior to their incorporation into the accretionary wedge. Subsequently, the Breccia nappe was thrust on top of the Klippen nappe (Lemoine 1984 and Fig. 2). The fact that the Breccia nappe and underlying Klippen nappe are disharmonically folded is taken to imply that they were deformed independently at the beginning of the folding events (Jeannet & Heim 1919-1920).

The 'Zone Submédiane' at the base of various thrust sheets in the Préalpes Médianes Rigides has been interpreted to be constructed of distinct flysch units in earlier publications (Lugeon & Gagnebin 1941). McConell & De Raaf (1929) specified the name, but described the zone as a digitation of the Niesen nappe, dismembered into lenses by the overthrusting of the Klippen nappe. Today, the Zone Submédiane is known as a tectonic mélange with components of Penninic and Ultrahelvetic origin (Weidmann et al. 1976). The mélange is exposed in the southern part of the Klippen nappe at the border to the Niesen nappe and between different imbricates of the Préalpes Médianes Rigides. Its extension below the Klippen nappe to the north is not constrained.

The Niesen nappe contains upper Cretaceous and Tertiary flysch-type sediments from the Valais trough (Trümpy 1960, Homewood 1974). Today, it is the lower- and southernmost unit and is restricted to the Swiss part of the Préalpes (Préalpes Romandes).

The Ultrahelvetics (in the past also known as 'Zone des Cols' or 'Préalpes Internes') are composed of Wildflysch, breccias and shales. They are exposed in an area between the Helvetic units and the base of the Niesen nappe as well as at the northern front of the Préalpes, forming a cushion underneath the Prealpine stack. They represent a chaotic and complex deformed zone of lenses and small nappes (Jeanbourquin 1994), originating from south of the Helvetic and near the external Valais zone.

2.2 Stratigraphy of the Klippen nappe

The sedimentary history of the Briançonnais domain started with deposition of Permotriassic quartzites, followed by the formation of probably thin (eventually tectonically thinned) lower Triassic evaporites and dolomites in a coastal shabka (Lemoine et al. 1986). In middle Triassic times, a carbonate platform developed, on which the massive to thick-bedded middle Triassic carbonates were deposited. These now form the body of the Préalpes Médianes Rigides (Baud 1972, 1987). Sedimentation on this platform gave way to the precipitation of thick Carnian evaporites, which later acted as the detachment layer for the folded sheets of the Préalpes Médianes Plastiques. These evaporitic rocks probably developed their greatest thicknesses in the northern part of the basin (Sub-Briançonnais).

A second (upper Triassic) carbonate platform led to the deposition of Norian 'blonde' dolomites, which form the basal layer of the Préalpes Médianes Plastiques above the detachment layer. First indications of extensional tectonics are marked by Carnian breccias.

After the Early Liassic main rifting event, the Briançonnais rim-basin became divided into different facies domains by synsedimentary faults. Thicknesses of Liassic units are generally small, but change significantly parallel and perpendicular to strike (Mettraux & Mosar 1989, Weidmann 1992), giving rise to a confusing nomenclature of Liassic deposits in the literature (see Borel 1997, p.17-34 for a review). Liassic rocks often contain quartz bearing dolomites and limestones or dark cherts and normally produce a distinct relief. The bituminous 'Heiti-Lias', the southernmost unit with outcrops of Liassic rocks, is characterised by dark limestones interlayered with black shales and shows thicknesses up to 200 m in our field area; total thickness is known to be about 500 m. An uplift of the northern Tethys rift shoulder (Toarcien) caused karstification and erosion towards the rift shoulder (SE; Mettraux & Mosar 1989, Baud & Masson 1975). As a result, Liassic sediments are not preserved in the Préalpes Médianes Rigides. There, the transgressive contact to the middle Jurassic sediments make an angular unconformity with the underlying Triassic of 10°.

The emerged Briançonnais rift shoulder to the south and the proceeding subsidence of the sub-Briançonnais basin to the north led to two different middle Jurassic facies realms (Furrer 1979). In the subsiding sub-Briançonnais basin, sedimentation of up to 1000 m of the 'Zoophycus Dogger' (named after the zoophycus fossil) consisting of dark limestones interlayered with black shales, reef carbonates and distal turbiditic sequences took place. To the south, on the emerged Briançonnais platform, about 100 m of the lagoonal, coalbearing 'Mytilus Dogger' was deposited, its thickness decreasing to the south (Septfontaine 1983, 1995).

In Late Jurassic times, a new carbonate system developed with platform carbonates to the south and resediments in the northern part of the basin (Heinz 1985, Heinz & Isenschmid 1988). In general, the very light grey and massive micritic upper Jurassic rocks form the morphological and structural skeleton of the Préalpes Médianes Plastiques. Late Jurassic sediments are normally about 300-400 m thick, but in the slope area between northern and southern facies realms, thicknesses are generally reduced to 120 m or less (Isenschmid 1979).

The transition from the massive upper Jurassic carbonates to the overlying thin bedded pelagic limestones (*Neocom* in the older literature or *Calcaires Plaquetés*, Spicher 1966) with cherts and shales is progressive. Lower Cretaceous rocks are normally less competent and intensely folded. They are only deposited in the sub-Briançonnais domain and are absent to the south, probably owing to synsedimentary normal faulting and erosion. There, upper Cretaceous pelagic limestones and marls (Couches Rouges) directly overly karstified upper Jurassic limestones (Wegmüller 1953).

A change in sedimentary conditions occurred in early Late Cretaceous times to alternating sedimentation and erosion conditions (Baud & Septfontaine 1980). The red, green or grey marly limestones (Couches Rouges) extend across the whole Klippen nappe and the adjacent Breccia nappe basin (Guillaume 1986).

Eocene Flysch sediments, almost entirely eroded in the Préalpes Médianes Plastiques, complete the sedimentary history of the Klippen nappe and signal the beginning of the Oligocene orogenic events.

2.3 Structure of the Klippen nappe

The general structural style of the Médianes Plastiques part of the Klippen nappe is characterised by large-scale fold structures, arranged en échelon and segmented by sinistral and dextral strike-slip faults (Plancherel 1979). The southern part of the nappe, in contrast, is made up of rigid imbricate thrust sheets. It is not the intention of this paper to describe small-scale structures and internal deformation in detail. Extensive work on that topic may be found in Mosar (1989, 1991, 1997), and Mosar & Borel (1992). In the following we discuss the large scale aspects of nappe internal deformation.

The folds of the Préalpes Médianes Plastiques have a detachment fold character. Foreland limbs are often cut by thrust faults and only the backlimbs are exposed. Thrust faults commonly developed at locations of important thickness or facies changes in the carbonate sequence. Thrust faults and fold limbs were steepened owing to compressional events in a later stage of deformation. In the Gantrisch region, backlimbs and thrust faults are vertical or even rotated into a northward dipping orientation (Fig. 4, P2). In the area near Kaiseregg, where folds and thrusts seem to be less steepened, backlimbs dip moderately to the south (Fig. 4, P1).

The vertical to subvertical strike-slip faults strike about N10 for sinistral and N110 for dextral displacements (Fig. 3). Two different interpretations exist for the formation of these fault systems. According to Plancherel (1979) the left-lateral faults not only deform the Prealpine nappe stack, but also extend into the Molasse of the Swiss Plateau. They are thought to root in the basement and movements along these faults are interpreted by Plancherel to be responsible for the fold development in the Préalpes Médianes Plastiques. This interpretation implies that the emplacement of the Préalpes and the main phase of deformation are two different events: (1) emplacement of the Préalpes (Oligocene) and (2) main phase of folding in connection with the formation of strike-slip faults. A different interpretation, favoured here, relates the strike-slip faults with individual fold-and-thrust structures of the Klippen nappe only (Mosar & Borel 1992). It explains the strike-slip system as transfer zones (tear faults), which root in the detachment horizon and which are kinematically linked to the thrust planes. The faults developed synkinematically with nappe transport and nappe internal fold formation.

The Médianes Rigides thrust slices dip gently to the NW in the area of investigation. Going west this dip increases (see Mosar 1991, profile Rübli-Gummfluh). Bedding is normally subparallel to thrust faults. In the Préalpes Médianes Rigides one main thrust sheet with a complete sequence from middle Triassic to upper Cretaceous rocks predominates. It is underlain by one or more secondary imbricates, the position of which are still not precisely defined. Genge (1958) described two imbricates of the Préalpes Médianes Rigides as 'Wierihorn'- and 'Spillgerten' imbricates. We define the 'Spillgerten imbricate' with its complete Mesozoic sequence as the 'Main imbricate'. To the east, it extends to the Seehorn and further east to the Abendberg. A ramp structure with a back thrust developed in the Main imbricate (Fig. 3, 4). The offset is largest in the Niderhorn area (Fig. 4, P1) and fades out to the east towards Turnen and Abendberg. This back thrust cannot be mapped westward across the Breccia nappe and the Nappe Supérieure, but a continuation between Rübli and Gummfluh imbricates is at least possible, as already suggested by Mosar (1991).

The Rothorn south of the Spillgerte belongs to a thrust sheet made up of middle and upper Triassic carbonates only. It is separated from the overlying Main imbricate by the Zone Submédiane. The Wierihorn imbricate of Genge (1958) con-

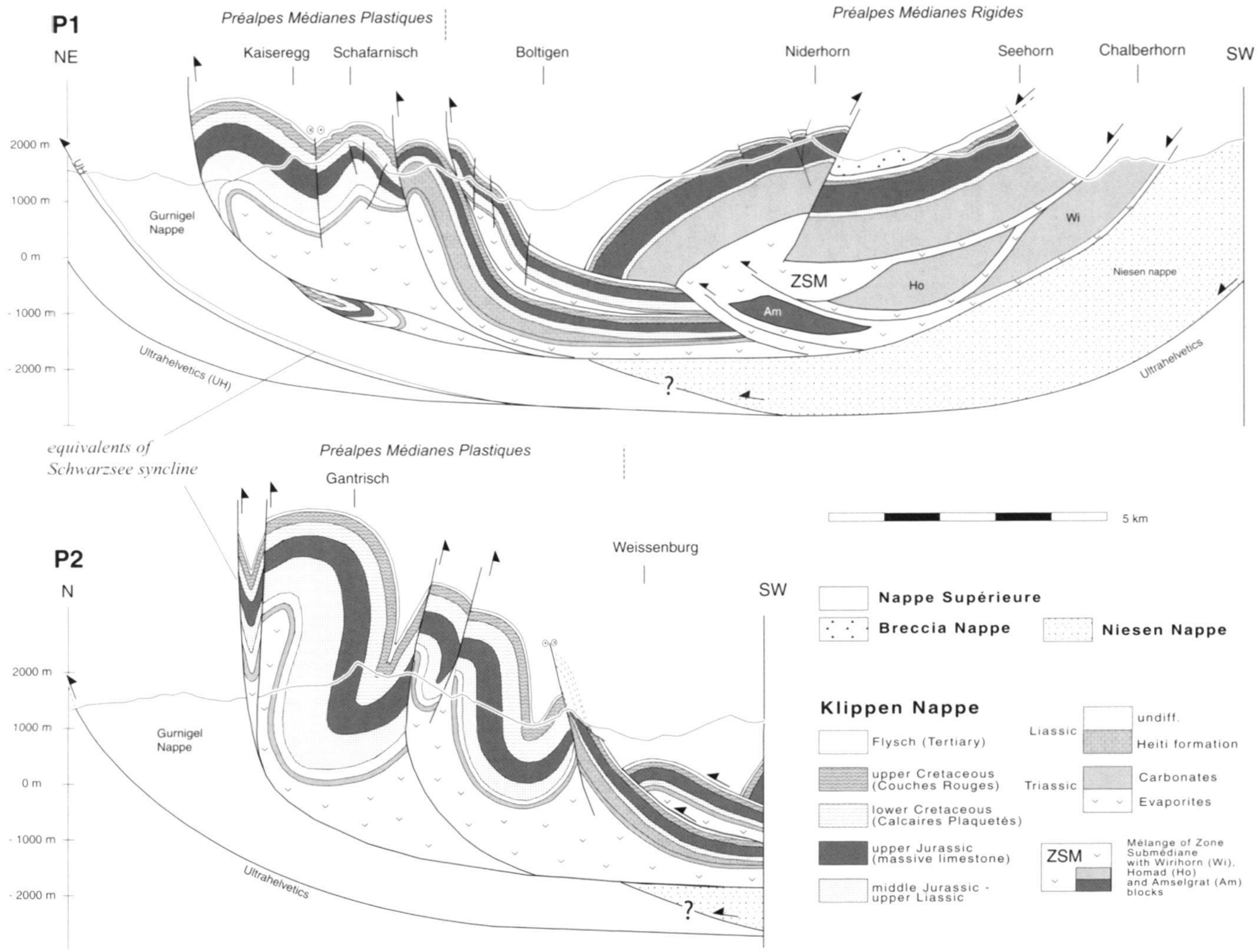

Fig. 4. Cross sections of the Klippen nappe between a) Kaiseregg and Chalberhorn (P1); b) Gantrisch and Simmen Valley (P2). For exact locations see Fig. 3. Am: Amselgrat/Zünegg lenses, Ho: Homad imbricate, Wi: Wierihorn imbricate.

tains the same stratigraphic layers (Jeannet & Rabowski 1912) and is assumed to be a continuation of the Triassic layers of the Rothorn.

An additional lens of Middle Jurassic carbonates is situated between Main- and Wierihorn imbricates in the Homad region, and its tectonic position is not entirely clear. In a cross section by Lugeon & Gagnebin (1941), the Triassic of the Homad is (according to the geological map of Rabowski (1912) linked with the basal Triassic of the Main imbricate northeast of the Seehorn. On the structural map of Mosar (1991) it is described as an imbricate of its own, separated from the Main imbricate by a thrust fault. The solution by Lugeon & Gagnebin would imply an abrupt bending of the Homad Triassic below the Diemtig valley (see Lugeon & Gagnebin 1941, Fig. 4), for which we see no evidence. We prefer to consider the Homad as a thrust slice of its own, limited and surrounded by the complex mélange of various exotic rock types of the Zone Submédiane. The occurrence of gypsum and cargneules in the area surrounding Schwenden, which are also components of the Zone Submédiane, support this suggestion.

We therefore interpret the Homad- as well as the Wierihorn- and Rothorn imbricates as large 'blocks' with limited extension to the northeast and southwest (see Fig. 3), floating within a matrix of the Zone Submédiane mélange. In agreement with this concept, we explain two upper Jurassic lenses exposed to the southwest (Amselgrat, Arbenz 1947) and northeast (Züneggklippe, Genge 1928) of the study area, as two additional 'blocks' which are also completely separated from the main body of the Klippen Nappes. A detailed discussion of the origin of these blocks follows in sections 3 and 4.

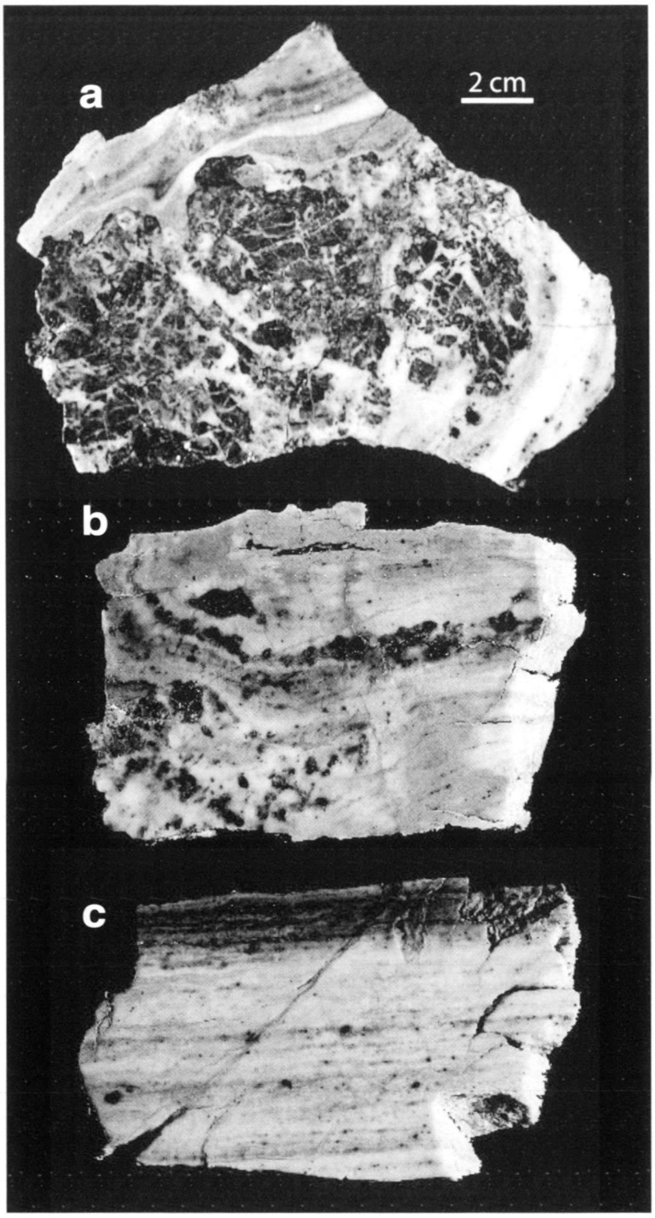

Fig. 5. Samples of evaporitic rocks showing different amounts of deformation (Col du Pillon, western Préalpes Romandes). a) gypsum-dolomite rock with high dolomite content (dark grey clasts), fractured and surrounded by gypsum. b) gypsum-dolomite rock with dolomite clasts arranged in layers. c) gypsum with mylonitic foliation and only a few small distributed dolomite fragments. See text for explanations.

2.4 The detachment horizon: evaporites and cargneules

The Triassic base of the Klippen nappe (and surrounding units) consisted initially of an interlayered anhydrite-dolomite horizon. Due to the very low shear resistance of anhydrite, it acted as the detachment horizon for the overlying sediments. Today, these Triassic rocks are exposed along Prealpine thrust and tear faults and within the Prealpine mélange zones, the anhydrite almost being entirely transformed to gypsum. In an earlier study, Hürlimann et al. (1996) analysed the base of the Gummfluh imbricate (an equivalent of the Main imbricate located further to the west). These authors postulate an early Late Cretaceous to early Eocene phase of SE directed synsedimentary thrusting, which was followed by NW directed thrusting after the middle Eocene. Mosar (1989) reported that the base of the Klippen is more strongly deformed compared to its upper parts and that the basal deformation suggests transport to the NW.

We studied the evaporite horizon by taking samples from the base of the Ultrahelvetics (Col du Pillon, Western Préalpes Romandes), the base of the Klippen nappe (Schwarzsee region) and from the Zone Submédiane southwest of the Spillgerte. A comparison of all samples show similarities in composition and structural features, regardless of their origin in the Prealpine nappe stack.

Fig. 5 displays three gypsum-dolomite samples, which show variable ratios of dolomite to gypsum. The sample shown in Fig. 5a has a high content of fractured dolomite (dark grey) in a matrix of white and light grey gypsum. The fractures are filled and injected with gypsum (formerly anhydrite). Boundaries between dolomite and gypsum are sharp. The fragments show several 'fitting' boundaries and the matrix shows a colour banding. In Fig. 5b the dolomite content and the sizes of fragments are smaller compared to Fig. 5a. Dolomite clasts are less coherent and boundaries are more diffuse, indicating a mixing of dolomite and gypsum in these areas (Herwegh & Pfiffner 1999). Fig. 5c includes only a small proportion of dolomite. Fragments are rare, have been intensely crushed into small pieces between 5 - 0.5 mm in diameter, and arranged in narrowly spaced (foliation) planes.

The chosen samples demonstrate different intensities of tectonization existing in the evaporitic detachment horizon. The loss of coherence between fragments and increasing mylonization and foliation of material indicate strain concentrations and associated locally higher strain rates from Fig. 5a to 5c.

According to the study of Jordan (1994) on the evaporite layers of the Jura mountains, changing dolomite contents are presumed to be responsible for the direct juxtaposition of highly sheared gypsum layers and almost undeformed regions predominated by dolomite. The decreasing dolomite content in samples 5a to 5c supports the suggestion that the dolomite content is the controlling factor for the intensity of deformation in Prealpine detachment material.

We interpret the observed structure of the evaporite samples as follows: After the fragmentation of dolomite layers in the brittle regime, fractures were filled with anhydrite, possibly by solution-redeposition processes. The viscous flow of anhydrite in regions including high shear strains led to the development of foliation planes. The transformation of anhydrite into gypsum close to the surface finally destroyed their original microfabric.

In most instances, evaporitic rocks are associated with cargneules (rauhwacke). In the older literature, cargneules were assumed to be linked to specific stratigraphic horizons.

Genge (1958) was the first to propose that cargneules are not primary stratigraphic horizons, but related to nappe transport and thrusting in the Préalpes Médianes. Today cargneules are known to be the product of three associated conditions (Herwegh & Pfiffner 1999, Jeanbourquin 1988, Schaad 1995): initial lithology, tectonization, and most importantly post-tectonic alteration. The brittle deformation of dolomites embedded in anhydrite opens pore spaces and gives way to intense dissolution and alteration processes. These studies suggest that cargneules are not primarily related to hydraulic fracturing during nappe transport, as suggested by Masson (1972), but are the secondary alteration product of the dolomite/evaporite sequences tectonized during nappe transport. Most cargneules in the Alps developed very recently and are a result of dissolution or even karstification of gypsum and anhydrite. Depending on the degree of tectonization and the dolomite/anhydrite ratio, different cargneules-types evolved.

Evaporites and cargneules are found at the base of almost all Prealpine units. They occur where thrust faults are parallel to bedding following the evaporite layer. Additionally, cargneules outcrop along tear faults cutting across the entire Klippen nappe.

The existence and continuity of a weak detachment horizon is regarded to be one of the main controlling features on the structural style and transport width of cover nappes. Detachment and folding of a nappe is only possible if the internal deformation and decoupling of the nappe is mediated by a sufficient thickness of weak layers (Pfiffner 1993).

An important point to note is that evaporitic detachment layers in the Préalpes Médianes Plastiques are of Late Triassic (Carnian) age, whereas in the Médianes Rigides they are located *below* thick bedded Middle Triassic carbonate sequences (Baud 1972). This implies that the carbonates of the southern part are decoupled from the footwall at a deeper level and therefore include thick bedded middle Triassic carbonates, which are missing in the Préalpes Médianes Plastiques. We further discuss this discontinuity in the detachment layer in sections 3 and 4.

3. Balanced cross sections and structures at depth

3.1 Structural subdivision of the Klippen nappe

The cross sections shown in Fig. 4 are area- and length-balanced and display the observed structural style. The interpretation at depth remains in part speculative, owing to the lack of surface and seismic data.

The Mesozoic sediments of the Klippen nappe units change facies perpendicular to strike (Fig. 3, 4). We defined five sectors from north to south, bounded by thrust faults and associated with important sediment thickness and facies changes. We found our subdivision to be in good agreement with the subdivision proposed by Borel & Mosar (2000), based on Liassic stratigraphy. They examined profiles in different areas of the western and eastern Préalpes and divided the Klippen nappe into five different sectors separated by 3 important Liassic paleofaults (Fig. 6a). For reasons of simplicity, we used the same sector terminology for our field area. Fig. 6b and 6c show the arrangement of our sectors in map view and in the cross sections P1 and P2.

Sector A corresponds to the external part of the paleobasin. In some parts of the study area, major portions of it have already been eroded or are hidden in the subsurface. Sector A is best exposed in cross section P2. It contains a complete sequence from upper Triassic, Jurassic, Cretaceous to Tertiary rocks; the Middle Jurassic sediments attain their maximum thickness in this sector. In profile P1, sector A is not exposed but is possibly present at depth (small lens shown in P1, which would correspond to the Schwarzsee syncline).

In sector B, the Middle Jurassic sequences are thinner in comparison to sector A, and the massive upper Jurassic Limestones thin out towards the south. Sinistral and dextral strike-slip and thrust faults cut the major fold structures in this sector.

In sector C, the Liassic limestones are replaced by the bituminous 'Heiti' facies. Additionally, the thicknesses of middle, upper Jurassic and upper Cretaceous rocks are strongly reduced. The lower Cretaceous limestones disappear completely from this sector to the south. Length and extension of the 'Heiti'-imbricate at depth is not very well constrained.

Sector D contains the 'Gastlosen imbricate' (named after the Gastlosen chain in the western Préalpes Romandes), and marks the transition between Préalpes Médianes Plastiques and Préalpes Médianes Rigides. Middle Jurassic rocks are developed in the shallow water and coalbearing 'Mytilus' facies. Owing to erosional events on the rift shoulder (Mettraux & Mosar 1989), Liassic rocks are missing from this sector to the south. The base of the upper Triassic carbonates contains breccias, similar to those found further to the south in sector E. The Gastlosen imbricate is only exposed in the western part of the study area and is presumably hidden to the east beneath the Nappe Supérieure.

Sector E contains the imbricates of the Préalpes Médianes Rigides. Here, the upper Jurassic massive limestones are thicker again and developed as platform carbonates. The Jurassic units of the Médianes Rigides are underlain by thick bedded upper and middle Triassic carbonate sequences.

Borel & Mosar (2000) presented a table containing calculations of sector lengths based on their field data. Their results are similar to the lengths obtained from our reconstruction (Tab. 1). Generally speaking most of the imbricates are somewhat shorter in our profiles. Considering that the synsedimentary faults are not exactly parallel to one another, variations of sector lengths are not surprising.

3.2 Seismic data

Seismic lines from NRP20 (W1) and industry (W1 + W7) are used to determine the basal thrust of the Klippen nappe (Fig. 7a, b and Fig. 8; Pfiffner et al. 1997). The resolution of the lines was not designed to image shallow structures in detail.

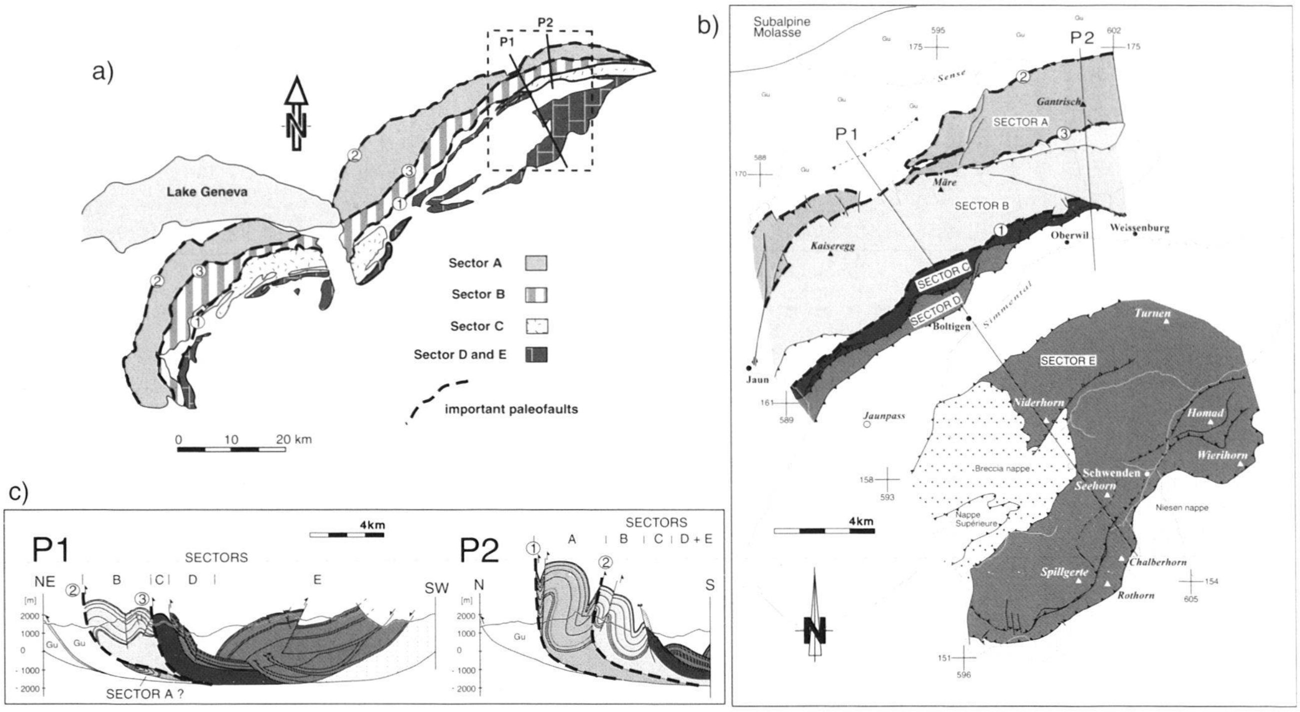

Fig. 6. a) Map of sectors A-E of the Klippen nappe (redrawn after Borel & Mosar 2000). b) map view of distribution of sectors in the area considered in this work. c) cross sections P1 and P2 showing sectors indicated in b). See text for explanations. Numbers 1, 2 and 3 refer to the timing of evolution of the paleofaults suggested by Borel & Mosar (2000).

Nevertheless, they can be used to determine the base of the Ultrahlevetics, Niesen and Klippen nappes, and the position of some nappe internal thrust faults. The data gap in line W7 corresponds to an area of difficult access around the Gantrisch.

The northern part of line W7 crosses the Gurnigel nappe. We interpret the southdipping reflections at a depth between 0.4 s - 1.0 s at the northern end of the section to stem from the base of the Gurnigel nappe. The contact to the overlying Klippen nappe outcrops near CDP (Common Depth Point) 490.

A prominent reflection band at the southern end of line W7, starting at a depth of 0.9 s TWT, is interpreted to be the evaporite base layer of the Klippen nappe overlying the Niesen nappe. It lines up with another significant reflection band at about the same depth at the northern end of line W1 (Pfiffner et al. 1997). This basal thrust rises northward to break the surface slightly north of the data gap in line W7 (dashed line). Some south dipping reflections south of the Gantrisch between 0.5 and 0.6 s TWT possibly trace a part of a branching thrust fault, which cuts through interlayered evaporite/carbonate material and folded sediments above. It is assumed to coincide with the thrust fault shown in profile P2, which is moderately inclined up to a depth of 700 m above sea level and then steepens upward towards the data gap in W7.

Due to a bend in the trace of the line W1 between CDPs 280 (W7) to 460 (W1) to a direction almost parallel to strike, this part of the lines is not interpreted.

To the south, between CDPs 450 and 250, two reflection bands are visible: the first one is located at a depth of about 0.3 s TWT and is assumed to indicate the base of the Main imbricate. A second one at about 0.8 - 0.9 TWT marks the base of the Zone Submédiane, which in turn overlies the Niesen nappe. We interpret the reflections beneath Zweisimmen at 0.6 to 0.9 s TWT, dipping south and north to stem from thrust lenses of the Zone Submédiane.

Two distinct north-dipping reflection bands can be correlated with the base of the Klippen nappe and the base of the Niesen nappe (overlying Ultrahlevetics, UH) outcropping north and south of Matten. We interpret that the Klippen nappe rides on a cushion of the Niesen nappe which extends to the north of Boltigen. The subhorizontal reflections beneath Matten located at 0.5 - 2.0 s are interpreted to stem from a Mesozoic carbonate sequence within the Ultrahelvetic thrust sheets, pertaining to the Helvetic nappes (see Pfiffner et al. 1997).

Maurer & Ansorge (1992) determined seismic velocities of up to 5.9 km/s for limestones of the Klippen nappe in the area around Jaunpass. Using 5.9 km/s to calculate the maximum depth position of the basal Klippen thrust, we obtain about 2.7

Tab. 1. Calculated sector lengths of restored cross sections from Borel & Mosar (2000) and this study (P1, P2). The (+4) km of our sector A indicates a part of this sector which is presumably hidden in subsurface (equivalent of *Langeneckgrat* und *Schwarzsee syncline*).

Profiles	SECTOR A	SECTOR B	SECTOR C	SECTOR D
Monts d'Hermoine-Roc d'Enfer	15 km	8.5 km	9 km	non-existent
Locum-Cornettes de Bise	10 km	2.5 km	10 km	6 km
Caux-Tour d'Ai	15 km	10 km	10 km	-
Moléson - Gummfluh	15 km	6 km	-	7 km
Hohmad-Turnen	12 km	5 km	2 km	-
P1	-	-	7 km	5.5 km
P2	6 (+4) km	7 km	-	-

km for the thickness of the Klippen nappe in the study area, which places the basal Klippen thrust at a maximum depth of 2 km below sea level.

3.3 Retrodeformation of the paleo-basin of the Klippen nappe

Besides our own field data, we base our retrodeformation on data from Baud & Septfontaine (1980), Borel (1997) and Furrer (1979).

For a synoptic view of the paleobasin in profile view, we combined the information from cross sections P1 and P2. Because Sectors A and B are best exposed along profile P1, we used this cross section to balance the paleobasin of the Préalpes Médianes Plastiques (Sub-Briançonnais). For reconstructions of sectors C, D and E, profile P2 is used.

We used the software program Geosec 4.0 in combination with intensive iterative work by hand for retrodeformation of single sectors and layers. Restorations are based on the principle of volume conservation (Suppe & Medwedeff 1985), a method which is applicable in the Préalpes where deformation and metamorphism is low to moderate (Mosar 1988b, 1989). The resulting balanced cross section (Fig. 9) should be only regarded qualitatively and should not be used to derive absolute values for basin subsidence and layer thicknesses, due to the various strike-slip faults and thickness changes parallel to strike.

3.3.1 Paleofaults

The sector limits in the Klippen nappe coincide with important sediment thickness and facies changes. We therefore infer paleofaults to be located between the different sectors and used them as 'pin lines' to restore the sectors. This is most likely a simplification with regard to the real environment. We placed the paleofaults at the positions where thrust faults separate fold sheets and imbricates today, regardless of the exact location of thickness changes within single formations. Some of the large synsedimentary faults may represent various smaller ones. In addition, the shape of some layers shown in the cross sections are adjusted to a simplified geometry of the paleobasin and presumably do not represent the exact pattern of units (e.g. the Heiti-Lias unit in sector C).

In the area of investigation, the northern end of the Préalpes Médianes Plastiques sedimentary basin is not very well constrained. The southdipping border fault at the northern end of the Klippen paleobasin is supposed to separate the sub-Briançonnais basin from a basement high, which parts the Briançonnais realm from the Valais trough. This high be traced from Môle, Moléson to Mythen (MMM; Boller 1963). Badoux (1965) described three slices with reduced thicknesses in the external part of the Médianes Plastiques in the western Préalpes Romandes (see also Weidmann 1992, Mosar 1994). They are interpreted to be related to the same high at the northern end of the sub-Briançonnais paleobasin. Northeast of Gantrisch, a small imbricate at the northern end of sector A (Langeneckgrat) has been mapped by Beck & Gerber (1925). We projected and inserted this lens into cross section P2 in Fig. 4. An equivalent slice of Sector A sediments is exposed in the area of Schwarzsee (see enlarged map on Fig. 3) and was projected into P1 (Fig. 4). These slices are bordered by paleofaults as indicated by the abrupt thickness changes shown in Fig. 8).

The paleofault separating sectors A and B is assumed to be north dipping, indicating the transition from a relatively deep to a shallower part of the sub-Briançonnais basin, where units change their thickness and facies.

The fault at the passage into the Heiti-basin is shown to be south dipping, in concert with increased subsidence in this part of the paleobasin at Liassic times, according to Borel (1997), Borel & Mosar (2000) and Mettraux & Mosar (1989). More likely, this region was affected by a series of synsedimentary faults active at different times. Basin subsidence in Liassic times must have changed into uplift within a transpressive regime, in order to explain the reduced layer thicknesses of middle Jurassic and Cretaceous units in a 'horst' position (sectors C and D). An equivalent phenomenon is described by Septfontaine (1995) in the Chablais area.

Another paleofault, active during Late Jurassic times, between sectors D and E is inferred. It explains the sudden increase in thickness of upper Jurassic sediments from this point to the south.

3.3.2 Origin of individual elements of the Klippen nappe

Evaporitic layers at the base of the Préalpine cover sediments form the basal detachment of the Klippen nappe. The absolute thickness of the evaporitic layers in our reconstruction is speculative. For the northern part of the Klippen Nappe, the profile construction and the frequent occurrence of cargneules at the surface point to a relatively thick evaporite horizon, thinning to the south (Fig. 9). Below sectors C and D, the thickness of the upper Triassic evaporites was presumably smaller, but still thick enough to allow decoupling of the imbricates C and D from underlying Triassic units. The fact that Jurassic and Triassic units in the Préalpes Médianes Rigides are still welded together on top of each other suggests that the upper Triassic evaporite horizon was either very thin or absent in that area.

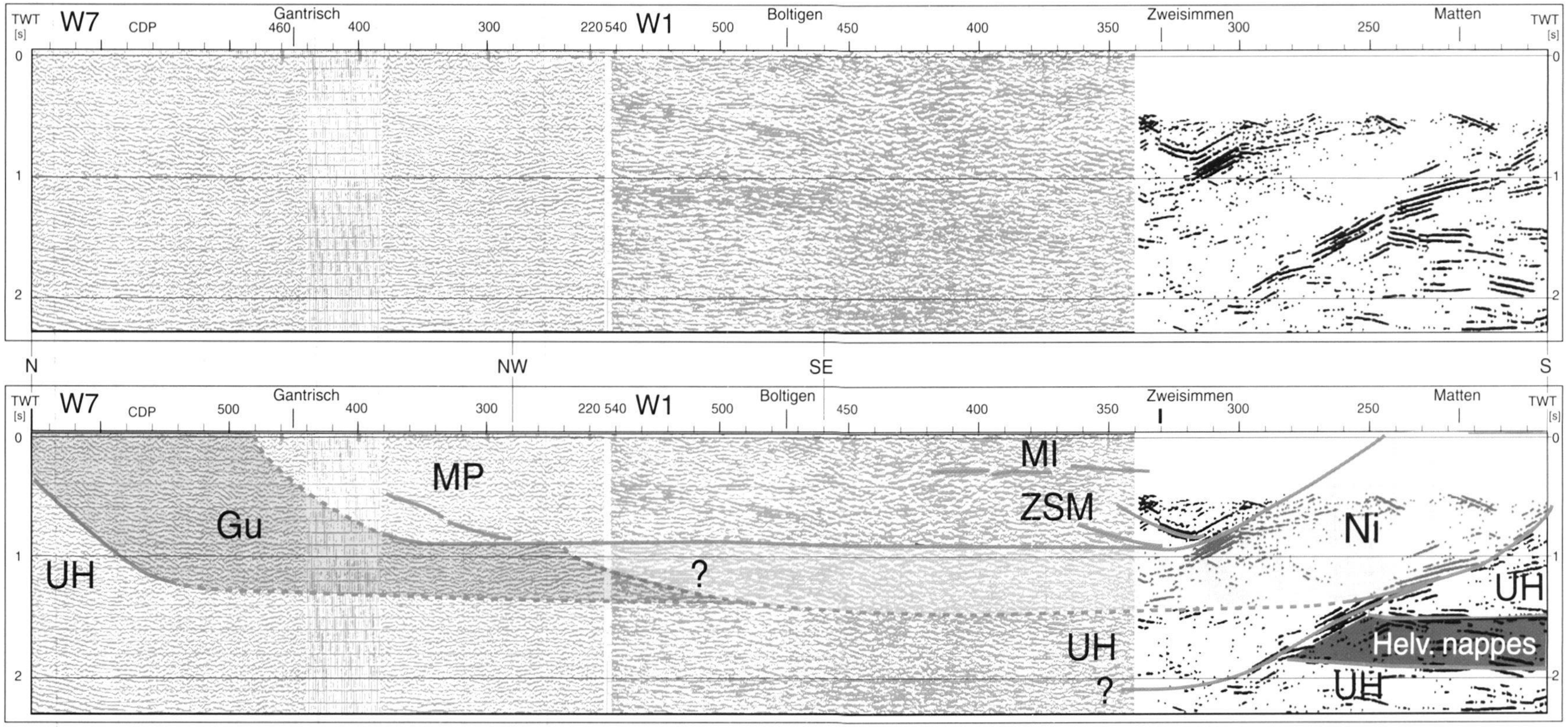

Fig. 7. a) Seismic lines W7 (NRP20) and W1 from NRP20, uninterpreted sections. Line W1 is time migrated. 0 TWT corresponds to a height of 700m above sea level in both lines; b) Same sections interpreted. UH: Ultrahelvetics, NN: Niesen nappe, ZSM: Zone Submédiane, MI: Main imbricate of Médianes Rigides, MP: Médianes Plastiques.

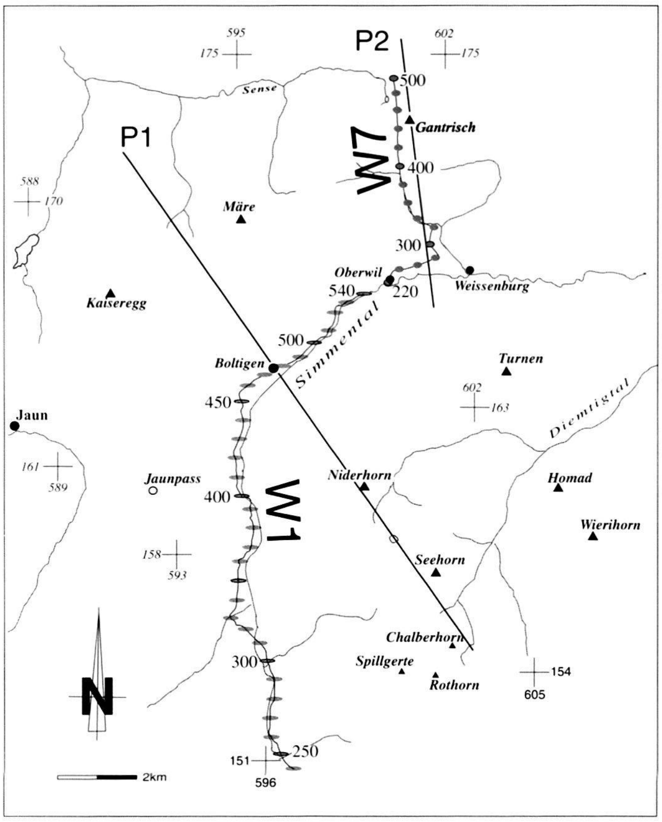

Fig. 8. Map showing the location of CDPs (Common Depth Points).

The middle Triassic evaporites between individual imbricates of the Préalpes Médianes Rigides are thin. Sartori (1987a) described marbles, dolomites, schists, gypsum and cargneules in the Siviez-Mischabel and Pontis digitations of the Bernhard nappe-complex, which are regarded to be the remnants of the autochthonous Briançonnais cover. The discontinuous nature of the middle Triassic evaporites was possibly responsible for them remaining attached to their base.

The Zone Submédiane contains components of Penninic to Ultrahelvetic origin. This suggests an incorporation of elements at the base of the Klippen nappe base during transport. We take the thrust slices and lenses below the Main imbricate (Homad, Amselgrat/Zünegg) (Fig. 4) to be larger members of this zone. The Wierihorn/Rothorn imbricates pinch out to the east and west in a similar manner and are considered to represent very large elements of the Zone Submédiane mélange.

Apart from the Main imbricate, the stratigraphic sequence of all other elements is fragmentary. In the Homad and Wierihorn lenses, the entire Jurassic to Tertiary sediment sequence is missing. Lenses consisting of mostly upper Jurassic carbonates overlying evaporites and cargneules are found at the Amselgrat to the west and Zünegg to the east of the study area (see Fig. 1) We suggest the these elements are scraped off from its footwall in the course of the detachment of the Main imbricate (Spillgerte, Niderhorn) and its emplacement onto sector D.

The present position of the Wierihorn/Rothorn imbricate beneath the Main imbricate suggests an origin of this block located to the north of the Main imbricate. The absence of the uppermost 100 m carbonates of the Spillgerten (Main imbricate) carbonates (Genge 1958), which might be caused by Early Jurassic erosion in the direction of the southeastern Briançonnais margin, also indicates a northerly origin. Baud (1972) regarded the dolomite breccias found at the base of the Gastlosen imbricate (sector D) to be the same as those at the base of the Seehorn (sector E, Main imbricate), and postulated a directly neighbouring origin of Sector D and the Main imbricate. We follow his interpretation and suggest that the Triassic rocks of the Wierihorn imbricate are part of the footwall of sector D (the Gastlosen imbricate), which itself was detached from the Wierihorn carbonates along upper Triassic evaporites.

Another complication is the source of the Homad lens. As for the Wierihorn imbricate, Jurassic and Cretaceous units are missing (Fig. 3 and 4). They may be represented by the Jurassic carbonate lenses (Amselgrat and Zünegg) west and east of Homad (Fig. 1). We envisage that these lenses have been decoupled from their Triassic base (the Homad carbonates), and have been incorporated into the mélange of the Zone Submédiane in the course of deformation. A small remainder of upper Triassic evaporites below the Jurassic sequence could have aided decoupling. The geometry of Amselgrat/Zünegg and Homad lenses in our reconstruction is speculative. We do not know how much of the original volume was lost by erosion or is covered in the subsurface.

3.3.3 The 'Gurnigel High' north of Kaiseregg and Märe

Inspection of Fig. 6 reveals that in profile P1, sector B is in direct contact with the Gurnigel nappe. Sector A shows a significant reduction of sediment thickness in the Schwarzsee area (see inset in Fig. 3). The high amplitude folds of sector A in the surroundings of the Gantrisch die out towards the west, disappear on the trace of P1 and reappear as a syncline with strongly reduced formation thicknesses in the Schwarzsee area. This zone of reduced stratigraphic thickness might be related to the MMM basement high discussed above. It is interesting to note that the geological map (Atlas sheet 36, Tercier & Bieri 1961), shows the existence of an internal thrust fault within the Gurnigel nappe in the area around profile P1. The thrust fault (shown in Figs. 3, 6b and 9c) places two imbricates of Gurnigel flysch onto each other. The base of the upper imbricate is formed of Wildflysch (Ultrahelvetics), which was presumably scraped off from the Ultrahelvetic nappes located below.

We explain the presence of this Gurnigel thrust sheet at the northern end of P1 by an advancing embayment in the frontal Klippen nappe (Fig. 9c). Owing to primary thickness reductions, the structures of sector A in the Gantrisch area diminish and vanish in the area of the trace of P1 (Figs. 3 and 9c). They then reappear farther west in the Schwarzsee area.

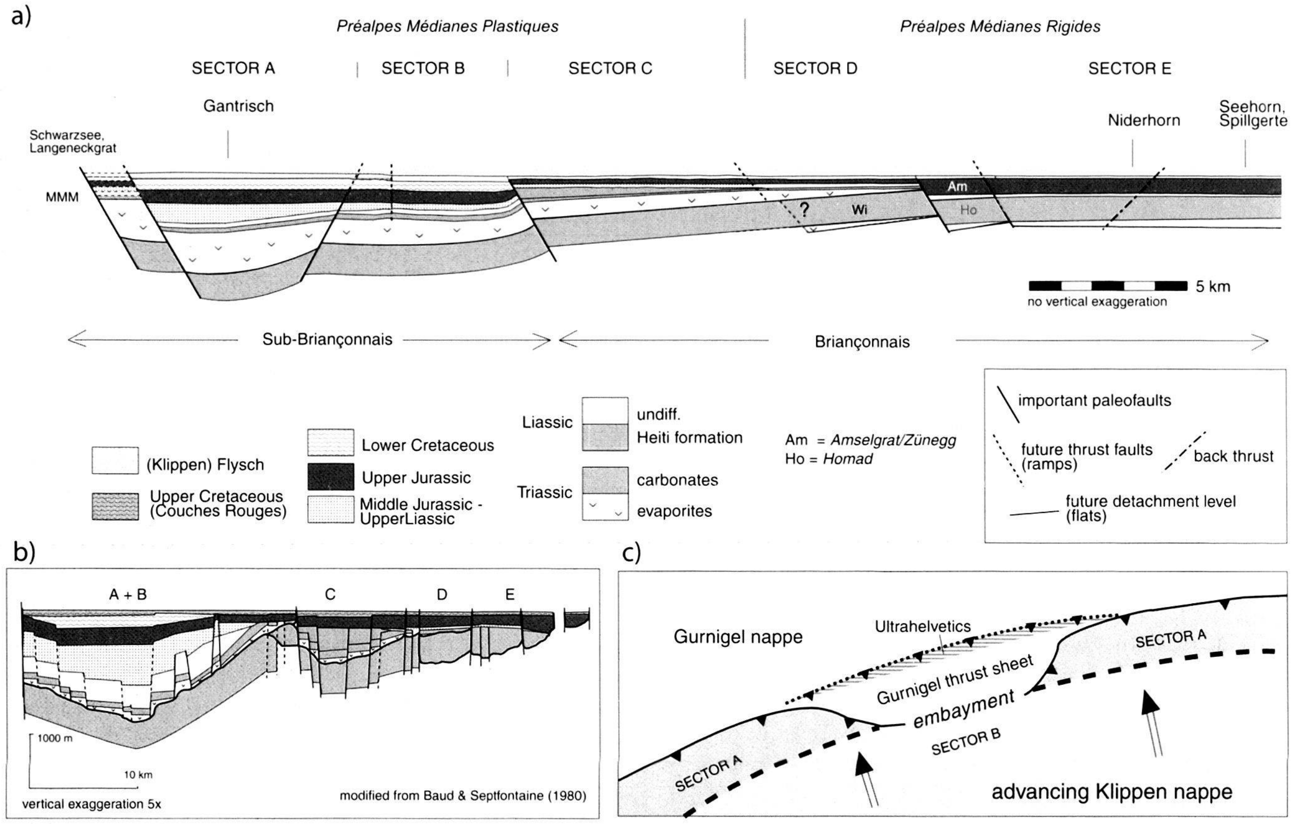

Fig. 9. a) Restored cross section obtained by combining sectors of profiles P1 and P2 (see text for explanations). Sector length of Am, Ho is speculative. MMM: Môle-, Moléson-, Mythen- 'High'. b) Reconstruction of the Klippen nappe paleobasin after Baud & Septfontaine (1980), obtained from cross sections in the Rhône valley by unfolding and replacing missing parts using the concept of minimal solution. It shows large similarities in detachment level and basin geometry when compared to our restored section. c) Scheme of embayment in the frontal Klippen nappe in the area of cross section P1 (map view). See text for explanations.

In the course of the advancement of the Klippen nappe, the empty space at its front, caused by the pinching out of sector A structures, was filled by material incorporated from the footwall. It is thus quite logical that the upper Gurnigel imbricate is located exactly in front of this embayment. The thin bedded sediments of sector A, which are exposed east of Schwarzsee, did not reach the surface in this area and are assumed to be hidden in subsurface below sector B (Fig. 3 and 6).

4. Kinematic model of the internal deformation of the Klippen nappe

As discussed earlier, the mechanical properties of stratigraphic successions of sectors A to E show characteristic differences, which are reflected by the difference in style of structure of these domains. The internal deformation of the Klippen nappe strongly depends on the distribution of the mechanically weak evaporite layers within the nappe (Fig. 9). This includes not only the thickness of the detachment layers, but also the discontinuity of these layers caused by Mesozoic faulting, and by the thicknesses and layering of the mechanically strong layers.

Two significant factors determine whether a weak layer is used as a detachment horizon: (1) the thickness ratio between competent and incompetent layers has to be large enough, (2) a laterally continuous layer of weak material needs to be available (Pfiffner 1993; Schaad 1995). The continuity of horizons can be disturbed by non-deposition, erosion or by faulting in a subsiding basin. In the case of the Klippen nappe, the distribution of Triassic evaporites seems to be governed by Jurassic faults.

The carbonate sequence described by Sartori (1987a) in the Siviez-Mischabel and Pontis nappes are regarded to be composed of Briançonnais sediments which remained attached on their basement in the absence of a continuous detachment horizon (e.g. base of Triassic carbonates in the northern Briançonnais). The absence of late Triassic evaporites in the Préalpes Médianes Rigides on the other hand is probably related to the emersion of the rift shoulder, eroding Liassic and Triassic sediments gradually to the southeast.

In the case of the Helvetic nappes, detachment folds form above a detachment horizon, provided the thickness ratio n of weak versus competent layers is $n > 0.5$ (Pfiffner 1993). In contrast, deformation seems mainly controlled by imbricate thrusting if this thickness ratio is $n \leq 0.5$. The differences in structural style observed in the Klippen nappe can be explained in a similar way. The geological interpretation of seismic data suggests that the Préalpes Médianes Plastiques are likely to have developed on top of thick evaporites ($n > 0.5$) and the structural style there is characterised by folds (Figs. 9 and 4). In contrast, the imbricates of the Préalpes Médianes Rigides are related to a rather thin evaporite horizon ($n < 0.5$).

The Briançonnais paleobasin is characterised by a small-scale subsidence and uplift pattern (see e.g. Borel 1997). Examples are the upper Cretaceous 'Calcaires Plaquetés', which were only deposited in sectors A and B, or the Heiti facies, deposited only in sector C.

In general, the Préalpes Médianes Plastiques contain more mechanically weak units (e.g. the thick Zoophycus Dogger, Calcaires Plaquetés and Couches Rouges) than the Préalpes Médianes Rigides. In the latter, only the thin Mytilus Dogger and Couches Rouges are mechanically weak layers separating thick competent carbonate units. The interlayering of competent and incompetent units in the Préalpes Médianes Plastiques could have enhanced development of fold structures, as demonstrated by studies of Chester et al. (1991) and Wissing (2002).

In addition, model studies of Wiltschko & Eastman (1983) and Schedl & Wiltschko (1987) highlight the importance of stress concentrations at basement heterogeneities (e.g. 'horst' structures), which act as a mechanism for the localising of deformation and the initiation of thrust faults. Our restoration of the Briançonnais paleobasin, based on retrodeformation using the previously described assumptions, reveals the following (Fig. 10 A):

- The basal evaporite detachment horizon is not at the same stratigraphic level everywhere (middle Triassic in sector E, upper Triassic in sector A-C).
- The detachment horizon is offset by Mesozoic faults.
- In sector D, both detachment horizons exist.
- Sectors A and B contain a thick layered sequence of competent limestones and weak marly sequences of Jurassic (and Cretaceous/Tertiary) age.
- Sectors C and D are characterised by a much thinner sequence.
- Sector E is dominated by thick Triassic and upper Jurassic competent carbonates.
- Several Jurassic faults offset layering

In a first step (shown in Fig. 10 B), shortening of the Klippen nappe activated the lower Triassic evaporite detachment horizon in sector E; the displaced carbonates of the Main imbricate (MI), formed a ramp anticline, which developed a back thrust above the footwall ramp **(1)**.

Similar backthrusts are reported from analogue experiments (Morse 1978 ; Schreurs et al. 2001). Continued shortening activated the detachment horizon beneath Amselgrat/Zünegg (Am) and Homad (Ho) units, which led to the separation of the Jurassic and Triassic strata of the Amselgrat and Homad slices, respectively (**1ab**). We interpret this process of fragmentation, which was possibly also influenced by Mesozoic faults, to have initiated the mélange now recognised in the Zone Submédiane. Subsequent shortening reversed the stacking order of the Homad and Amselgrat slices (Triassic now overlying Jurassic).

As deformation in the footwall of the Main imbricate proceeded, two additional imbricates formed, one consisting of Jurassic carbonates (Gastlosen imbricate, Ga), the other of Triassic carbonates (Wierihorn slice, Wi).

The emplacement of sector C (Heiti imbricate) onto sector B was again controlled by focusing deformation on a Mesozoic fault (**2b**). In later stages (Fig. 10 C), the Gastlosen and Heiti imbricates were detached along the Late Triassic evaporites (**2a**, **2b**), but both remained (coherent) thrust sheets, probably owing to the thickness of the detachment horizon, which was much thinner than the overlying Jurassic/Cretaceous sequence. In contrast, sectors A and B were folded above a much thicker detachment horizon. The relative sequence of faults **2a**, **2b**, **2c** shown in Fig. 10 is not constrained by structural data.

Sediment thicknesses suggest that the north-dipping paleofault between sector A and B was a normal fault, which became reactivated as a thrust fault (**3a**). We envisage that the paleofault separating sectors A and B retained its steep north dip in the course of nappe internal deformation. Folding in the adjacent areas produced a syncline to the north and an anticline to the south and slip along the fault raised sector B relative to sector A. This scenario can only be envisaged if one assumes a coeval folding above a thick detachment horizon, maintaining the fault in an orientation favourable to continued slip.

Transport along the basal thrust of the Klippen nappe (**3b**) emplaced the whole Briançonnais paleobasin onto the north Penninic Niesen paleobasin and ultimately into a more external position. The fact that the basal thrust is nowhere seen to be incorporated into internal deformation of the Klippen nappe, suggests that transport and internal deformation occurred coevally.

5. Conclusions

Our study suggests that the structural style of the Klippen nappe is controlled by the existence of a mechanically weak evaporite horizon and a series of synsedimentary normal faults, which crosscut the former sedimentary basin. Paleofaults controlled the initiation and location of thrust faults, which separate different stratigraphic sectors of the Klippen nappe.

The Triassic evaporite layer acted as a detachment horizon for the Klippen nappe. This detachment horizon consisted ini-

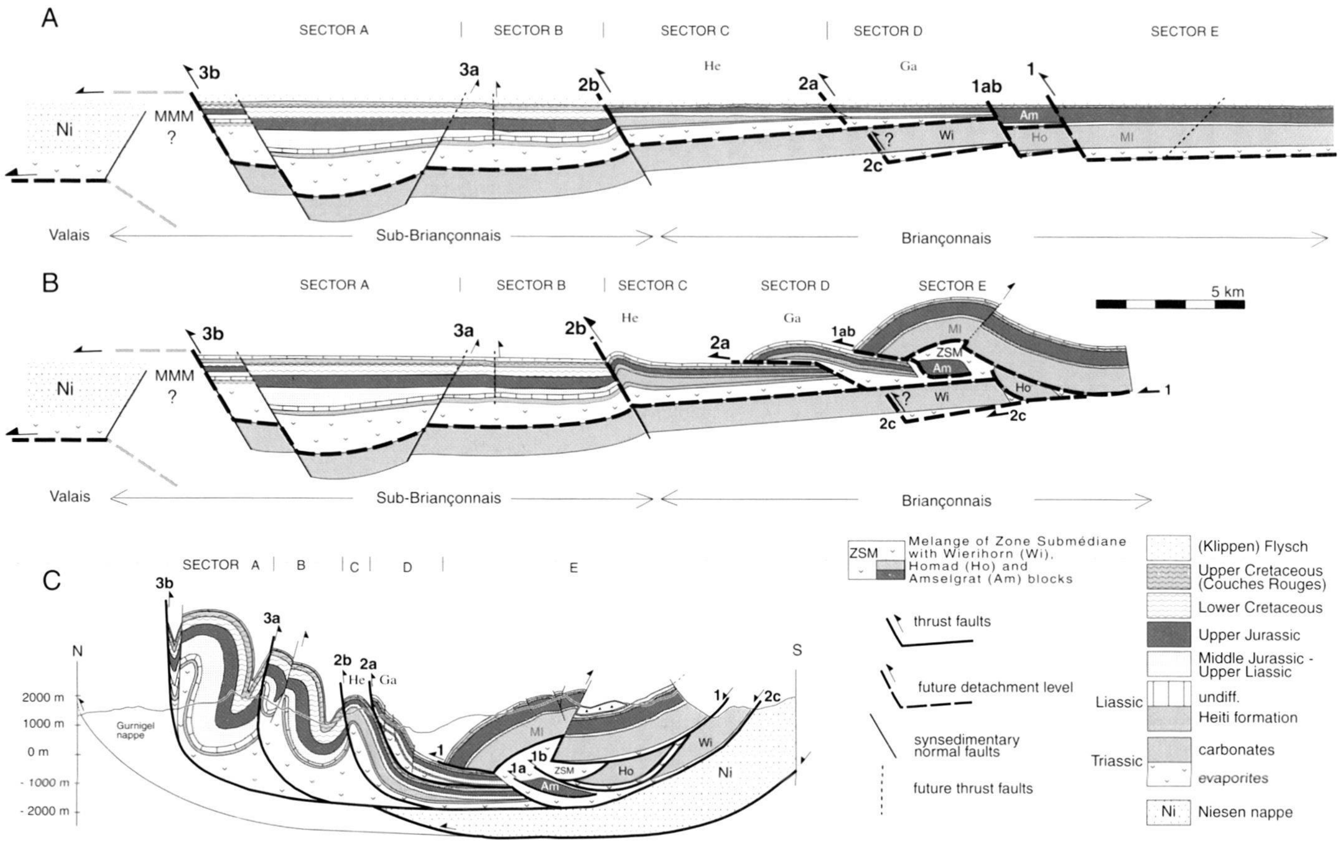

Fig. 10. Scheme of nappe internal deformation of the Klippen nappe in time. a) Initial stage showing future detachment levels. b) Intermediate stage showing onset of deformation in the southern partof the nappe. Sector E is chosen to be in the final position with respect to sector D at this stage of deformation. Sectors A and B are set to be undeformed up to this stage; c) Present day stage displaying a synoptic profile (combination of P1 (south) and P2 (north). MMM: Môle-, Moléson-, Mythen- 'High', Am: Amselgrat/Zünegg lenses, Ho: Homad imbricate, Wi: Wierihorn imbricate, MI Main imbricate, Ni: Niesen nappe.

tially of dolomite and anhydrite layers. Incipient deformation caused fragmentation of the dolomite layers, while anhydrite filled the opening fractures possibly by a combination of solution-redeposition processes. Subsequent viscous flow of the anhydrite during nappe transport resulted in a foliation. Alteration processes transformed these rocks and led to the formation of gypsum and cargneules.

The thickness of this detachment horizon presumably varied. A larger thickness in the northern part of the Klippen nappe supported the development of detachment of the Préalpes Médianes Plastiques. In the southern part, the Préalpes Médianes Rigides, a large rigid imbricate (Main imbricate) formed by detachment along a thin evaporite layer.

Large blocks of Triassic (Homad, Wierihorn, Rothorn) and Jurassic (Amselgrat, Zünegg) carbonates, which are separated from the main body of the Médianes Rigides, are interpreted to be fragments pertaining to the underlying Zone Submédiane. The latter developed as a tectonic mélange and incorporated material from paleogeographic domains north of the Main imbricate.

Seismic data place the base of the Klippen nappe base thrust at around 2000 m below sealevel. The underlying N-Penninic Niesen nappe extends northward about half way across the Klippen nappe. Further north, the Gurnigel nappe which is of S-Penninic origin, underlies the Klippen nappe. Although the contact itself remains speculative, the present-day position of the two units points to a complex sequence of nappe stacking. A reconstruction of the Tertiary evolution of the entire nappe stack suggest that these nappes formed within an accretionary wedge, in which tectonic underplating was associated with out-of-sequence thrusting.

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