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Lithostratigraphy and U-Pb zircon dating in the overturned limb of the Siviez-Mischabel nappe: a new key for Middle Penninic nappe geometry

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Key words: alps, Middle Penninic, Siviez-Mischabel nappe, Permo-Carboniferous, Randa orthogneiss, zircon typology, U-Pb geochronology

ABSTRACT

Detailed field work and zircon analysis have improved the knowledge of the lithostratigraphy at the base of the Siviez-Mischabel nappe in the Mattertal (St-Niklaus-Törbel area). They confirm the existence of an overturned limb and clarify the structure of the St-Niklaus syncline. The following formations can be observed:

- Polymetamorphic gneisses; composed of paragneisses, amphibolites and micaschists (Bielen Unit, pre-Ordovician).
- Fine-grained, greyish quartzite and graywacke with kerogen-rich horizons (Törbel Formation, presumed Carboniferous).
- Green or white micaschists characterized by brown carbonate spots associated with white conglomeratic quartzites (Moosalp Formation, Early Permian).
- Massive, green or white, fine grained, microconglomeratic or conglomeratic quartzites with characteristic pink quartz pebbles (Bruneggjoch Formation, Late Permian-Early Triassic).

This coherent overturned sequence can be observed from the St-Niklaus area to the Moosalp pass to the north. Detailed mapping revealed that the St-Niklaus syncline is symmetrical and connects the overturned limb of the Siviez-Mischabel nappe to the normal series of the Upper Stalden zone. U-Pb zircon geochronology on magmatic and detrital zircons allowed constraining ages of these formations. Detrital zircons display ages ranging from 2900 ± 50 to 520 ± 4 Ma in the Törbel Formation, and from 514 ± 6 to 292 ± 9 Ma in the Moosalp Formation. In addition, the Permian Randa orthogneiss is intrusive into the polymetamorphic gneisses and into the Permo-Carboniferous metasediments of the overturned limb of the Siviez-Mischabel nappe. This revision clarified also the lithostratigraphy of the nearby and subjacent Lower Stalden zone composed of an overturned limb with Permo-Carboniferous formations. This has critical implications for the tectonic setting of the nappes in the region, speaking for few recumbent folds with well preserved normal and overturned limbs instead of a succession of imbricate thrust sheets in a normal stratigraphic position.

1. Introduction

The Siviez-Mischabel nappe is commonly considered to be a huge recumbent fold with an amplitude of more than 40 km (Escher 1988; Escher et al. 1988). This nappe is made of polymetamorphic gneisses (Proterozoic or Early Palaeozoic) surrounded by metasedimentary series (Cambrian? to Palaeogene) (Thélin et al. 1990, Sartori et al. 2006). In the Mattertal, the metasedimentary series (Permo-Carboniferous to Early Triassic; Escher 1988) from the base of the Siviez-Mischabel nappe are part of the recumbent St-Niklaus syncline. On the published geological map of Bearth (1978), the structure of this St-Niklaus fold is complex, mostly cored by a supposed Permo-Carboniferous formation and separated from the polymetamorphic gneisses of the Siviez-Mischabel nappe by a tectonic contact. More recently in a nearby area, Markley et al. (1999) proposed that the "Permo-Triassic" quartzites, traditionally assumed to be part of the overturned limb of the nappe, are in fact slices in an upright position repeated by several thrusts. The existence of a clear overturned limb in the Siviez-Mischabel nappe has therefore been challenged. The lithostratigraphy in the normal limb of the nappe has been recently synthesized (Sartori et al. 2006), however without any detail on the structure at the base of the Siviez-Mischabel nappe.

We will present the lithostratigraphy at the base of the Siviez-Mischabel nappe as a result of recent detailed mapping in the Mattertal region, from Törbel in the north to St-Niklaus in the south. Due to the absence of preserved fossils in such rocks, time-scale markers (e.g. dark organic matter horizons) together with in-situ U-Pb dating by LA-ICP-MS of detrital and magmatic zircons allow to constrain the age of the observed formations.

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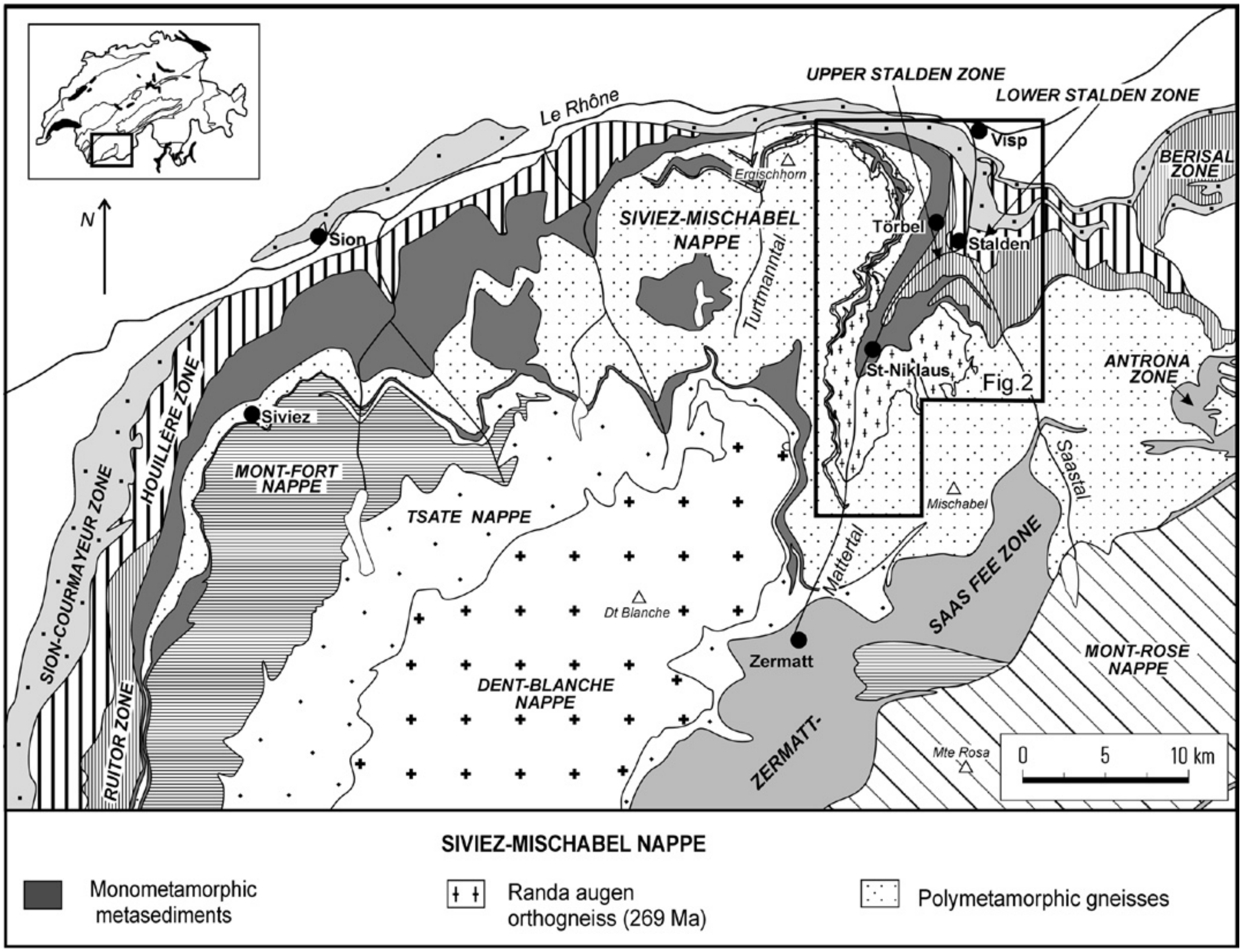


Fig. 1. Location of the studied area (black box) on the structural map of the Penninic units, modified after Escher (1988) and Sartori et al. (2006).

2. Geological Setting

The Siviez-Mischabel nappe extends geographically over 100 km from the north-west of Italy to the east of Wallis in Switzerland (Escher 1988). Its thickness increases progressively eastwards until reaching its maximum between Turtmanntal and Mattertal in Wallis (Fig. 1).

Structurally, this nappe is one of the tectonic subdivisions of the Grand-St-Bernard nappe of Argand (1909, 1911). This super-nappe was separated into distinct tectonic units (Escher 1988; Sartori et al. 2006), from bottom to top: (a) the Houillère zone, (b) the Ruitor zone, (c) the Siviez-Mischabel nappe and (d) the Mont-Fort nappe (Fig. 1). The Siviez-Mischabel nappe is usually considered to be a recumbent fold of more than 40 km amplitude. Markley et al. (1998, 2002) have dated its emplacement at 41–36 Ma ($^{40}Ar/^{39}Ar$ on white mica in Permo-Triassic metasediments) during the Alpine orogeny.

In the Mattertal, the tectonic subdivisions of the Grand-St-Bernard nappe, initially proposed by Bearth (1963), reported on the published 1:25000 geological map (Bearth 1978) and modified by Escher (1988), are different to the classical nappe nomenclature mentioned above. In this region, the following tectonic units were defined, from top to bottom: (a) the Siviez-Mischabel nappe, (b) the Upper Stalden zone and (c) the Lower Stalden zone (Fig. 2). The tectonic setting of the nappes of the region is sketched in Figure 3. The St-Niklaus syncline is a recumbent fold which core is composed by monometamorphic sedimentary series (Bearth 1978; Escher 1988). This syncline is wrongly considered as an independent tectonic zone by Sartori et al. 2006. According to the cartography presented below, this recumbent syncline connects the overturned limb of the Siviez-Mischabel nappe to the normal limb of the Upper Stalden zone. Sartori et al. 2006 proposed that the Siviez-Mischabel nappe could have been cut by several shear zones after

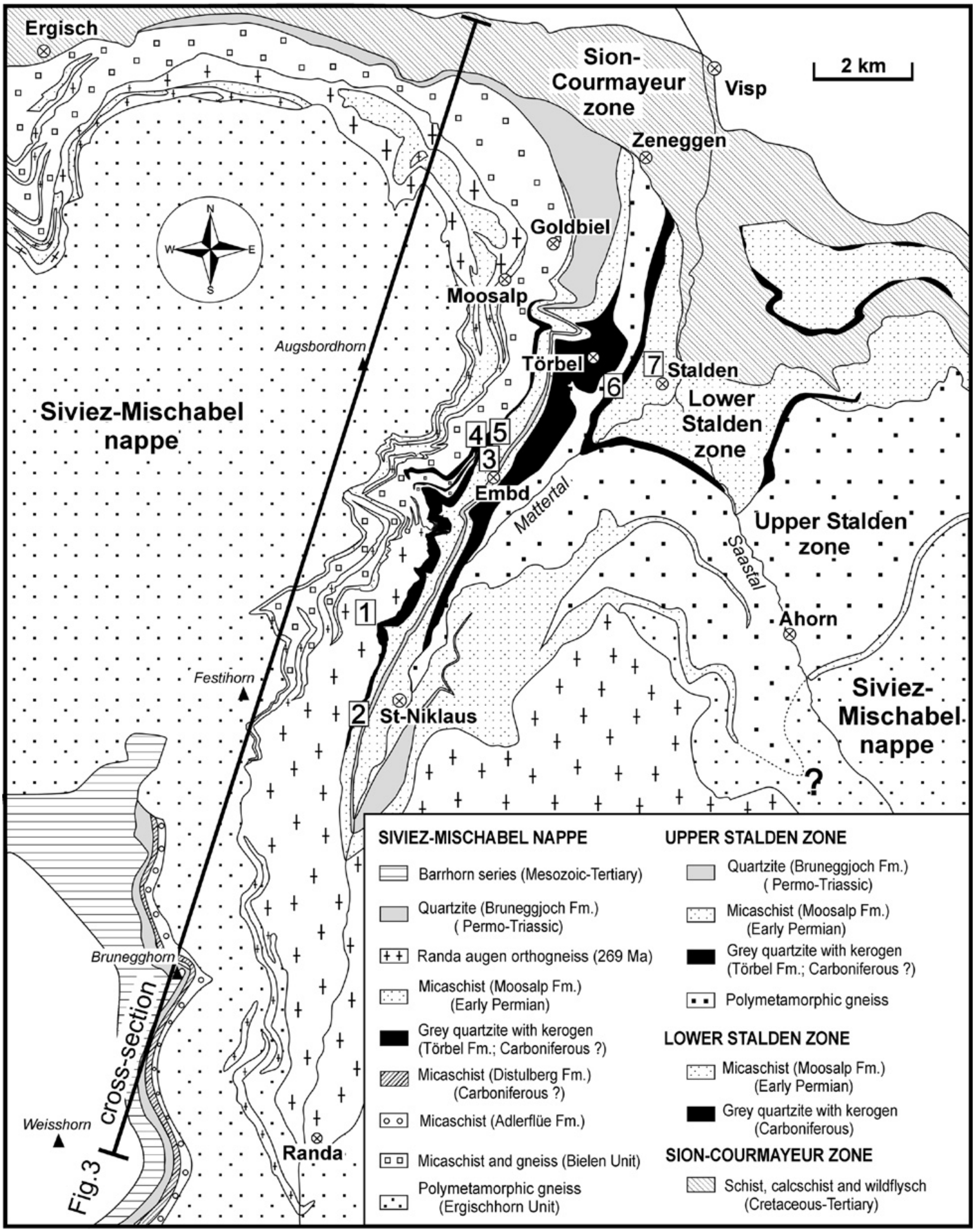


Fig. 2. Geological map in the Mattertal and Saastal modified from Thélin (1987). Additional information is from Werenfels (1924), Bearth (1978), Sartori (1990) and Marthaler (unpublished). The St-Niklaus syncline is symmetrical and connects the overturned limb of the Siviez-Mischabel nappe to the normal serie of the Upper Stalden zone. This syncline crops out in the Mattertal and can be followed to the Saastal where it splits into two branches, one extending east of the Saastal. 1 to 7: location of samples used for zircon dating (1: FB100, 2: FG260, 3: FG403, 4: FG405, 5: FG424, 6: FG512, 7: FG502).

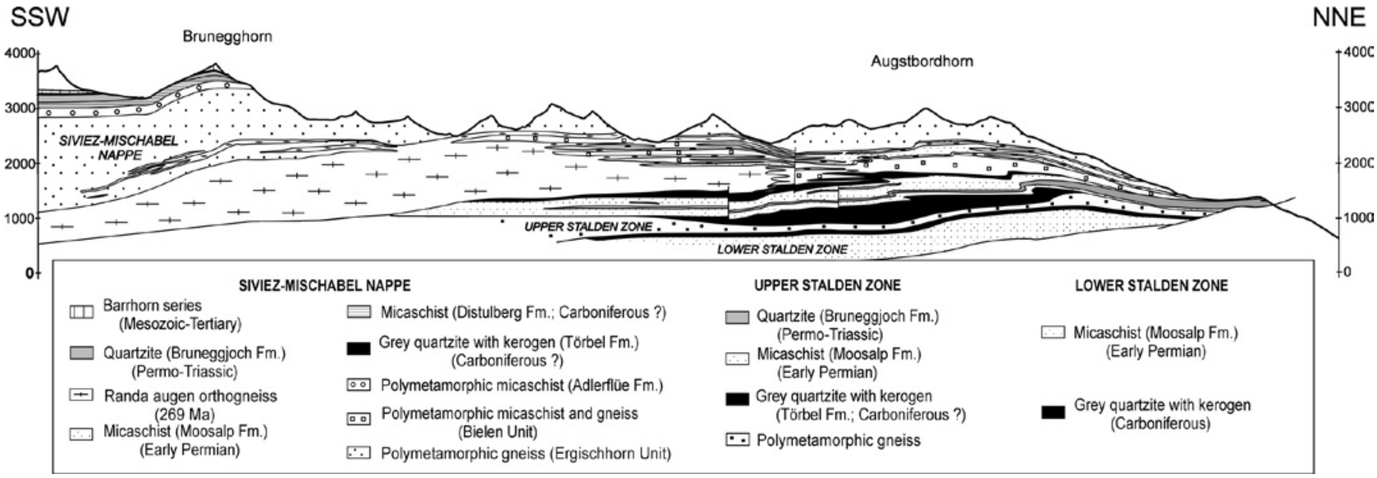


Fig. 3. Cross-section through the Siviez-Mischabel nappe and the Upper Stalden zone (profile trace indicated on Fig. 2). The St-Niklaus syncline is symmetrical and connects the overturned limb of the Siviez-Mischabel nappe to the normal limb of the Upper Stalden zone.

the Siviez-Mischabel nappe emplacement; however we did not observe evidence of such post-nappe shear zones in the overturned limb of the nappe. In the Mattertal, structures related to the nappe emplacement are superposed by deformations related to the Simplon ductile shear zone (35–15 Ma) and to late back-folding to the south as described by Steck (1984, 1987, 1990). Below, the Lower Stalden zone can be correlated with the Permo-Carboniferous series of the Houillère zone, as proposed by Bearth (1963) and Thélin & Ayrton (1983).

The Siviez-Mischabel nappe displays the most complete lithostratigraphic sequence of the tectonic units mentioned above. The nappe is cored by polymetamorphic gneisses with tectonic structures related to the Alpine orogeny and to pre-existing orogenies (Variscan and older), and is wrapped by detrital monometamorphic series only affected by the Alpine orogeny (Escher 1988; Thélin et al. 1993). The lithostratigraphy at the base of the Siviez-Mischabel nappe is presented in Figure 4. The new detailed geological map revealed a stratigraphic succession of detrital series presumably of Carboniferous to Early Triassic age on pre-Ordovician polymetamorphic gneisses. The Randa orthogneiss is a porphyritic late Variscan granite dated at 269 +/–2 Ma (Bussy et al. 1996a) and is intrusive into most of the formations (see Fig. 2). Mesozoic to Palaeogene series are lacking due to Alpine deformation, thrusting and transport into the Prealpine units (Baud & Septfontaine 1980; Escher et al. 1993).

3. Stratigraphy

3.1 Normal limb of the Siviez-Mischabel nappe

The normal limb of the Siviez-Mischabel nappe has been well documented (Sartori & Thélin 1987; Sartori 1990; Thélin et al. 1993) and recently harmonized by Sartori et al. 2006. It is composed from bottom to top by the following rock types:

Polymetamorphic gneisses:

a) The *Ergischhorn Unit* (Thélin 1983): supposed to be Proterozoic or Cambrian in age (Thélin et al. 1990; Sartori et al. 2006). It is composed of siliceous paragneiss and associated amphibolites. Most typical are grey-greenish micaceous gneisses and schists with thin quartz bands or nodules, migmatitic, aphanitic, massive, and well banded gneisses.
b) The *Adlerflüe Formation* (Proterozoic?, Sartori et al. 2006) composed of amphibolites and augen-schist horizons with albite porphyroblasts.
c) The *Lirec Formation* (Cambrian, Sartori et al. 2006) composed of amphibolites and biotite-chlorite-garnet gneisses. This unit was intruded by the Thyon A-type metagranite (500 ± 4 Ma; Bussy et al. 1996b) around the limit between Cambrian and Ordovician.

The (b) and (c) formations, structurally above the Ergischhorn Unit, are recent subdivisions in the *Barneuza Unit* defined initially by Sartori & Thélin 1987.

Metasedimentary series:

a) The *Distulberg Formation* (Sartori 1990): described as graphitic micaschists, ankerite bearing micaschists, albitic schists and quartzite containing abundant metagabbros, prasinites and metaquartz porphyries. This formation is not dated. According to its graphite content, a Carboniferous age was initially supposed (e.g. Sartori 1990), however an Upper Cambrian age has been recently proposed according to correlations with "black schists" of the Vanoise area (Sartori et al. 2006).
b) The *Col du Chassoure Formation* (Sartori et al. 2006): Not strictly observed in the normal limb of the nappe, it composed an important part of the frontal part of the nappe. It is composed of Permian series with high variety of rock

types, as dark schists, schists with quartz and sericite and schists with abundant carbonates. It may contain ovardites and quartz porphyries

c) The *Bruneggjoch Formation* (Sartori 1990): *Permo-Triassic series* up to locally 200 m of thickness (Escher 1988; Sartori 1990; Thélin et al. 1993; Sartori et al. 2006): phyllitic quartzites (5–10 m) overlaid by white or green, sericitic, more or less conglomeratic quartzites with pink or white quartz pebbles (Briançonnais Verrucano-type; Trümpy 1966). It grades into white and tabular quartzites (0–50 m) called the Sous le Rocher Member (Sartori et al. 2006) and considered to be Early Triassic (Scythien, Sartori 1990).

d) *Triassic to Eocene formations* (Marthaler 1984; Sartori 1987, 1990): divided in two series in the Barrhorn area; the Barrhorn series and the Toûno series. These formations are absent in the other parts of the nappe (front and overturned limb) due to detachment from their substratum during Alpine deformation and can be identified now in the Préalpes Médianes Rigides (Trümpy 1955; Sartori 1990; Sartori & Marthaler 1994).

3.2 Overturned limb of the Siviez-Mischabel nappe

Recent detailed field work in the Mattertal reveals that the base of the Siviez-Mischabel nappe displays four distinct overturned formations in addition to the Randa orthogneiss. The best preserved lithostratigraphic cross-section in the overturned limb outcrops on the west side of the Mattertal, in the Embd region (Fig. 5). The base of the limb crops out above Rohrmatte (1540 m, coord: 630.35/118.95). The following formations are observed from top to bottom (Fig. 6):

3.2.1 Bielen Unit

This unit is mostly composed of augen micaschists with albite porphyroblasts, micaschists, and garnet gneisses (Fig. 7A), in association with amphibolite bands or lenses. It was defined in the Bielen region by Sartori & Thélin (1987). This formation with a thickness around 300 m can be followed continuously from Grossberg (629.00/117.35) in the south to Goldbiel (631.20/122.95) in the north of the Mattertal. It is situated below a large intrusive apophyse of the Randa orthogneiss and above the Törbel Formation that will be described later (Fig. 5). Most of this formation is composed by micaschists with centimetre large albite porphyroblasts, except in its middle part where it is composed of porphyroblast-free banded gneisses and micaschists (around 80 m thick). The Bielen Unit occurs also in the core of the Siviez-Mischabel nappe in the Jungtal area (above Jungen, see Fig. 5). There, it is essentially composed of micaschists with albite porphyroblasts and occurs in deca-

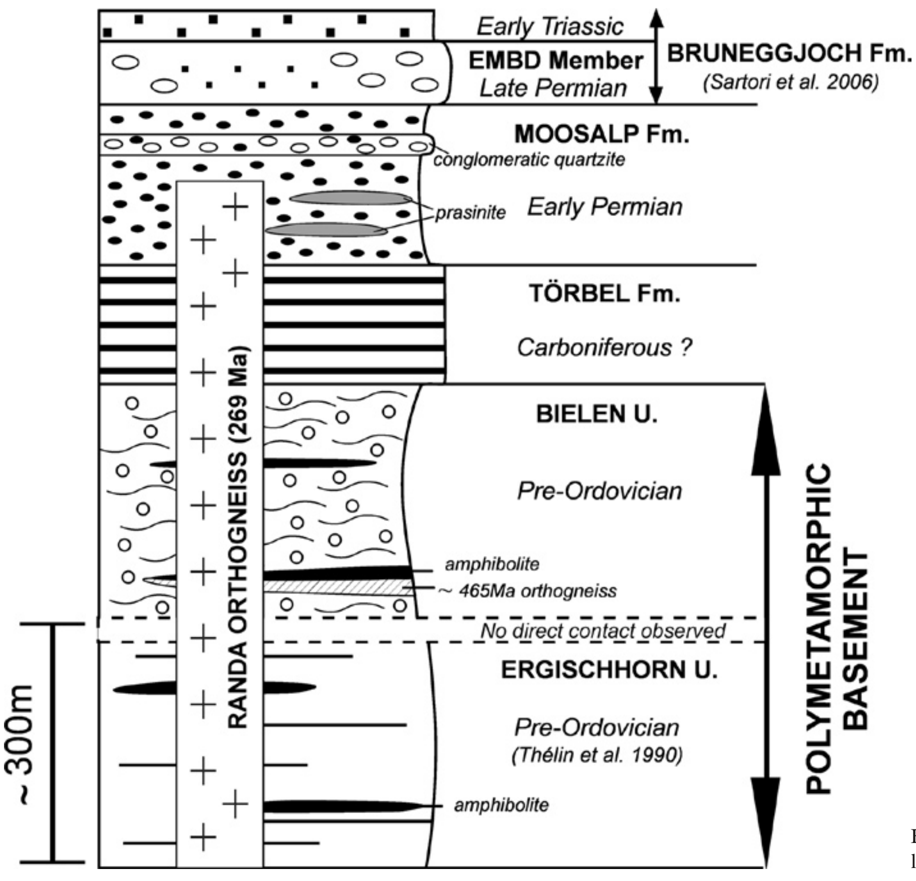


Fig. 4. Synthetic lithostratigraphy in the overturned limb of the Siviez-Mischabel nappe in the Mattertal.

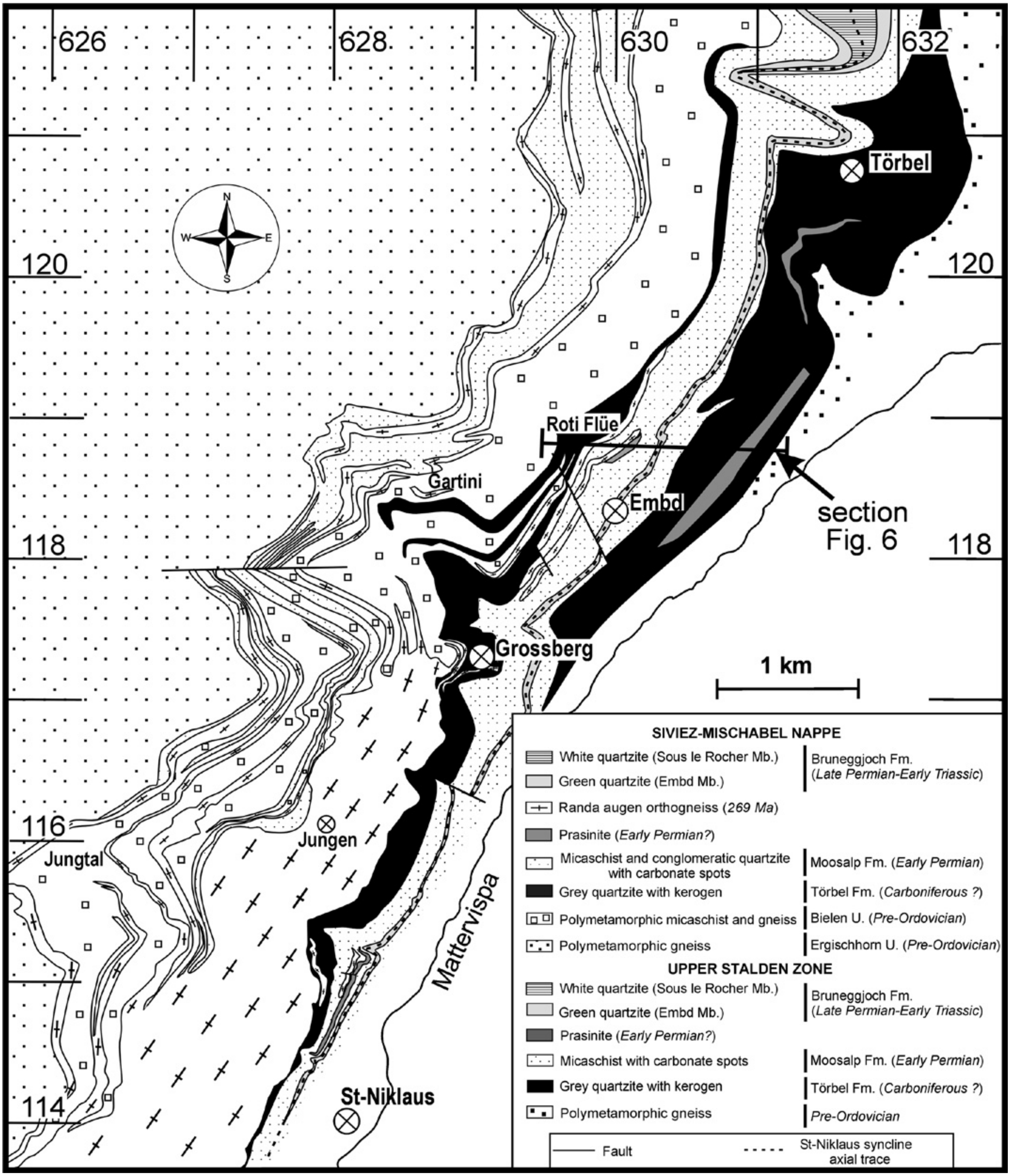


Fig. 5. Geological map of the west side of the Mattertal. The Permian Randa orthogneiss is intrusive into the Bielen Unit, the Törbel Formation and the Moosalp Formation. The observed stratigraphic contacts between the formations are folded by folds of decametre to kilometre in sizes.

metre thick levels intercalated with apophyses of the Randa orthogneiss and with the Moosalp Formation (presented below). This is probably caused by kilometre long isoclinal folds. The lower stratigraphic part of the formation is limited by the Ergischhorn Unit and the upper part by the Törbel Formation or the Moosalp Formation (see below). In the normal limb of the nappe, this unit seems to be an equivalent of the polymetamorphic and eclogite-bearing Adlerflüe Formation (Sartori et al. 2006) from the Barneuza Unit (Sartori & Thélin 1987).

Albite porphyroblasts (size of 0.2–1.0 cm) from the micaschists are unzoned monocrystals, containing inclusions of quartz, biotite, phengite, few subidiomorphic garnets (around 0.1 mm) often forming clusters or «atoll» aggregates, rutile and ilmenite. Inclusions, except for garnet, usually form a folded and slightly discordant foliation compared to the main foliation composed by phengite, chloritized biotite, chlorite, quartz, K-feldspar, albite, calcite, tourmaline, garnet, zircon, apatite and oxides (details in Sartori & Thélin 1987).

In addition to amphibolites, the Bielen Unit contains a few Ordovician porphyritic orthogneisses (see below) and is intruded by few dikes of the Randa orthogneiss (Jungtal, Grossberg and Gartini localities, see Fig. 5).

3.2.2 Törbel Formation

The village of Törbel (631.8/120.8/1520 m) is built on this formation and has been chosen as type locality. In the Törbel village, the formation is thick, well exposed and easy to access (beside the street road). The type region of this formation is the Embd area on the 1:25000 national topographic sheet n° 1328 of "St-Niklaus", where it is well exposed and the contacts with the surrounding formations can be observed. In this area, a type section has been defined (Fig. 6). The Törbel formation is composed of fine-grained, greyish quartzites and graywackes. It is characterized by small grain size, grey-green colour and decimetre thick horizons rich in organic matter (kerogen) that have been frequently qualified as "graphitic" (Fig. 7B). The lower stratigraphic part of the formation is limited by the Bielen Unit composed of micaschists with centimetre large albite porphyroblasts and large centimetre long micas. The upper part of the formation is limited by the Moosalp Formation composed of green micaschists with few Fe-carbonates or by metre-thick bands of leucocratic orthogneiss.

The Törbel Formation is well exposed in the overturned limb of the Siviez-Mischabel nappe in the Roti Flüe mountain pasture (629.9/118.8) above Embd (Fig. 5). It extends continuously from the south of St-Niklaus to the north-west of Törbel in the north (1:25000 sheet n° 1308 "St-Niklaus" (Bearth 1978)), with a maximum thickness of 150 m decreasing progressively from its centre. This formation, however, is strongly isoclinally folded and the stratigraphic thickness is difficult to estimate. The formation occurs not only at the base of the Siviez-Mischabel nappe but also below it at the top of the Upper Stalden zone (Fig. 6). In this tectonic unit, this formation with variable thickness (max. 350 m) extends at least from Derfji (below Embd) to a major fault near Zeneggen in the north (Marthaler, unpublished).

In the Törbel Formation, quartzites and graywackes are composed of quartz (93–97%), phengite (3–7%), chloritized biotite (2–3%), chlorite (1%), albite (1%), rare xenomorphic small almandine-rich garnet (0.06–0.15 mm, X_{alm} = 62–66%), pistacite (0–1%), apatite, calcite and zircon. The more micaceous horizons are composed of phengite (90–98%), chlorite (1–3%), quartz (1%), subidiomorphic to xenomorphic slightly zoned garnet (1–2%, 0.06–0.5 mm, X_{alm} rim = 64–65%; X_{alm} core = 61–62%), pistacite (1–2%), sphene (1%), rutile, apatite, calcite, tourmaline and zircon.

In the Embd-Törbel area, this formation contains a large band (50 m thick, 2.5 km long) of dark prasinite, not banded, with micro-grained border facies, which was already mapped by Bearth (1978). It is composed of amphibole (1 mm–2 cm; 60–70%), sphene (10%), plagioclase (5–10%), calcite (5%), epidote (3–5%), chlorite (5%), phlogopite (2%), phengite (<1%), ilmenite and rutile. This formation also contains metre to decametre thick leucocratic orthogneisses frequently porphyritic with pluricentimetre long microcline phenocrysts. Most of these metagranitoids are very probably late Variscan, as intrusive leucocratic aplites connected to the Randa orthogneiss can be observed on the pass between St-Niklaus and Jungen (Fig. 8).

Horizons rich in organic matter

The dark horizons rich in organic matter are relatively rare and occur locally in decimetre thick levels (5 to 40 cm thick) between quartzite and metagraywacke beds (Fig. 7B). These horizons contain 1.1 to 4.1 wt% of organic carbon measured by coulometry (Table 1) mostly in association with fine-grained quartz, albite and white mica determined by XRD. No distinct peak of graphite is observed by XRD. The $\delta^{13}C$ isotopic composition of the organic matter, mostly kerogen, is around –31‰. The carbon isotopic composition of primary kerogen is known to be controlled by several factors, including variable contribution of marine plankton, bacteria, algae and land plants, redox condition, organic productivity, ratio of marine/terrestrial biomass, variation in the productivity rate and concentration of atmospheric CO_2. Diagenetic and hydrothermal chemical and bacterial degradation may change the source isotopic signature of the kerogen, but the isotopic composition of kerogens is little affected by maturation (Whelan & Thompson-Rizer 1993), unless stages of catagenetic alteration of organic matter have been reached (appreciably above the anthracite stage). According to Lewan (1986), who studied a large sample set of kerogen covering the whole Phanerozoic, light kerogen (–26 to –35‰) is expected to occur in restricted basins (~200 m deep) with stratified water. In addition, such low values fit better with terrigenous kerogens (–26 to –28‰) than open-sea ones (–20 to –23‰) (Galimov 1980).

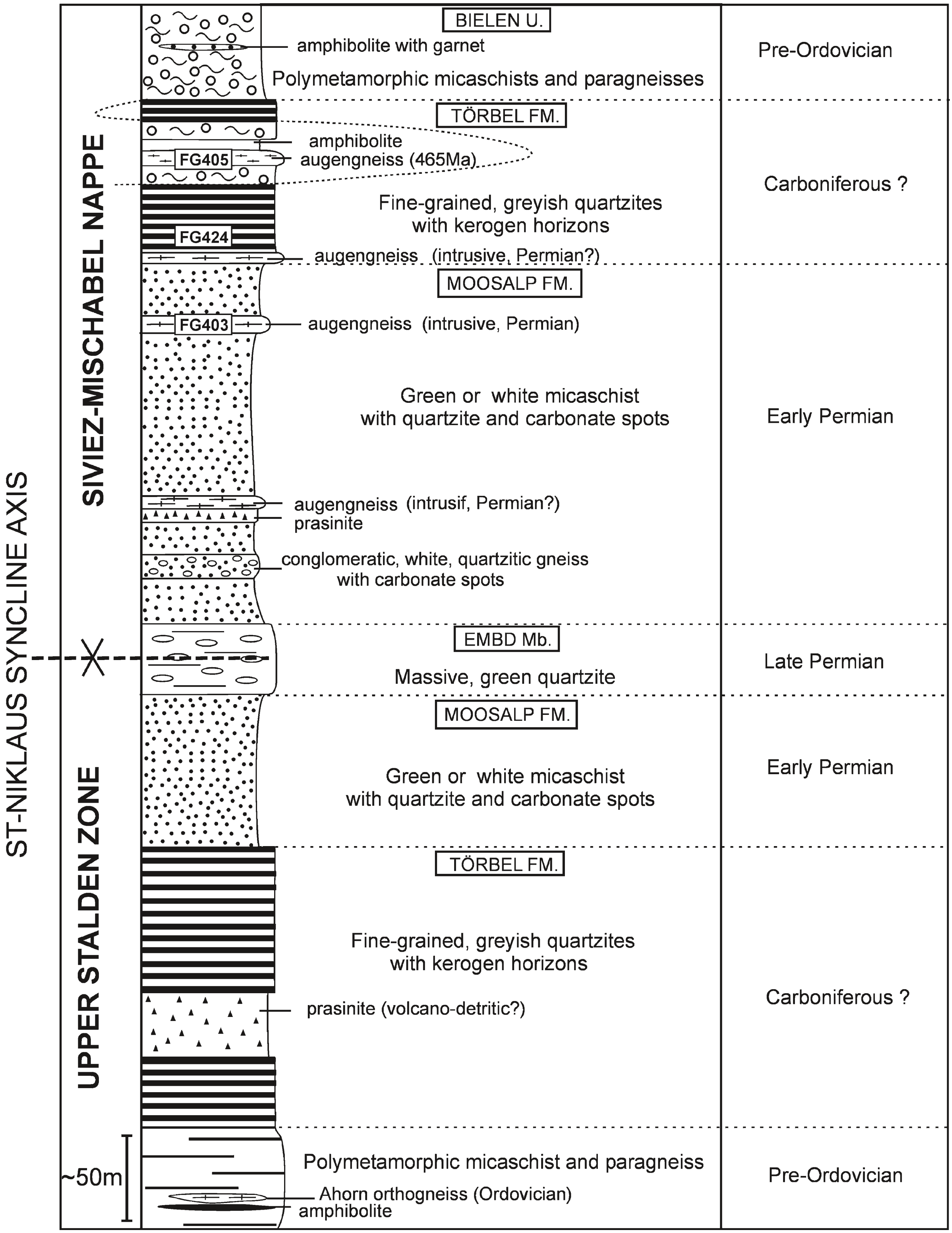


Fig. 6. Lithostratigraphic section through the St-Niklaus syncline on the west side of the Mattertal (location on Figure 5).

Table 1. δ[13]C values of the organic matter sampled in the Törbel Formation from the St-Niklaus syncline. The insoluble organic matter (kerogen) was obtained by acidification of the extracted samples with 6 N HCl for 32 hours at 50 °C. The kerogen (aliquots of 0.1 to 0.5 mg) were analyzed for C-isotopic composition using a Carlo Erba 1108 elemental analyzer (EA) connected to a Finnigan MAT Delta S IRMS via a Conflo III split interface (EA/IRMS). The stable C isotope ratios are reported in the delta (δ) notation as the per mil (‰) deviation relative to the Vienna Pee Dee Belemnite (V-PDB) international standard. The reproducibility of the EA/IRMS analyses, monitored by replicate analyses of laboratory working standards was better than ±0.1”. The reference gas was calibrated with international reference material (USGS-24 graphite: –15.9”; NBS-22 oil: –29.7”; IAEA-PEF1 polyethylene foil: –31.77”).

Formation	sample location	proportion of C	δ^{13}C PDB	C[type]	origin
Törbel	(A) St-Niklaus synclinal normal limb coord: 631.4/120.0	1.47 %wt	-31.1‰	kerogen	continental
Törbel	(B) St-Niklaus synclinal inverted limb coord: 629.6/118.8	4.08 %wt	-31.2‰	kerogen	continental

3.2.3 Moosalp Formation

The Moosalp Formation is mostly composed of greenish or whitish micaschists and metagraywackes characterized by brown centimetre large carbonate spots. These carbonates are mostly present in the most siliceous and coarser grained decimetre thick horizons (Fig. 7C). The carbonate may represent locally up to 30% of the rock volume giving a more tanned-green colour to the rock. This formation also contains other rock types such as quartzite, conglomerate, marble and green schist.

This formation was defined by Thélin (1987) as “Moosalp series” in the Moosalp area (630.0/122.2) on the west bank of the Mattervispa. The Moosalp Formation has been gathered with other formations and rock types in the Permian “Col de Chassoure Formation” by Sartori et al. 2006, however due to the specific facies of the Moosalp Formation in this part of the nappe, it will be described here as an independent entity.

In the studied region, the Moosalp Formation has a much larger geographic extension than described by Thélin (1987) or Sartori & Thélin (1987). This formation was initially defined and only described between two major Randa orthogneiss apophyses from west of the Ergisch area, in the Rhône Valley, to Jungen area on the west side of the Mattervispa. New detailed mapping revealed its presence from 1 km south of the village of St-Niklaus to 2 km north of the village of Törbel. There, it crops out at two levels (~150 m and ~80 m thick) symmetric with respect to quartzites composing the core of the St-Niklaus syncline (Fig. 5). The formation can also be followed as far as the eastern side of the Saastal, where it decreases in thickness down to discontinuous occurrences in the Mattwaldhorn area (Bearth 1972; Steck et al. 1999). Outside the Siviez-Mischabel nappe, this formation also crops out in a large part of the Lower Stalden zone (Fig. 2) as already suggested by the work of Bearth (1963).

The Moosalp Formation generally consists of greenish micaschists composed of phengite (25–60%), chlorite (15–25%), quartz (25–40%), biotite and chloritized biotite (2–3%), albite (5–15%), Mn-ferroan dolomite (1–20%), calcite (1–2%), pistacite (1–2%), stilpnomelane (0–1%), Fe-oxides (1–2%; ilmenite, hematite), apatite, zircon, and tourmaline. K-feldspar is generally absent or strongly albitized. Pluricentimetre large rounded or elongated quartz nodules are frequently associated with this facies. Rare chloritoid-bearing micaschists (Fe-chloritoid; MgO = 1.6–2.0 wt%, FeO = 25.9–27.0 wt%) occur only in the normal limb of the St-Niklaus syncline, at the base of the formation (e.g. Törbel or on the west bank of the Saastal).

In the overturned limb of the St-Niklaus syncline, the micaschists of the Moosalp Formation are frequently in association with a variety of conglomerates and quartzites, and also with rare Ca-rich and marble horizons. Quartzites and conglomerates can be observed at different stratigraphic levels, but occur mostly on the top of the formation. The conglomeratic horizons are discontinuous, decimetre or metre thick, and display sharp contacts with the surrounding micaschists. Most of them are leucocratic, composed of broken rounded K-feldspar (5–10%, 1–4 cm), white mica (30–35%), albite (5%), quartz (40–50%) and frequently Fe-carbonates (5–10%). Green conglomerates with centimetre large quartz pebbles also frequently occur. Ca-rich horizons are metre-thick, massive, greyish, composed of quartz (40–45%), zoisite (10%), phengite (25%), albite (5–10%), sphene (1–2%) and subidiomorphic, zoned, green amphibole (10–15%; 0.5–1 mm). Marble horizons have been observed in the Moosalp area (Palaczeck 1976) and in the Lower Stalden zone (Bearth 1980). In this last area, the metre thick marble layer (20 cm thick) is discontinuous, isoclinally folded, displays a yellow-brown patina and is mostly composed of calcite (0.2–0.5 mm, 90–95%), rounded xenomorphic albite (0.1–0.9 mm, 5%), rounded quartz (0.1–0.3 mm, 1–3%) and rare lamellar white mica (0.1–0.2 mm).

The Moosalp Formation also contains several deformed apophyses of the Permian Randa orthogneiss (Thélin 1987, e.g. Jungtal or Moosalp area) and few metre to decametre thick leucocratic dikes, most of them probably linked to the Randa orthogneiss even if disconnected at outcrop, as supposed by zircon morphology and dating (see 6.3). The formation also contains ovardites and prasinites. The prasinites are composed of zoned green-blue amphibole (core: barroisite, rim: mg-horn-

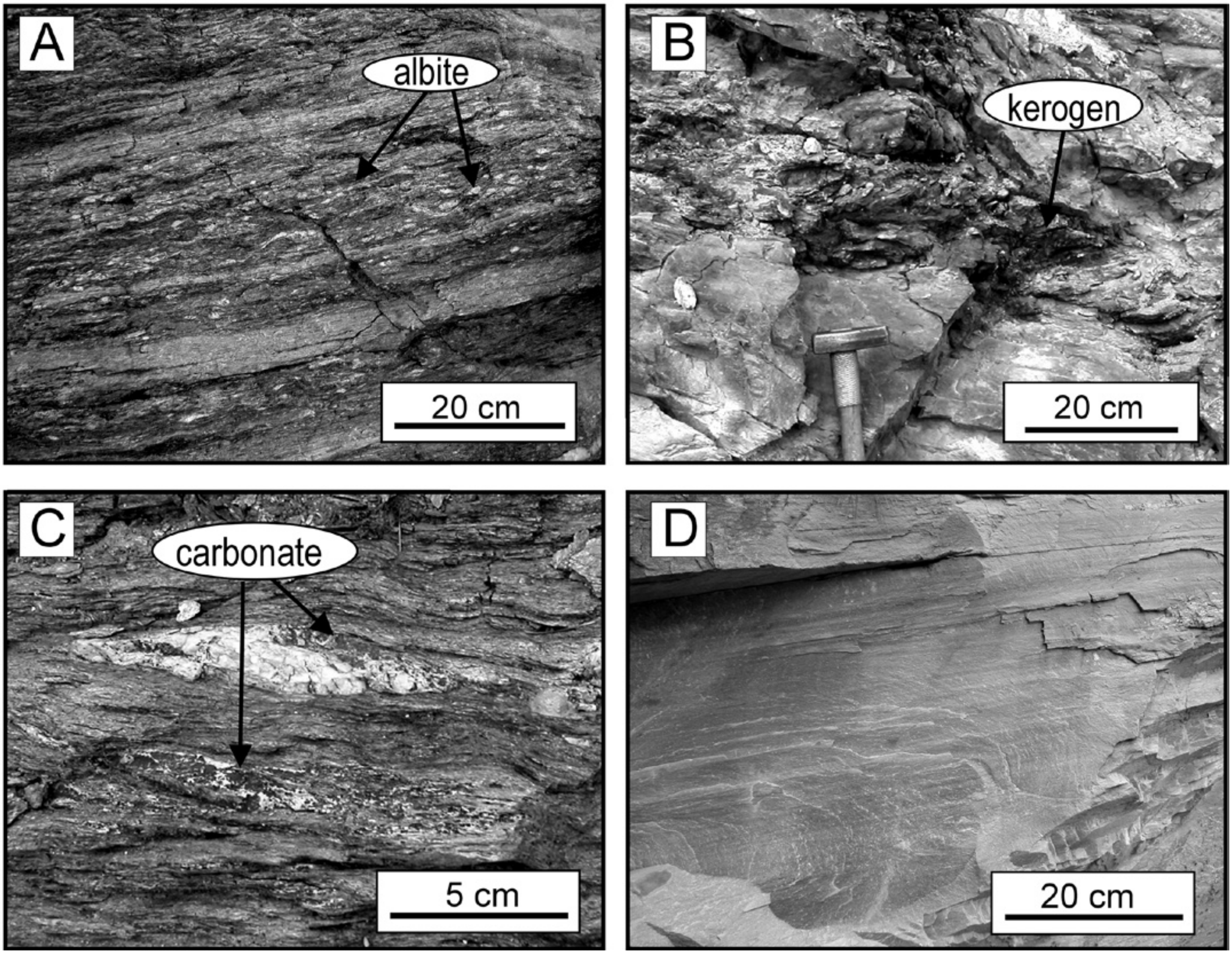


Fig. 7. Illustration of the formations in the overturned limb of the Siviez-Mischabel nappe. (A) Augen micaschists with albite porphyroblasts (Bielen U.); (B) quartzite with kerogen horizon (Törbel Fm.); (C) micaschist with Fe-dolomite spots (Moosalp Fm.); (D) green quartzite (Embd Member: base of the Brunegg-joch Fm.).

blende) (30%), clinozoisite (5%), albite (20%), chlorite (40%), Fe-oxides (2–3%), sphene (1%) and quartz (<1%).

Carbonate mineralogy in the Moosalp Formation

The ferroan dolomite (dolomite with $Fe^{2+}/Mg+Fe^{2+} < 0.2$, Chang et al. 1998) is the characteristic marker of the Moosalp Formation. It forms mostly individual grains (0.5–2.0 mm) disseminated in the rocks but can be concentrated in the quartz-albite horizons where it forms pluricentimetre long brownish aggregates (Fig. 7C). In thin section, this dolomite is uncoloured, mostly skeletal but with euhedral grain shape, in general monocrystalline, but partly polycrystalline with only 2–3 sub-grains. It has a typical brownish-mottled aspect due to its strong Mn-Fe-mineralization in cleavage planes. It contains frequent inclusions of quartz and also of small phengite and pistacite grains (25–50 µm). In many places, this dolomite is partially or totally dissolved, probably by surface alteration, leaving typical small holes partially filled with brownish material on weathered surfaces. In addition, calcite grains replace some parts of the dolomite crystal. The microprobe analysis of dolomite in zones preserved from alteration revealed a relatively high content in Mn (3.0–5.3 mol.% $MnCO_3$, Table 2A). Calcite displays mostly aggregates of subhedral to anhedral grains, generally free of inclusion except for rounded quartz and phengite. It also contains some Mn (2.1–2.9 mol.% $MnCO_3$; Table 2B). The high Mn content in carbonates could be partly explained by fluids related to basic intrusions, according to the frequent occurrence of green rocks in the formation.

Table 2. Representative microprobe analyses and atomic proportions of carbonates from the Moosalp Formation. A: Ferroan dolomite, B: calcite. *CO_2 calculated stoichiometrically to minimize matrix effects. Chemistry determined in the Laboratoire de Microanalyse Electronique of the Lausanne University, with a CAMECA-SX50 electron microprobe operating at 15,0 kV and 14,5 nA. Counting time was 30 s on each peak and 15 s on each side of the peak for the background.

A	Fe-dol1a	Fe-dol2a	Fe-dol2b	Fe-dol2c	Fe-dol3	Fe-dol4
MgO	16.89	18.08	16.27	18.84	17.40	17.26
CaO	33.70	30.20	33.96	30.03	34.05	30.69
MnO	2.79	4.17	3.78	2.37	2.37	2.69
FeO	3.98	4.72	3.86	5.12	4.11	5.15
CO_2*	42.60	42.80	42.09	43.61	42.02	44.17
TOTAL	99.96	99.97	99.95	99.96	99.94	99.97
Numbers of cations on the basis of 1(O)						
Fe	0.050	0.059	0.048	0.064	0.051	0.066
Mn	0.035	0.053	0.048	0.030	0.030	0.035
Mg	0.376	0.404	0.362	0.422	0.382	0.395
Ca	0.539	0.484	0.543	0.484	0.538	0.504
Σ cations	1.00	1.00	1.00	1.00	1.00	1.00
Fe/(Fe+Mg)	0.12	0.13	0.12	0.13	0.12	0.14
B	cc1	cc2a	cc2b	cc3	cc4	cc5
MgO	0.97	1.50	1.13	1.06	1.59	1.33
CaO	56.36	56.02	56.51	55.85	55.33	62.82
MnO	2.02	2.07	2.06	2.18	2.04	1.81
FeO	0.84	1.09	0.88	0.82	1.11	0.84
CO_2*	39.76	39.23	39.41	40.03	39.87	33.19
TOTAL	99.95	99.92	99.98	99.93	99.94	99.98
Numbers of cations on the basis of 1(O)						
Fe	0.011	0.014	0.011	0.011	0.014	0.010
Mn	0.027	0.027	0.027	0.029	0.027	0.021
Mg	0.023	0.034	0.026	0.025	0.037	0.028
Ca	0.940	0.924	0.936	0.936	0.922	0.941
Σ cations	1.00	1.00	1.00	1.00	1.00	1.00

3.2.4 Bruneggjoch Formation

The Bruneggjoch Formation was defined by Sartori (1990) in the normal limb of the Siviez-Mischabel nappe and is composed of two different quartzite types.

The lower part of the formation, mostly in sharp contact with white or green micaschists of the Moosalp Formation, is composed of massive, green, fine grained, microconglomeratic or conglomeratic quartzite (Fig. 7D). It is the typical rock extracted from the Kalpetran quarry to build roofs in the region. This quartzite is easy to access in the Embd locality (630.05/118.40/1415 m). In this locality, it is well exposed and the contacts with the surrounding formations can be easily observed. Consequently we propose to call Embd Member this quartzite type, as it has until yet not been named. This member is around 20 metres thick along the Mattertal. Characteristic conglomerates with pink quartz pebbles (Briançonnais Verrucano-type; Trümpy 1966), occurring in various places (Embd, Törbel), are part of this quartzite. It crops out on the west side of the Mattertal in a zone of plurikilometre long extension, forming the core of the St-Niklaus syncline. This quartzite contains broken microcline grains (2–5%, 0.5–2 mm) with albitic rims and pressure shadows composed of quartz and phengite. The matrix is composed of quartz (75–55%, 0.01–0.3 mm), subidiomorphic phengite (25–40%, 0.05–0.5 mm) and accessory albite (0.1–0.2 mm).

From the Törbel area to the north, the Embd Member grades into tabular white quartzite (Fig. 5) which corresponds to the upper part of the Bruneggjoch Formation. This second type of quartzite composed the Sous le Rocher Member defined in the Prealps of Hautes-Savoie by Sartori et al. 2006. This white quartzite, assumed to be Early Triassic (Scythian; Sartori 1990), is massive and microconglomeratic. It can be observed discontinuously along the Mattertal, it crops out only northern of Törbel village and southern of St-Niklaus village on the east side of the Mattertal. It is composed of millimetre large (1–2 mm) recrystallized quartz pebbles and rounded K-feldspar clasts (2–5 mm). Quartz pebbles are more abundant than K-feldspar. The matrix is composed of dynamically recrystallized quartz (0.1–0.2 mm; 80 vol%.) and phengite (0.05–0.2 mm; 1–2 vol%.).

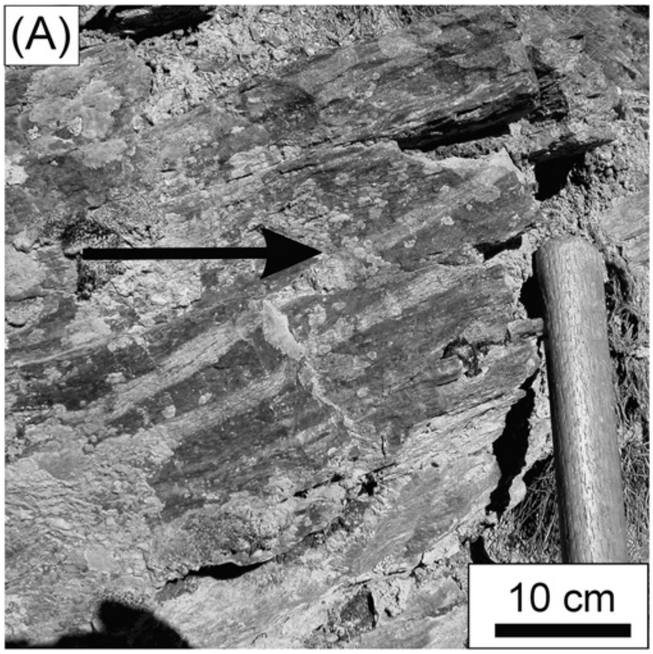
3.3 Normal limb of the Upper Stalden zone

In this zone, the cartography revealed a normal limb symmetrical to the overturned limb of the Siviez-Mischabel nappe (Figure 3). The bottom of this normal limb is composed of polymetamorphic gneiss similar to polymetamorphic gneiss of the Ergischhorn Unit (Fig. 6). These gneisses contain a lot of amphibolites and Ordovician augen orthogneiss, as for example the Ahorn augengneiss dated at 457 ± 2 Ma (Bussy, unpublished). Three formations can be observed above this gneiss, from bottom to top: (a) The Törbel Formation, (b) The Moosalp Formation, and (c) the Bruneggjoch Formation. Consequently, the metasedimentary formations above the polymetamorphic gneisses are forming a kilometre long recumbent St-Niklaus syncline.

4 Descriptions of the Contacts

In the studied region, the contacts between the formations in the overturned limb of the Siviez-Mischabel nappe display evidence of stratigraphic continuity, even if they have been deformed and folded during the Alpine orogeny. No tectonic discontinuity, fault or mylonite is observed at these contacts and consequently they are interpreted as stratigraphic.

- The contact between the Bielen Unit and the Törbel Formation is sharp or slightly gradational (< 0.5 m thick), primarily marked by the strong contrast in the size of the metamorphic micas between the two formations. In the reference profile (Fig. 6) it can be observed several times, probably due to kilometre long isoclinal folds.
- The contact between the Törbel Formation and the Moosalp Formation is gradational over 2 or 3 metres. The massive grey metagraywackes of the Törbel Formation become progressively more greenish and micaceous at its top with the simultaneous occurence of carbonate (Fe-dolomite) spots.



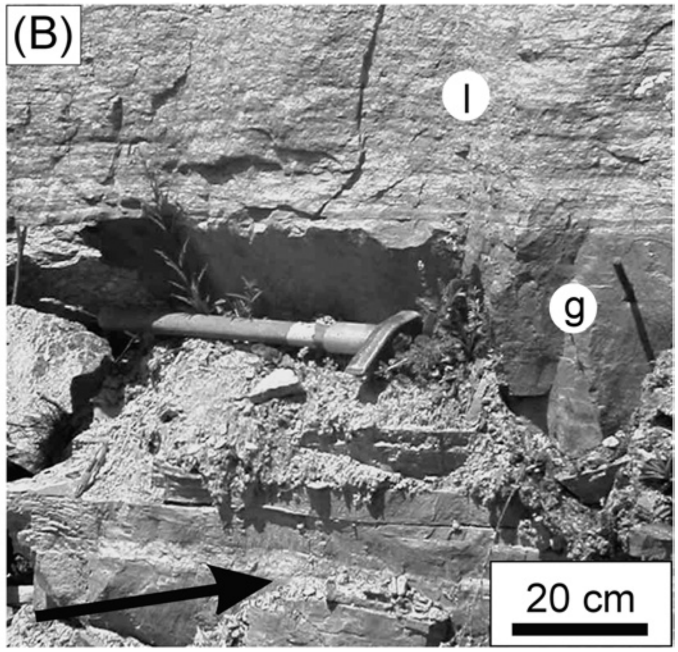


Fig. 8. Metre long leucocratic aplites connected to the Randa orthogneiss into the underlying quartzites of the Törbel Fm. (g) at the base of the Siviez-Mischabel nappe. (A) Arrow: aplites connected to the main body of the Randa orthogneiss in the St-Niklaus area (626.1/115.5). (B) Arrow: metric aplite below the leucocratic border facies (l) of the Randa orthogneiss (627.2/113.1).

In few places, metre-thick leuco-orthogneisses of Permian age according to zircon analysis mark this contact.

– The contact between the Moosalp Formation and the Bruneggjoch Formation is mostly sharp. In many places, however, the Moosalp Formation becomes more leucocratic towards its top and the contact may be gradational over a few centimetres, with centimetre thick alternation of micaschist and quartzite.

In the normal limb of the Upper Stalden zone, the contacts between the formations also provide evidence of stratigraphic continuity. The contact between the Bruneggjoch Formation and the underlying Moosalp Formation is sharp, but, in many places, the Moosalp Formation becomes more leucocratic towards its top, with centimetre thick alternation between micaschist and quartzite (over 20–30 cm). The contact between the Moosalp Formation and the underlying Törbel Formation is gradational over a few metres.

5 Intrusive Granitoids

Several metre-thick bands of porphyritic and leucocratic orthogneiss are observed in the overturned limb of the Siviez-Mischabel nappe, except in the Bruneggjoch Formation. These orthogneisses occur at the contact between formations or within the formations. The attribution and age interpretation of these granitoids are difficult based only on field arguments. However, even if disconnected at outcrop, we propose that these granitoids are mostly genetically related to the neighboring Permian Randa orthogneiss. This attribution is based on the abundant aplitic dikes clearly connected to the Randa orthogneiss in the surrounding gneisses (Fig. 8) and on studies of zircon typology and ages in disconnected orthogneiss bands (see 6.3).

The Randa orthogneiss

The Randa orthogneiss is derived from a subalkaline porphyritic Permian (late Variscan) granite dated at 269 ± 2 Ma (Bussy et al. 1996a). Its main body occurs along the Mattertal where its thickness can reach 1000 m, with numerous apophyses extending to the frontal part of the Siviez-Mischabel nappe (Fig. 5). It has been mapped in its internal area by Bearth (1964, 1978) and its magmatic history has been studied by Thélin (1987). This orthogneiss is mainly porphyritic with K-feldspar phenocrysts. It displays, however, several contrasting facies due to primary magmatic heterogeneities. Microgranitic border facies, primary discordant contacts with the surrounding rocks (e.g. with the Moosalp Formation), apophyses and leucocratic aplites can be observed. Schlierens, as well as mafic and xenolithic enclaves are abundant. It is also associated with dark quartz-porphyries (0.5–1 cm quartz phenocrysts) in decametre thick zones. The central body is mainly porphyritic with K-feldspar phenocrysts (0.5–3 cm) and quartz aggregates. The overall mineralogy of the porphyritic facies is quartz (25–30%), microcline (25–30%), albite (15–20%), phengite (15–25%), chlorite (5–10%), epidote (pistacite, allanite) (2–5%), ilmenite and Fe-oxides (3–5%),

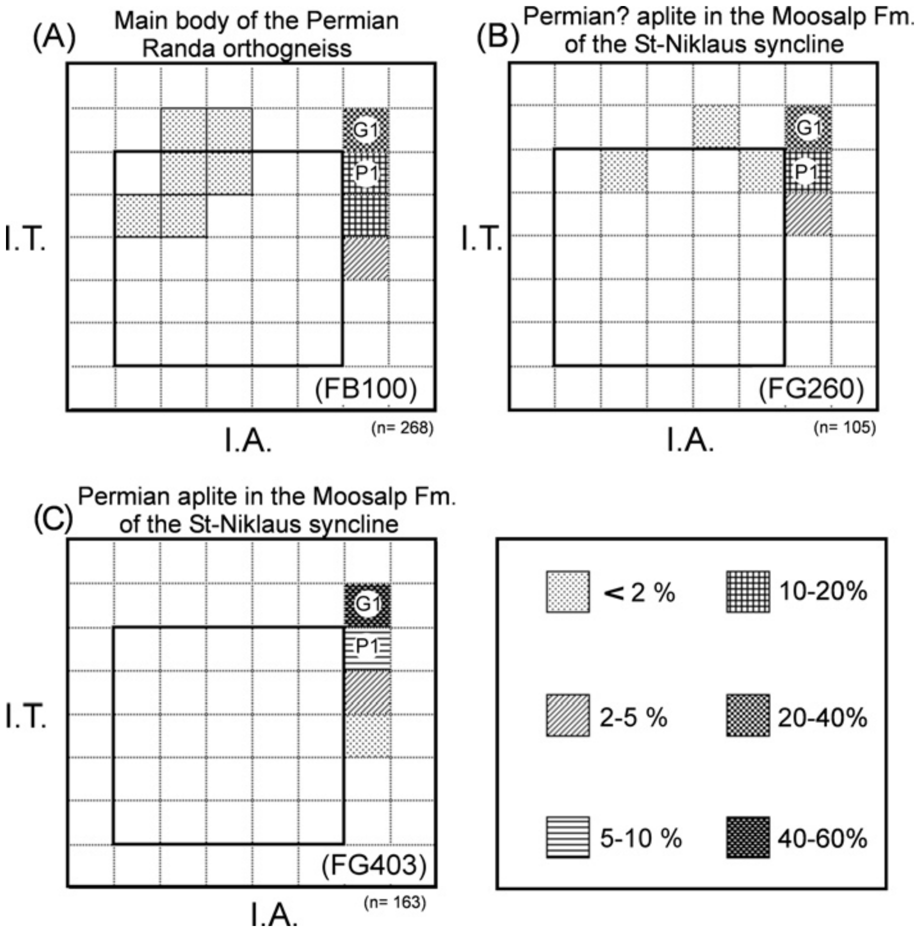


Fig. 9. Typological diagrams of zircon morphology after Pupin (1980). Location of samples presented on Fig. 2. (A) Main body of the Randa orthogneiss. Zircons display hybrid type morphology, mostly alkaline- or subalkaline-type with some content of aluminous-type (I.A. = 671 and I.T. = 304); (B) Leucocratic aplite in the Törbel Fm. in the overturned limb of the Siviez-Mischabel nappe. Zircons display alkaline or sub-alkaline morphologies with some content of aluminous type (I.A = 685 and I.T = 241) very similar to the morphology observed in the Randa orthogneiss; (C) Permian (see datation on Figure 11B) orthogneiss in the Moosalp Fm. in the overturned limb of the St-Niklaus syncline. Zircons display alkaline- or sub-alkaline-type morphologies (I.A = 695 and I.T = 261) in agreement with the morphology observed in the Randa orthogneiss.

green biotite (1–2%), sphene (1%), and rare calcite (<1%) with rutile, tourmaline, garnet, zircon and apatite as accessory phases. The xenomorphic habitus (small and rounded) of the green biotite speaks for a metamorphic origin.

Near the contact with the surrounding formations (Bielen U., Moosalp Fm.), the main body of this orthogneiss displays a leucocratic and microgranular border facies, with frequent centimeter thick dark mica-rich zones related to magmatic heterogeneities (schlieren). This facies is about 100 m thick at the topographic top, but is only meter-thick at the topographic base. It is composed of microcline (25%), polycrystalline quartz (25–30%), albite (20%), phengite (25–30%), and rare chlorite (<1%), with apatite, zircon, oxides, pyrite and tourmaline as accessory phases.

Numerous apophyses are connected to the Randa orthogneiss. The main apophyses (kilometer long and more than 10 meter thick) are observed in the northern part of the Mattertal and extend to the frontal part of the nappe (Thélin 1987). They are mainly porphyritic with big K-feldspar phenocrysts (up to 7 cm long) in a microgranular matrix. New investigations revealed the frequent presence of a microgranular leucocratic border facies, around 2–5 methers thick (e.g. Jungtal or Gartini area). Such a border facies as well as associated tourmaline-rich dikes are typical of preserved intrusive relations with the country rock (Moosalp Fm., Törbel Fm., Bielen U. and Ergischhorn U.).

The granitoids in the overturned limb of the Siviez-Mischabel nappe

In the overturned limb of the Siviez-Mischabel nappe, porphyritic and leucocratic orthogneiss layers (0.4 to 3 m thick, > 30 m long) are frequently observed in the Törbel Fm. and Moosalp Fm. Most of them are parallel to the main foliation. One of them was already mapped by Bearth (1978) above the St-Niklaus village (coord: 628.1/115.0). In thin section, they display evidence for magmatic texture with centimetre long anhedral polycrystalline microcline grains containing a lot of millimetre-large inclusions of plagioclase and quartz. These orthogneisses display the following mineralogical composition: microcline (20%), albite (20–25%), polycrystalline and monocrystalline quartz (35–40%), white mica (10–15%), apatite and zircon.

On the reference section through the overturned limb of the Siviez-Mischabel nappe, at least three bands of leucocratic and porphyritic metagranitoids have been observed (Fig. 6). The attribution and interpretation of these granitoids are difficult and zircon typology and dating is therefore crucial. Two orthogneiss bands sampled in the Moosalp Fm. produce zircon typology diagrams very similar to those of the main body of the Randa orthogneiss (Fig. 9). They are therefore considered to be related. For sample FG403, this relation seems to be confirmed by U-Pb dating of zircons (see 6.3). The presence of Permian intrusions in the Moosalp Formation below the main body of the Permian Randa orthogneiss, points to the close connection between the Randa intrusion and the metasedimentary series below it. The presence of a huge thrust separating the two rock bodies seems unlikely. On the contrary, these data are compatible with the assumption of an overturned limb in the Siviez-Mischabel nappe.

6 LA-ICP-MS U-Pb zircon dating

6.1 Introduction

In order to set a time frame to the observed lithostratigraphy, we performed *in situ* U-Pb isotopic dating of detrital and magmatic zircons by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). This is the most suitable technique in terms of rapidity and analytical costs to date a large number of grains required for the characterization of zircon populations in sedimentary rocks (Košler et al. 2002). Accuracy and precision of the calculated ages are currently comparable to other *in situ* dating techniques (i.e. SIMS, SHRIMP) as recently demonstrated by Košler et al. (2002), Jeffries et al. (2003), Tiepolo (2003), and Harris et al. (2004).

However, the LA-ICP-MS technique has only a moderate spatial resolution due to sensitivity limitations, which requires an ablation spot size ideally between 40 and 60 microns in diameter. As a consequence, mixed ages corresponding to different zircon growth events (inherited core, magmatic growth, metamorphic overgrowth) cannot be easily avoided (Košler et al. 2002). In addition, very small and thin zircons are difficult to analyse, which might bias the resulting age distribution histogram. In spite of these problems, this study provides important time constraints in the interpretation of the lithostratigraphy.

6.2 Analytical procedure

Zircons were isolated using standard heavy-liquid and magnetic techniques, after a first separation by panning in soapy water. Typology characterization (Pupin 1980) was done on carbon-coated crystals deposited on a conductive double-sided tape using a scanning electron microscope. Zircons selected for dating were thermally annealed in porcelain crucibles at 850 °C for 24h, and then leached in concentrated HF at 130 °C for 12h, in order to improve concordancy of ages (Mattinson 2001). Crystals not affected by the thermal and chemical treatment described above were then mounted in epoxy blocks and hand-polished for SEM cathodoluminescence imaging (CL), to unravel the internal structures of the grains.

U-Pb measurements were performed using a Lambda Physik Excimer ArF (193 nm) laser coupled to Perkin-Elmer ELAN 6100 mass spectrometer. Helium was used as carrier gas in the ablation cell (1.1 L/min). Each analysis consisted of a sequence of 50s of gas blank measurement, followed by a >40 s laser ablation on fixed spots 30 to 40 µm in diameter. Laser parameters were 30 kV and 4 Hz (12 J/cm^2). Instrumental and ablation-related fractionation of Pb and U were corrected by using zircon 91500 (1065 Ma) as an external standard with acquisition parameters strictly identical to those used for unknown zircons (e.g. ablation pit diameter, integration time of the signal). Each run consisted of a series of 12 analyses of unknown zircons bracketed by sets of four standard measurements. Ages were calculated off line with the LAMTRACE 2.10 software (Jackson 2001), using the following isotopic ratios for the 91500 zircon standard: ^{207}Pb/^{206}Pb = 0.0749; ^{207}Pb/^{235}U = 1.8502; ^{206}Pb/^{238}U = 0.1792). Multiple analyses of the standard have concordant age of 1062.3 ± 3.2 Ma, similar within analytical error to the certified age of 1065.4 ± 0.3 Ma (Wiedenbeck et al. 1995).

6.3 Results (Table 3)

6.3.1 Zircon ages in the St-Niklaus syncline area

Törbel Formation

Detrital zircons from a quartz-rich horizon of the Törbel Formation have been extracted and dated. The sample (FG424; 629.8/118.9) is from the upper stratigraphic level of the formation (Fig. 6), in the Embd area. Zircon grains display variable sizes (90–150 µm long) and morphology (broken, anhedral, rounded, and euhedral). Many zircons contain an inherited core visible on cathodoluminescence (CL) images. Hence, laser ablation has been performed as much as possible in areas with well developed oscillatory zoning formed during a single magmatic growth event. However, a contribution by old inherited cores cannot be totally excluded due to the moderate spatial resolution of the LA-ICP-MS technique. Consequently, the obtained ages may in some cases be mixed ages older than the magmatic event. On the other hand, age underestimation due to the involvement of Alpine metamorphic overgrowths has been carefully avoided on the basis of CL images.

The obtained ages are dominantly concordant and range from 2900 ± 50 to 520 ± 4 Ma (Fig. 10a). When several ablation pits have been drilled in the same grain, only the youngest age has been kept for statistics to minimize inheritance bias. From 91 grains, 57% are younger than 760 Ma and only 2.5% younger than 550 Ma. The youngest zircon is 524 Ma, consequently we consider that the maximum age of the Törbel Formation is Mid-Cambrian. The ages scattered over several peaks ca. 3.0, 2.6–2.4, 2.2–2.0, 1.8–1.7, 1.1–0.9, and 0.8–0.5 Ga (Fig. 10b) as observed in other part of the European continental crust (e.g. Gebauer et al. 1989). The Late Proterozoic peak between 800 and 550 Ma is evidence of the Pan-African orogenic cycle. These Pan-African

Table 3. U-Pb isotopic results for ablated zircons.

	atomic ratio						apparent age (Ma)					
	206/238	1σ	207/235	1σ	207/206	1σ	206/238	2σ	207/235	2σ	207/206	2σ
(A) St-Niklaus syncline												
Törbel Formation (FG424), detrital zircons												
(1)	0.5144	0.61%	13.3533	0.61%	0.18824	0.57%	**2675**	27	2705	11	2726	20
(2)	0.0913	0.71%	0.7770	1.29%	0.06170	1.22%	**563**	8	584	11	662	52
(3)	0.0896	1.03%	0.7858	1.20%	0.06359	0.88%	**553**	11	589	11	726	38
(4)	0.0863	0.42%	0.7187	0.82%	0.06039	0.86%	**534**	4	550	7	616	36
(5)	0.0839	0.43%	0.7536	0.59%	0.06512	0.60%	**520**	4	570	5	778	26
Ordovician orthogneiss in the Bielen Unit (FG405)												
(6)	0.0749	0.78%	0.5941	1.67%	0.05752	1.84%	**466**	7	474	13	510	80
(7)	0.0740	0.89%	0.5921	1.91%	0.05803	1.89%	**460**	8	472	14	530	82
(8)	0.0726	0.77%	0.5728	1.77%	0.05725	1.65%	**452**	7	460	13	500	72
(9)	0.0716	0.70%	0.5722	1.59%	0.05791	1.51%	**446**	6	459	12	526	66
(10)	0.0721	0.65%	0.5735	1.55%	0.05769	1.56%	**449**	6	460	11	518	70
Permian orthogneiss in the Moosalp Formation (FG403)												
(11)	0.0537	0.85%	0.4624	1.28%	0.06239	1.11%	**337**	6	386	8	686	48
(12)	0.0526	0.99%	0.4233	1.14%	0.05832	0.88%	**331**	6	358	7	540	38
(13)	0.0517	1.41%	0.4408	2.06%	0.06187	1.66%	**325**	9	371	13	668	72
(14)	0.0505	1.28%	0.4171	1.68%	0.05991	1.26%	**317**	8	354	10	600	54
(B) Lower Stalden Zone												
Törbel Formation (FG512), detrital zircons												
(15)	0.0972	0.78%	0.8339	2.59%	0.06221	2.62%	**598**	9	616	24	680	112
(16)	0.0848	0.72%	0.6999	2.46%	0.05982	2.41%	**525**	7	539	21	596	106
(17)	0.0752	0.93%	0.5773	2.30%	0.05569	2.14%	**467**	8	463	17	438	96
(18)	0.0716	1.07%	0.5588	3.82%	0.05658	3.95%	**446**	9	451	28	474	176
(19)	0.0672	0.96%	0.5148	3.11%	0.05553	2.60%	**419**	8	422	21	432	116
Moosalp Formation (FG502), detrital zircons												
(20)	0.2765	0.52%	3.7129	0.74%	0.09736	0.65%	**1574**	15	1574	12	1574	26
(21)	0.0644	1.35%	0.5100	1.42%	0.05742	0.87%	**402**	11	418	10	506	38
(22)	0.0615	2.08%	0.4826	1.94%	0.0569	1.25%	**385**	16	400	13	486	56
(23)	0.0602	1.24%	0.4979	1.26%	0.05996	0.85%	**377**	9	410	9	602	38
(24)	0.0473	0.95%	0.3796	1.08%	0.05815	0.90%	**298**	6	327	6	534	40

zircons are usually interpreted to derive from Gondwana (Gebauer et al. 1989, Schaltegger 1993).

Orthogneiss in the Bielen Unit

Many metre-thick augen orthogneiss bands are located in the Bielen Unit, frequently associated with greenschists and amphibolites. Zircons have been extracted from one of these porphyritic (1–4 cm large K-feldspar phenocrysts) gneisses (sample FG405), located at site 4 in Figure 2. These are pale pink grains ranging from 70 to 150 µm in length. Small, anhedral or broken crystals represent about 35% of the total population. More than 90% of the identifiable grains correspond to G or P1 types in Pupin's classification (1980), with I.A and I.T coordinates of 700 and 230, respectively. Such a morphological distribution is typical of late-crystallized zircons from alkaline to sub-alkaline granites, although late-crystallized zircons from other granite types also tend to display the same morphology (convergence effect). The zircons display a well developed oscillatory CL zoning, typical of magmatic growth conditions. Most ages are concordant within errors around 460 Ma (Fig. 11A). Some analytical points plot outside this intercept age and away from the Concordia; older apparent ages are ascribed to mixing effects with inherited cores observed on CL images, whereas younger apparent ages may result from some residual Pb loss.

Ordovician metagranites in the middle Penninic nappes have rarely been documented. The obtained age of this “Bielen” orthogneiss is clearly younger than the 500 Ma-old A-type Thyon granite (Bussy et al. 1996b), which is intrusive into the normal limb of the Siviez-Mischabel nappe. It could be correlated with the 465 Ma-old granitoid intrusions observed in the Ruitor zone (Guillot et al. 2002), or in the Upper Stalden zone (Ahorn augengneiss at 457 ± 2 Ma; Bussy, unpublished), suggesting a similar tectonic evolution of these polymetamor-

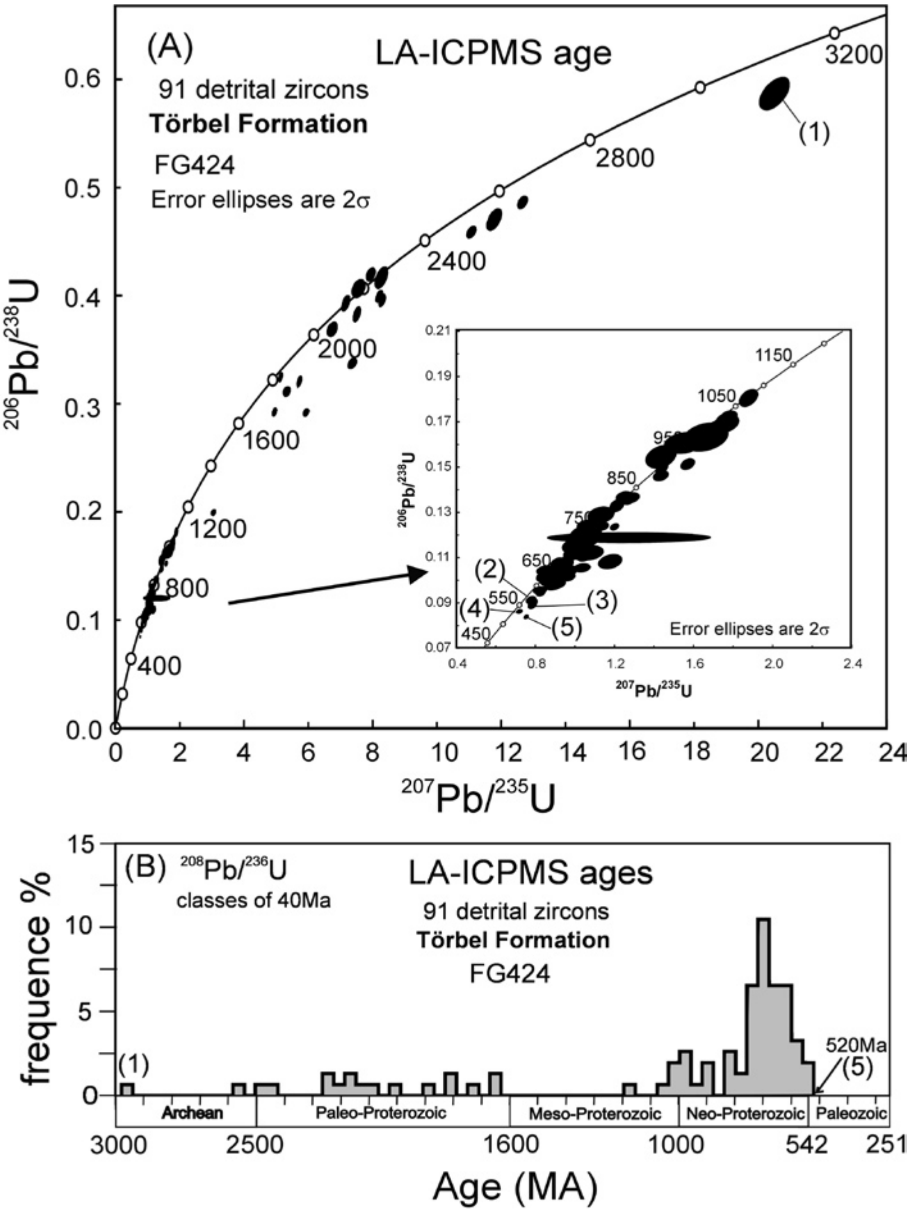


Fig. 10. (A) Concordia diagram showing data points measured on detrital zircons of one sample from the Törbel Formation, LA-ICPMS. Data are well concordant for ages younger than 1200 Ma. (B) Histogram of zircon ages in the Törbel Formation. Each class covers an interval of 40 ma. Data numbered after Table 3. The chronostratigraphic units are from Gradstein et al. (2004).

phic gneisses and those of the Siviez-Mischabel nappe during Paleozoic times.

Orthogneiss in the core of the St-Niklaus syncline

Zircons from two leucocratic orthogneiss samples from the overturned limb of the Siviez-Mischabel nappe (Moosalp Fm., samples FG260 and FG403, sampling sites 2 and 3 in Fig. 2) are pale pink and range from 80 to 150 µm in length. About 50 to 60% are small, anhedral or broken. CL imaging reveals a well developed oscillatory zoning pointing to magmatic growth and a high proportion of inherited cores. More than 70% of the identifiable grains correspond to G and P1 morphological types with some rare (inherited?) zircons with a well-developed {211} pyramidal form (S2, S5, L4 types). According to Pupin (1980), the G and P zircons are typical of alkaline granites, whereas the few others grew in aluminous melts. The obtained main points of these zircons are I.A = 685, I.T = 241 (FG260) and I.A = 695, I.T = 261 (FG403), as represented in Figure 9. This typological distribution is very similar to that of zircons of the Randa orthogneiss, mostly subalkaline type with rare (inherited?) aluminous-type zircons (I.A. = 671 and I.T. = 304; Fig. 9).

Zircons from sample FG403 were dated using the LA-ICPMS technique. The obtained zircon ages broadly plot into three groups of data on a Concordia diagram (Fig. 11B). A first

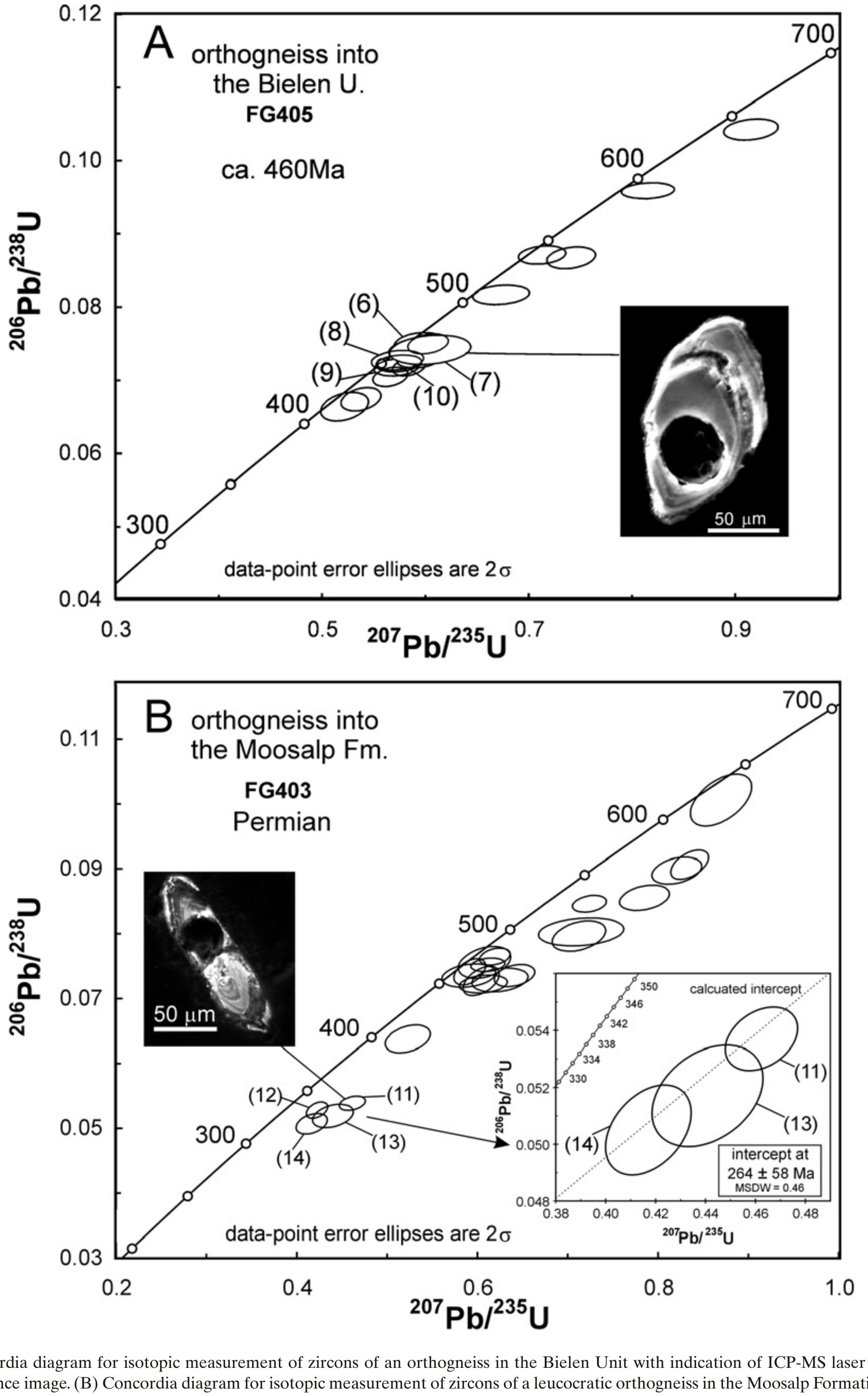


Fig. 11. (A) Concordia diagram for isotopic measurement of zircons of an orthogneiss in the Bielen Unit with indication of ICP-MS laser analytical spot on cathodoluminescence image. (B) Concordia diagram for isotopic measurement of zircons of a leucocratic orthogneiss in the Moosalp Formation with indication of ICP-MS laser analytical spot on cathodoluminescence image. Data numbered after Table 3.

group consists of zircon cores, which gather close to the Concordia curve at ca. 460 Ma. The good coherence of this data set suggests inheritance of zircons from Ordovician granitoids of the "Bielen type" described above. A second group displays older and significantly discordant apparent ages, which also correspond to inner zircon zones. They are interpreted as mixed ages involving an inherited component older than 500 Ma and one or two other components, which may include the 460 Ma magmatic event and/or the Permian magmatic event described thereafter.

A third group of data is defined by analyses 11 to 14 in Fig. 11B. These four ellipses plot discordantly at $^{206}Pb/^{238}U$ apparent ages between 317 and 337 Ma (Tab. 3). They correspond to analytical spots with well developed oscillatory zoning in CL imaging, ascribed to magmatic growth. Considering that Pb loss is minimized by pre-analytical treatment of the grains, the position of these four ellipses should only result from the combination of an inherited component and a magmatic episode younger than 317 Ma, but pre-Triassic according to stratigraphic constraints. A Carboniferous age for this magmatic event cannot be dismissed, as already observed in similar terrains of the Houillère zone in the Savoie area (323–324 Ma metagranite of Costa Citrin, Bertrand et al. 1998). However, regional geology rather suggests a Permian age, which is also indicated by the lower intercept age of 264 ± 58 Ma defined by a discordia line drawn through points 11, 13 and 14 (see insert Fig. 11B).

The following conclusions can be deduced from the zircon age data:

- Most of the orthogneisses observed in the core of the St-Niklaus syncline could be Permian and probably related to the Randa intrusion, in agreement with zircon typology. The presence of these metagranitoids below the main Randa orthogneiss body points to the close connection between this main granitic intrusion and the metasedimentary series below it.
- Small, metre-thick magmatic bodies are difficult to date, due to the strong input of inherited zircons from the country-rock during magma emplacement (Harris et al. 2004). In such cases, many single grain analyses are necessary to obtain a relevant age.

7 Ages of the Formations

The *Bielen Unit*: We assume a pre-Late Ordovician age relying on zircon U-Pb ages from a porphyritic orthogneiss (around 460 Ma) intrusive into it. In the past, Pre-Carboniferous ages were attributed to this unit by Sartori & Thélin (1987) and Thélin et al. (1993). In this unit, the general large grain-size of the metamorphic micas (2–3 cm) speaks for crystallization under Variscan amphibolite-facies of metamorphism; furthermore, the presence of amphibolites, retro-eclogites and the 500 Ma Thyon orthogneiss (Bussy et al. 1996b) in its supposed stratigraphic equivalent Barneuza Unit (Sartori & Thélin 1987; Sartori et al. 2006) speaks also in favour of Pre-Ordovician polymetamorphic rocks.

The *Törbel Formation:* Detrital zircon ages speak for an age younger than middle Cambrian (Fig. 10). The small grain-size of the metamorphic micas (<6 mm, typical of greenschist facies metamorphism) greatly contrasts with the larger size of the micas from the polymetamorphic Bielen Unit, speaking for a monometamorphic formation free of Variscan structures and metamorphism, hardly compatible with an age older than Carboniferous. This is also supported by the presence of few horizons rich in organic matter, similar to the "graphitic" layers observed in the nearby Carboniferous Houillère zone (Fabre 1961; Greber 1965; Mercier & Beaudin 1987) and in the nearby Lower Stalden zone, which is confirmed to be post-Silurian (this work, see below). The low crystallinity of organic matter (kerogen) also speaks for a formation free of high grade Variscan metamorphism (e.g. Landis 1971; Bustin et al. 1995). Finally, Randa orthogneiss apophyses are clearly intrusive into this formation (Fig. 2 and Fig. 3), so that it cannot be younger than middle Permian. Consequently, we infer a Carboniferous age for the Törbel Formation.

The *Moosalp Formation:* It was supposed to be Late Carboniferous or Early Permian after Thélin (1987). According to the observed lithostratigraphy in the overturned limb of the Siviez-Mischabel nappe, an Early Permian age seems the most reasonable for this formation. The Randa granite (269 ± 2 Ma, Bussy et al. 1996a) is clearly intrusive (leucocratic border facies, discordant contacts) into it, so that it cannot be younger than middle Permian. Moreover the youngest zircon (U/Pb) dated in a leucocratic and quartzitic paragneiss from the equivalent formation in the Lower Stalden zone gives an age of 298 ± 6 Ma (see 9.2), so that the Moosalp Formation cannot be much older than the limit Carboniferous-Permian.

The *Bruneggjoch Formation*: Late Permian to Early Triassic as proposed by Sartori et al. (2006). The base of the formation (Embd Member) is late Permian. The absence of Randa apophyses and the presence of Verrucano-type pink quartz pebbles support this age. The upper part of the formation (Sous le Rocher Member), composed of tabular and massive white quartzites (Fig. 4), is traditionally assumed to be Early Triassic (Sartori 1990).

8 Consequences for the tectonic Setting of the Siviez-Mischabel Nappe

This revised stratigraphy has critical implications for the tectonic setting of the Siviez-Mischabel nappe. In contrast to the published geological map of the west side of the Mattertal (Bearth 1978), where the St-Niklaus syncline is complex and separated from the polymetamorphic gneisses of the Siviez-Mischabel nappe by a tectonic contact, the St-Niklaus syncline is symmetrical in this area and connects the overturned limb of the Siviez-Mischabel nappe to the normal series of the Upper Stalden zone, as represented in Figure 3. The presence of numerous orthogneisses bands attached to the main body of the

Randa orthogneiss in the Törbel Formation and Moosalp Formation of the overturned limb of the Siviez-Mischabel nappe is a critical argument against an important shear zone separating the Randa orthogneiss from the metasedimentary series of the overturned limb.

The recumbent St-Niklaus syncline can be followed from the Mattertal to the Saastal where it splits into two branches, one of which extending east of the Saastal has already been described by Bearth (1963). The core of this syncline is composed from north to south in the Mattertal by tabular massive white quartzites grading to green quartzites (the Bruneggjoch Formation) with the Moosalp Formation around them, as represented in Figure 5.

Consequently, the base of the Siviez-Mischabel nappe displays a coherent overturned sequence. This interpretation is consistent with the generally accepted folded geometry of the Siviez-Mischabel nappe (Escher 1988; Escher et al. 1993) and other gneissic nappes in the Central Alps (e.g. Steck 1987), but it sharply contrasts with the assumption of imbricate thrusts in normal stratigraphic position recently proposed for this nappe (Markley et al. 1999).

9 Implications for nearby Nappes

This revised stratigraphy has critical consequences, apart from the Siviez-Mischabel nappe, for the tectonic setting of the Middle Penninic nappes of the region, and particularly on the nearby Upper Stalden zone and Lower Stalden zone (Fig. 2).

9.1 The Upper Stalden zone

The Upper Stalden zone was until now considered to be exclusively composed of polymetamorphic gneisses similar to the Ergischhorn or Berisal gneisses (Bearth 1963; Bearth 1972; Escher 1988), and to be tectonically separated by a thrust from the overlying St-Niklaus syncline. The new stratigraphy and symmetry of this syncline revealed by cartography speak for the stratigraphical superposition of Permo-Carboniferous formations on the polymetamorphic gneisses of the Upper Stalden zone (Fig. 6). It forms a well developed sequence in normal stratigraphic position. Consequently, the nomenclature of Bearth (1963) for this zone should be revised. We propose to consider the Upper Stalden zone as the normal limb of a nappe composed of gneisses and its associated metasedimentary cover.

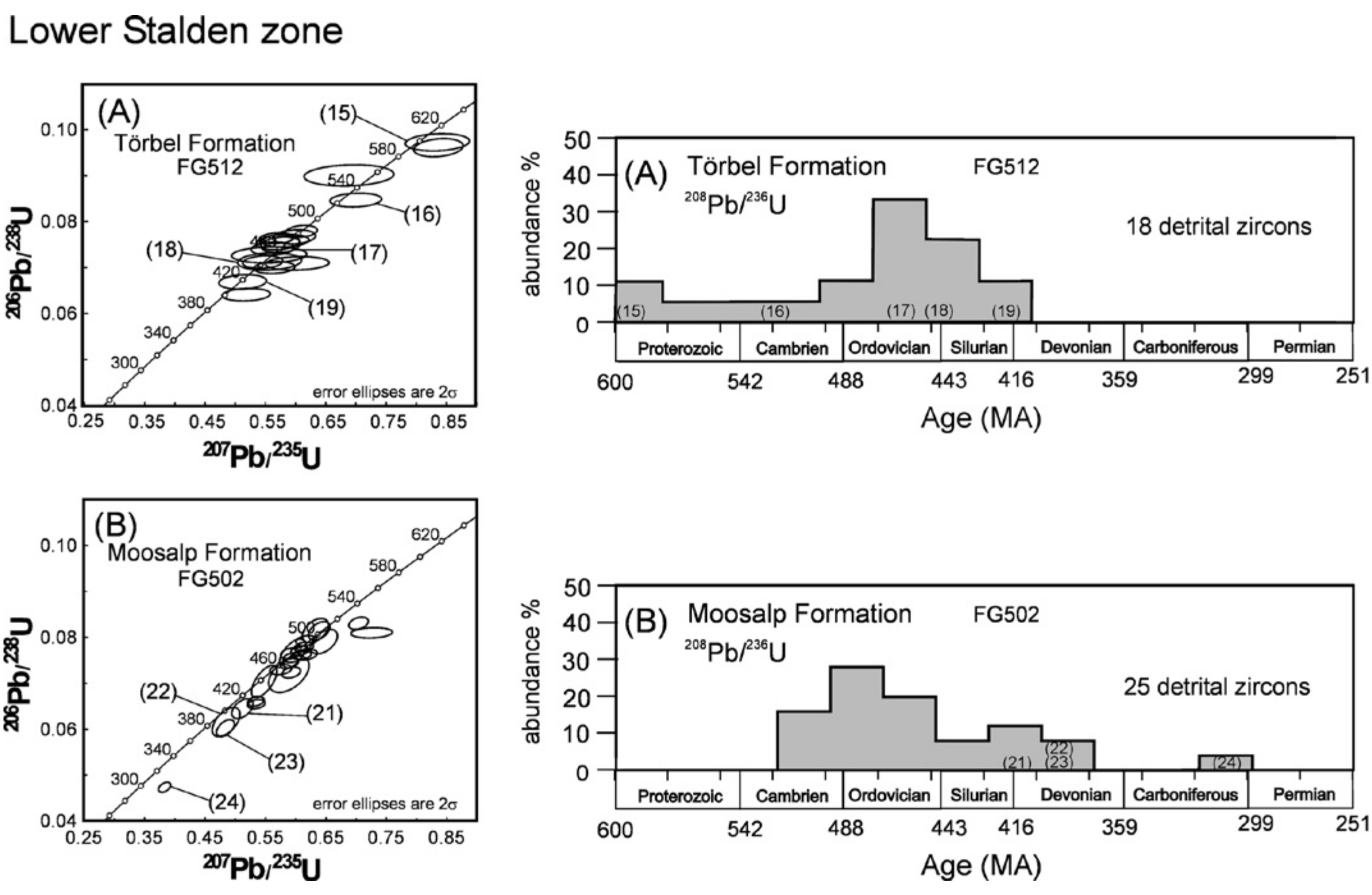


Fig. 12. Zircon analyses in the Lower Stalden zone. (A) histogram of zircon ages in the graphitic formation (Törbel Fm.), each class covers an interval of 25 Ma.; (B) histogram of zircon ages in the Moosalp Formation, each class covers an interval of 25 Ma. Data numbered after Table 3. The chronostratigraphic units are from Gradstein et al. (2004).

9.2 The Lower Stalden zone

The Lower Stalden zone is considered to be composed of Permo-Carboniferous and Permo-Triassic series (e.g. Escher 1988). This zone around the Stalden locality displays two superposed and distinct formations: (1) dark horizons rich in organic matter in a 50 m-thick grey quartzite (as already observed by Werenfels (1924) and Bearth (1978)); (2) a 100 m-thick green micaschist unit with Fe-carbonates (Bearth 1963). The formation rich in organic matter lies with a metre-thick gradational contact above the green micaschists. This lithostratigraphic succession is equivalent to what is observed at the base of the Siviez-Mischabel nappe, where the Törbel Formation is lying above the Moosalp Formation. According to the lithostratigraphy proposed for the base of the Siviez-Mischabel nappe, this Lower Stalden zone would consist of an overturned sequence of Permo-Carboniferous age. Zircons from these two formations have been dated to test this assumption.

Zircon analysis

Detrital zircons have been dated following the procedure presented in chapter 6.2. No Alpine metamorphic overgrowth has been observed. The results are presented in Table 3B and discussed below for each formation:

1) Most zircons from the grey quartzite horizon rich in organic matter (sample FG512) display concordant Ordovician ages (around 465 Ma, Fig. 12A). This point and the abundance of organic matter speak in favour of a Carboniferous age for this formation. However, and despite the small number of analysed zircons, the obtained zircon population seems to be different (many Ordovician zircons) from the population observed in the equivalent formation rich in kerogen of the St-Niklaus syncline. This result may indicate a geographical disconnection between two sedimentary sources during Carboniferous time and/or two disconnected sedimentary basins, or a preferential enrichment in Ordovician zircons of specific sedimentary layers.
2) Detrital zircons from a leucocratic and quartz-rich metagraywacke (FG502, location “7” on the Fig. 2) in the Moosalp Formation display a population consisting of idiomorphic pale pink grains about 100 μm long. Most identifiable grains correspond to P2-P3 type zircons (alkaline and peralkaline) according to Pupin (1980). Those zircons display ages from 514 ± 6 to 292 ± 9 Ma (Fig. 12B), so that this formation is Early Permian or younger.

Tectonic implications

Zircon analysis confirms the overturned sequence of Permo-Carboniferous age. This sequence occurs just below polymetamorphic gneisses of the Upper Stalden zone without obvious evidence of mylonitisaton at the contact. Consequently, the Lower Stalden zone could represent the overturned cover of the polymetamorphic gneisses from the Upper Stalden zone, forming a single nappe. However, more detailed field work all along this contact has to be done to confirm this assumption. In any case, the obtained ages and the tectonic position speak in favour of a possible correlation between the Lower Stalden zone and the Permo-Carboniferous series of the Houillère zone located to the west of this region (Fig. 1). This has already been proposed by Bearth (1972) and Thélin & Ayrton (1983).

10 Conclusions

The base of the Siviez-Mischabel nappe displays a coherent overturned sequence from the St-Niklaus area to the Moosalp pass to the north. The following formations are observed:

a) Fine-grained, greyish quartzite and greywacke with kerogen-rich horizons (Törbel Formation).
b) Green or white micaschists characterized by brown carbonate spots and associated with white conglomeratic quartzites (Moosalp Formation, Early Permian).
c) Massive, green or white, fine grained, microconglomeratic or conglomeratic quartzite with pink quartz pebbles (Bruneggjoch Formation, Late Permian-Early Triassic).

These formations compose the core of the St-Niklaus recumbent syncline, which is symmetrical and connects the polymetamorphic gneisses of the Siviez-Mischabel nappe to polymetamorphic gneisses of the Upper Stalden zone. This interpretation is concordant with the fold geometry of the Siviez-Mischabel nappe proposed by Escher (1988), as represented on Fig. 3. It contrasts with models of imbricate thrust sheets in normal stratigraphic position proposed by Markley et al. (1999). The precise description, definition and datation of Permo-Carboniferous formations, as well as their identification and mapping in the adjacent area and tectonic unit (Lower Stalden zone) can help to better understand the internal structure and tectonic relations of the Middle Penninic nappes east of the Mattertal.

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