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Ivan Mercolli, Giuseppe G. Biino & Jürgen Abrecht

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Geologic units of the Aar massif and their pre-Alpine rock associations: a critical review

by *Jürgen Abrecht*[1]

Abstract

While the evolution of the Mesozoic rocks belonging to the Helvetic realm in the Central Alps has been investigated in detail with respect to deposition, metamorphism, and deformation, much less is known about the pre-Mesozoic history of the basement rocks in the Helvetic domain. The present study is an attempt to summarize the petrography and geology of the pre-Variscan portions of the Aar massif. Often used subdivisions are critically discussed. The importance of considering the Variscan and Alpine retrograde alteration for any petro-tectonic subdivision of the Aar massif is demonstrated. The following main geologic units with similar lithologies and metamorphic evolution are distinguished: (1) The migmatitic *Innertkirchen-Lauterbrunnen Crystalline Zone* (ILC). (2) a zone comprising the *Erstfeld Gneiss Zone* (EGZ) with high-grade to anatectic metasedimentary rocks and minor orthogneisses, the *Guttannen Unit* (GU) consisting of a layered series of metasediments with strong retrogression, and the *Ofenhorn-Stampfhorn Unit* (OSU) with amphibolite-facies to anatectic metasediments and major mafic and ultramafic inclusions. (3) The Southern Gneiss Zone (SGZ) with high-grade to anatectic quartzofeldspatic and mafic rocks of igneous as well as of sedimentary origin. This subdivision is primarily based on the tectonic and metamorphic situation in the Western and Central Aar massif. However, lithologic units of the Eastern Aar massif can be attributed to the main units as outlined before.

Recent studies indicate a Caledonian age for the amphibolite-facies metamorphism and subsequent anatectic event in the *Innertkirchen-Lauterbrunnen Crystalline Zone* and the more internal units. No age data are available for the Southern Gneiss Zone but a similar metamorphic evolution is likely despite a probable different paleo-tectonic origin.

Keywords: orogeny, granite, metamorphic rocks, anatexis, Variscan basement, Aar massif, Central Alps.

Abbreviations

BaGr	Baltschieder granite
EGZ	Erstfeld Gneiss Zone
GaGr	Gastern granite
GrGr	Grimsel granodiorite
GU	Guttannen Unit
ILC	Innertkirchen-Lauterbrunnen Crystalline Zone
MiGr	Mittagfluh granite
OSU	Ofenhorn-Stampfhorn Unit
SGZ	Southern Gneiss Zone
ZAGr	(Central) Aar granite ("Zentraler Aaregranit")
Act	Actinolite
Ap	Apatite
Bio	Biotite
Calc	Calcite
Chl	Chlorite
Clz	Clinozoisite
Cpx	Clinopyroxene
Diops	Diopside
Ep	Epidote
Gt	Garnet
Hbl	Hornblende
Kf	Alkalifeldspar
Ky	Kyanite (Disthene)
Opa	Opaques
Ort	Orthite
Pin	Pinite
Plag	Plagioclase
Qtz	Quartz
Rut	Rutile
Ser	Sericite
Serp	Serpentine
Sill	Sillimanite
Stilp	Stilpnomelane
Tit	Titanite (Sphene)
Tourm	Tourmaline
Ves	Vesuvianite (Idocrase)
Woll	Wollastonite

[1] GEOTEST AG, Birkenstrasse 15, CH-3052 Zollikofen, Switzerland.

Introduction

The Aar-, Tavetsch- and Gotthard massifs represent the easternmost members of the external massifs and together with their Mesozoic and Tertiary cover they constitute the Helvetic realm of the central Swiss Alps. The Mesozoic cover on top of the crystalline basement has been mainly preserved in the North. In its more central and southern parts deeper and older portions of the pre-Mesozoic basement rocks are exposed. More than 25% of the Aar massif surface consist of Variscan intrusive rocks emplaced between the Lower and the Upper Carboniferous (SCHALTEGGER and CORFU, 1992). Small amounts of acid volcanic rocks related to the Carboniferous magmatism are found at numerous places in the Aar massif. Their importance for the interpretation of the crustal evolution during the Variscan has been demonstrated in some recent studies (SCHENKER, 1987; SCHENKER and ABRECHT, 1987; MERCOLLI and OBERHÄNSLI, 1988).

While the evolution of the Aar massif during the Variscan and the Alpine orogeny has been dealt with in many studies, in the present article only the pre-Variscan history, i.e. the Variscan basement is presented in some detail.

After the monographic descriptions of the Aar massif geology by VON FELLENBERG (1893), VON FELLENBERG et al. (1893), BALTZER (1888), SAUER (1900, 1905) and LOTZE (1914) in the 1920ies the Bernese professor HUGI initiated a more systematic treatment of the different Aar massif rock units. His and his student's petro-tectonic subdivision of the massif published in 1934 has been used by most later geologists to date. HUGI and his students clearly recognized the pre-intrusive age of the basement rocks but advocated a contact-metamorphic nature of most of the gneisses and schists associated with the Variscan intrusions. This view was only abandoned in the forties when HUGI's successor at the Bernese University, HUTTENLOCHER (1947), presented his study and new ideas on the origin of the high-grade basement rocks. HUGI's petro-tectonic map was partly revised by HÜGI (1956) and later by LABHART (1977). OBERHÄNSLI et al. (1988) reconsidered the role of the Upper Paleozoic sediments and volcanic rocks and pointed out their importance as time marker and their stratigraphic significance. More recently SCHALTEGGER (1992, 1993a, 1993b) made a number of important contributions with respect to the early history of the massif based on isotope age data.

This contribution is meant to cover the whole Aar massif. However, for historical reasons and because most recent studies bearing on the early evolution of the massif have been carried out in the western and central parts of the massif, these parts may have been treated unwillingly with more emphasis, last but not least due to the author's own experience and preference.

Geologic units of the Aar massif

Tectonic or geologic subdivisions of the Aar massif basement in the past were mainly based upon the central part of the massif due to its good exposures in a N–S cross-section along Grimselpass road (Figs 1 and 3). However, the subdivision defined along this section cannot be readily applied to the western and eastern parts because lithologic units and tectonic lines are not continuous from W to E and the Aar granite pluton truncates them in the internal parts of the massif. Moreover, many geologically important areas are covered by ice and snow or are situated in extreme Alpine areas and detailed informations are scarce or lacking. The main rock types constituting the geologic or tectonic units are summarized in tables 1–3. As shown on the geologic map (Fig. 1) the large Variscan intrusive body of the Aar granite forms the backbone of the massif. Both on its northern and its southern side of the intrusion we find the polymetamorphic rock series which form the pre-Variscan basement. Due to the sometimes cover-like position of these series with respect to the Aar granite, early workers interpreted them as the metamorphosed sedimentary cover of the granites. They were consequently summarized under the names "Nördliche Schieferhülle" and "Südliche Schieferhülle" (e.g. HUGI, 1922). These misleading names should be abandoned as they may suggest a contact-metamorphic overprint by the Variscan granites or even a post-granite tectonic emplacement of these rocks very much like the Mesozoic cover on top of the pre-Alpine basement. The name "Altkristallin" used by many workers comprises all pre-Variscan metamorphic rocks but should not be applied to the Variscan volcanics predating the intrusive rocks.

The basic lithostratigraphic subdivision of the Aar massif as proposed by BALTZER (1888), VON FELLENBERG (1893) and HEIM (1919) was mainly based on lithological and tectonic but hardly genetic considerations. Their subdivision was simplified by HUGI (1922) who introduced a genetic view and proposed two main units: the granitic intrusions and the country rock. We shall present a critical view of the subdivision widely accepted today and include petrological fieldwork and geochemical data gathered in the last 25

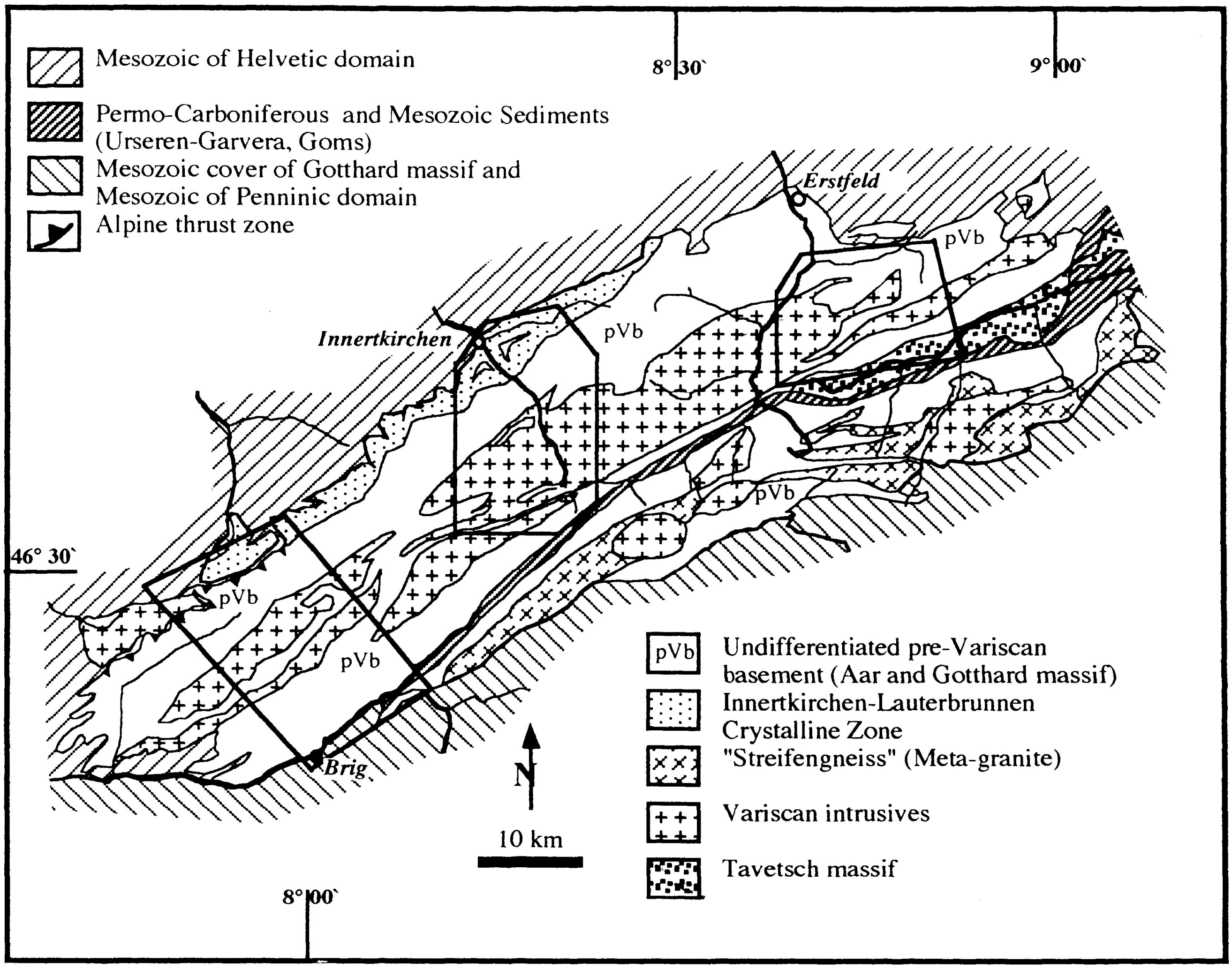


Fig. 1 Generalized map of the Aar and the Gotthard massif. Frames indicate areas covered by the maps (Figs 2, 3, and 4). Modified after von Raumer et al. (1993).

years. As becomes clear, the basic units of Baltzer (1888) and Hugi (1922) or Heim (1919) cannot simply be discarded because they have a sound basis in the extensive fieldwork done over more than forty years. Therefore, the present paper not only proposes a more recent view on the geology of the Aar massif, but also represents a recognition of the work of the early researchers of this massif.

Today's subdivision of the Aar massif is strongly in accordance with the scheme outlined some 70 years ago (e.g. Hugi, 1922) but far-reaching differences lie in the genetic interpretation of the units and their constituents. For example, Hugi's and his contemporaries' misinterpretation of the migmatitic gneisses as contact-metamorphic gneisses ("Injektionsgneise"). Moreover, the generally present foliation in the granitic gneisses was explained by magmatic rather than tectonic processes. Accordingly, the large masses of granitic gneisses extending from the Jungfrau area (640 200 / 154 400)[2] to the Maderanertal (698 000 / 180 000) were interpreted as granitic intrusions accompanied by their contact-metamorphic cover. Many arguments presented by former workers in favour of a magmatic origin of these gneisses today are easily accepted by modern geologists as clear indications of the sedimentary precursors of these rocks.

The lithostratigraphic units will be discussed from N to S and also with respect to their lateral changes from W to E. A comprehensive list of names for lithostratigraphic units of the Aar massif is given in von Raumer et al. (1993).

[2] Most geographic names used in the text could not be given on the geologic maps. In order to facilitate the reader to find the localities on topographic maps their Swiss coordinates are given in brackets. For the same reason the names are given in German as used in the "Schweizerische Landeskarte" 1:25 000 or 1:50 000.

Tab. 1 Main rock types and their mineral assemblages of the *Innertkirchen-Lauterbrunnen Crystalline Zone.*

Rock type	Assemblages	Remarks
Biotite gneisses	Plag, Qtz, Bio ± (Pin, Gt, Sill, Tourm, Calc, Tit, Or)	Always gneiss texture
Hornfelses	Plag, Qtz, Bio ± (Pin, Gt, Tourm, Calc, Tit, Opa)	Very fine-grained
Calc-silicate rocks	Diops, Ves, Gt, Calc ± (Qtz, Ap)	
Marbles	Calc, Diops, Ves, Gt ± (Woll, Qtz, Ap, Serp)	Serp pseudomorphs after olivine
Amphibolites	Hbl, Plag, Bio, Qtz, Ap, Zirc ± (Tit, Ep, Chl)	Hbl often replaced by biotite
Matrix (granitic gneiss)	Plag, Kf, Qtz, Pi (Cord), Bio, Ap, Zirc ± (Musc, Gt, Tourm, Calc, Tit, Opa)	Texture: magmatic to gneissic, migmatitic. "Pinite": pseudomorph after cordierite.

INNERTKIRCHEN-LAUTERBRUNNEN CRYSTALLINE ZONE (ILC)

The northernmost basement unit has been called Northern Gneiss Zone (SAUER, 1905), Innertkirchen granite (HEIM, 1919), Gastern-Innertkirchen granite Zone (HUGI, 934; HÜGI, 1956), Northern migmatites (RUTISHAUSER, 1973c), Northern Zone (including the Lauterbrunnen Crystalline; GULSON and RUTISHAUSER, 1976) or *Innertkirchen-Lauterbrunnen Crystalline Zone* (ABRECHT and SCHALTEGGER, 1988). We will apply the name *Innertkirchen-Lauterbrunnen Crystalline Zone* (= ILC) throughout this study. The strong similarities of the rocks exposed in the Innertkirchen area (660 000 / 173 000) with those from the Lauterbrunnental (633 000 / 149 000) have already been pointed out by HEIM (1919).

The ILC forms the northwesternmost tectonic unit of the massif and is only exposed in the central part of the massif (Figs 2 and 3). Along its northern boundary it is in mostly tectonic but locally in stratigraphic contact with the Permo-Carboniferous and Mesozoic sediments of the Helvetic domain (Fig. 8). At the Kanderfirn (Gasterntal; 625 000 / 146 000) it is intruded by the Variscan Gastern granite. However, it has recently been penetrated by a deep drill hole (619 050 / 144 950) in the frontal part of the Gasterntal seven kilometers west of the outcrops at the Kanderfirn.

The ILC consists of a migmatized series of metasediments (mainly sandstones to arkoses with intercalations of marls and limestones). The migmatitic aspect is often obscured by a strong deformation. Especially in the Grimsel section or along the Susten road (675 000 / 176 000) the rocks show an intense jointing with flat southward dipping cleavage planes which, according to LABHART (1966), are related to the Alpine upwelling of the massif. A differentiation into felsic lenses showing predominant brittle deformation and phyllitic shear zones is characteristic for this area. Often this deformation is related to Alpine thrust zones involving not only parts of the ILC but also the overthrusted Mesozoic cover sediments. KAMMER (1985, 1989), however, argued for a probable Variscan age of the schistosity planes in the ILC, due to their distinct and constant discordance with the axial schistosity planes of the basement-cover contacts.

Due to the often homogeneous igneous fabric of the migmatites, the ILC has been interpreted as a Lower Carboniferous intrusion (e.g. HUGI, 1922) with abundant sedimentary inclusions. However, RUTISHAUSER (1973b, 1974) demonstrated the sedimentary origin of the rock series which were strongly recrystallized by high-grade metamorphism and underwent partial melting. Sedimentary structures are preserved at some localities (Lauterbrunnen Valley, Kanderfirn) and described in detail by RUTISHAUSER (1973a, 1973b). He distinguished two main constituents of the complex: the granitic to granodioritic matrix and the inclusions of amphibolite, calc-silicate rocks, marble, hornfelses, and fine-grained biotite gneiss (see Tab. 1; Fig. 5). The inclusions represent disrupted sedimentary layers behaving as competent members during metamorphism and deformation while the matrix represents the incompetent part. He could even show that the variable matrix composition reflects the pre-anatectic sedimentary layering at a larger scale. The orientation of these matrix zones as well as of their foliation is parallel to the orientation and foliation of the inclusions generally occurring as boudins. Apart from the lithologies reported in table 1, ultramafic assemblages are occasionally found (e.g. hornblendite-pyroxenite along the eastern slope of the Glogghüs, 660 500 / 169 100; serpentinite in the Urbach Valley, 659 000 / 170 000).

In RUTISHAUSER (1973a) and RUTISHAUSER and HÜGI (1978) the ILC was considered as the product of an in-situ granitization by partial melting of a sedimentary rock series. In agreement with HÜGI (1956) they interpreted the contact between the Gastern granite (GaGr) and ILC as the intrusive contact. From detailed field studies along the contact between the ILC and the GaGr and geochemical arguments they concluded that the ILC represents an early stage of the formation of the Gastern granite from the same meta-sedimentary starting material, eventually intruding the country rock at a higher crustal level. This is supported by the almost identical Q-A-P and normative Q-Ab-Or values of the purported melt fraction of the ILC migmatites and the Gastern granite (RUTISHAUSER, 1978). For both RUTISHAUSER (1973b) and HÜGI (1956) the poly-metamorphic character of the country rock was beyond any doubt. RUTISHAUSER (1975) argued that, within a large crustal series increasingly metamorphosed from South to North, the ILC was the part with the highest degree of metamorphism and the GaGr represented the completely molten end product. SCHALTEGGER (1993a) determined a 303 ± 4 Ma age of this granite by U/Pb dating on zircons. Accepting RUTISHAUSER's reasoning, a Variscan age of the migmatization of the ILC has to be assumed. However, the polymetamorphic nature of the more southern gneisses is widely accepted due to structural (LABHART, 1965; STECK, 1966) and petrologic (SCHENKER and ABRECHT, 1987) reasons. And recently SCHALTEGGER (1992, 1993a) determined a Late Caledonian age (~ 445 Ma) of the migmatization by U–Pb analyses on zircons. Accordingly, a pre-Gastern granite age of the migmatization appears well established and is in accordance with an intrusive contact between the two units.

The basement rocks between ILC and the Aar granite intrusive body

Because the subdivision and definition of the basement between ILC and Aar granite has been a matter of debate for a long time and because of the variations both from N to S and W to E they are best treated together. For historical reasons the complete sequence will be divided into a Northern part (more or less coinciding with the so-called *Erstfeld Gneiss Zone* = EGZ) and a Southern part (more or less corresponding to the so-called Lötschen-Färnigen Zone or "Nördliche Schieferhülle"). The two parts have either been treated as two different tectono-stratigraphic units (e.g. HUGI, 1934) or simply combined as "Altkristallin" (LABHART, 1977). The difficulty of defining a boundary between the two zones based on petrographic differences has been realized for a long time (MORGENTHALER, 1921) and the wedge of Carboniferous to Mesozoic sediments ("Färniger Keil") was assumed to represent the tectonic contact.

Despite the often distinct petrographic differences between the rocks on either side of the fault zone later defined as an Alpine mylonite by KAMMER (1985) a clear boundary line is hardly justified since many lithologic differences are rather due to deformation and retrogression than of primary origin. This is especially the case where the dividing Carboniferous and Mesozoic sediments are missing. HÜGI (1955) pointed out the similarity of the two zones and suggested their combination under the name "Northern schist zone" or "Altkristallin". In the following section the lithologies observed from North to South will be described in more detail.

The relationship between the EGZ and the adjoining ILC has long been a matter of debate (Fig. 3). Their mutual contacts coincide with a mylonitic shear zone of Late Variscan age involving Carboniferous sediments (KAMMER, 1985). LABHART (1977) reports the occurrence of a large inclusion of EGZ-type rocks within the ILC and BURKHARD (1981), based on studies in the Grassen area (679 000 / 182 000), assumes an anatectic formation of the granitic ILC from rocks of the EGZ. SCHALTEGGER (1993a), based on lithologic and structural criteria and similar amphibolite-facies metamorphic overprint, concluded that the EGZ represents the protolith for the ILC.

NORTHERN PART: ERSTFELD GNEISS ZONE ("NORTHERN GNEISSES", SERICITE SCHISTS)

The rocks adjoining the ILC immediately to the S were for a long time taken as a Lower Carboniferous intrusive granite related to the Aar granite intrusion (HUGI, 1922a) although the dominantly sedimentary character of the zone (Erstfeld Gneiss zone = EGZ) was already recognized by SAUER (1905) and LOTZE (1914). Later also HUGI (1934), being aware of the variable character of this zone, assumed a sedimentary origin of at least some of the "Erstfeld gneisses". HUTTENLOCHER (1947) no longer assumed an intrusive origin of

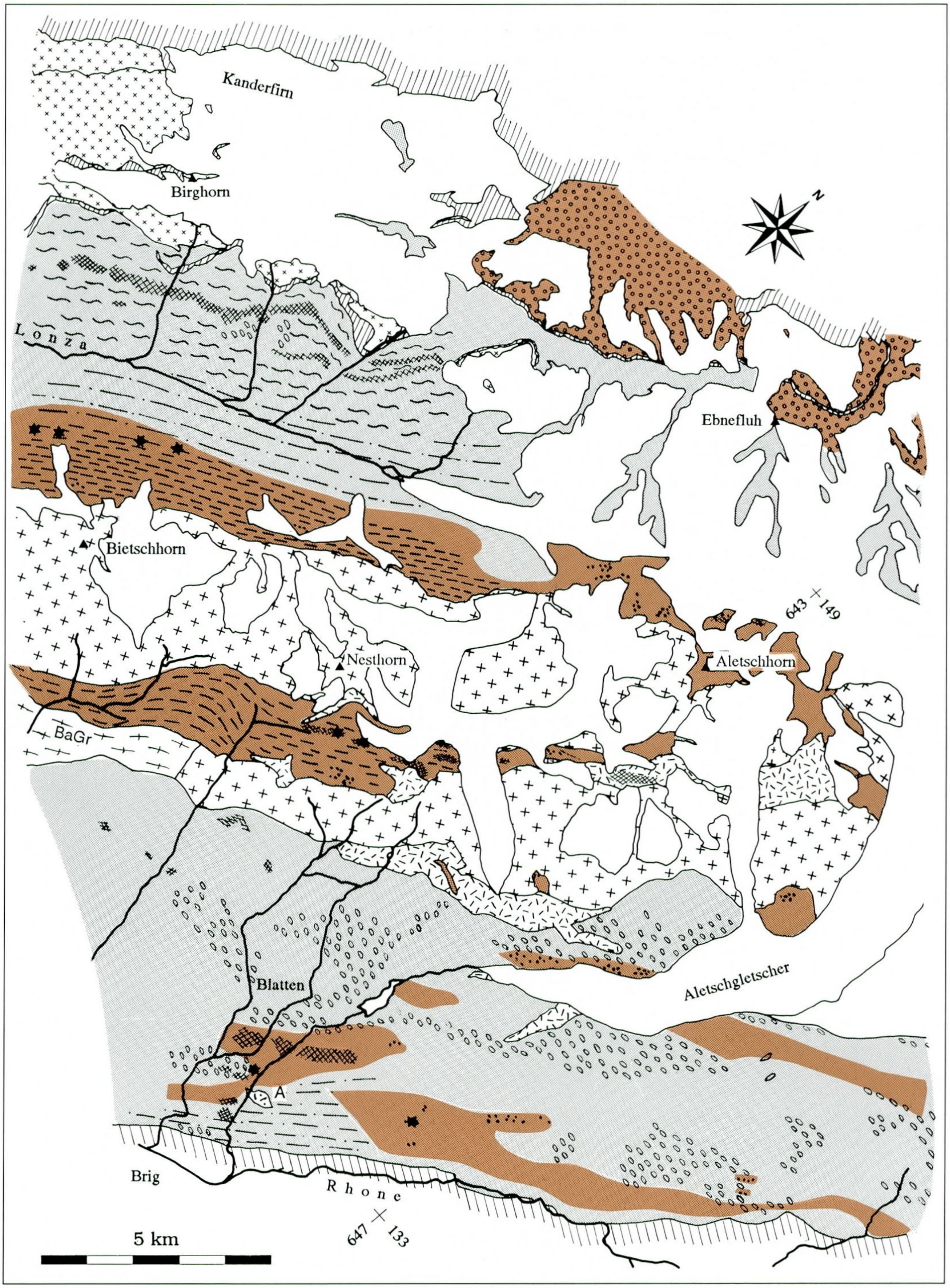


Fig. 2 Interpretative petrotectonic map of the Western Aar massif between Gasterntal and Rhone River (caption, comments and sources see p. 12).

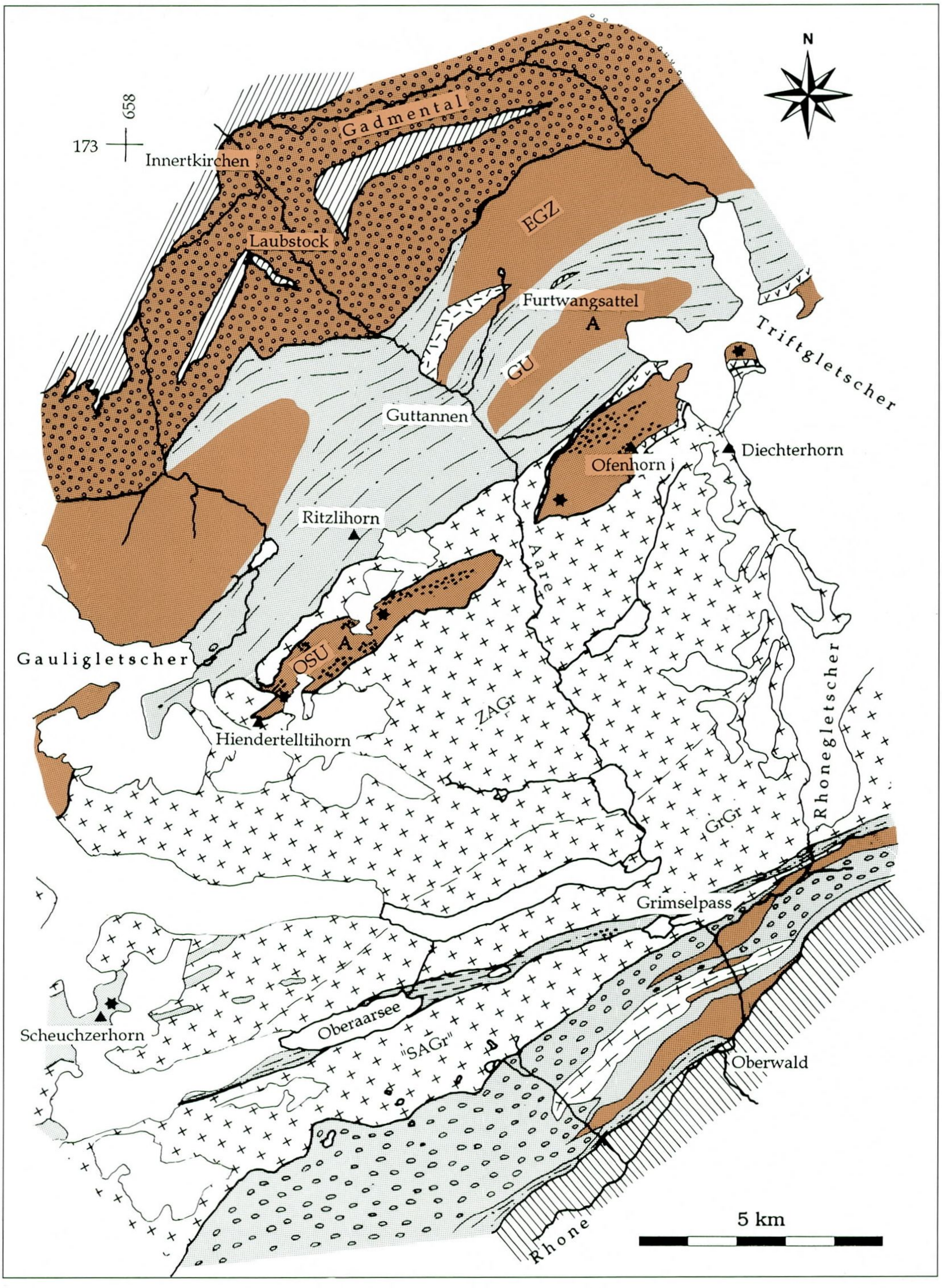


Fig. 3 Interpretative petrotectonic map of the Central Aar massif between innertkirchen and Oberwald (captions, comments and sources see p. 12).

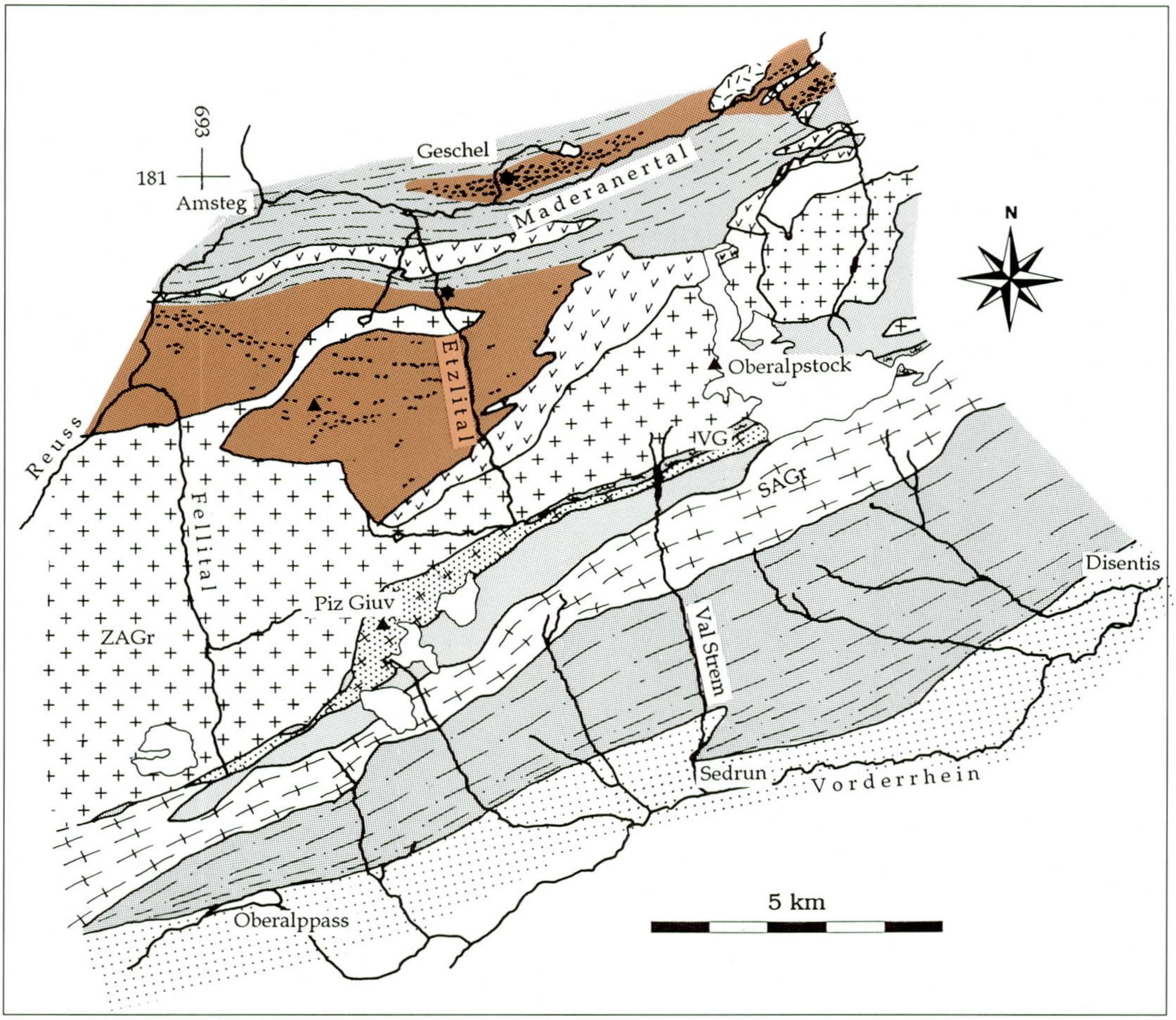


Fig. 4 Interpretative petrotectonic map of the Eastern Aar massif between Maderanertal and Tavetsch (captions, comments and sources see below).

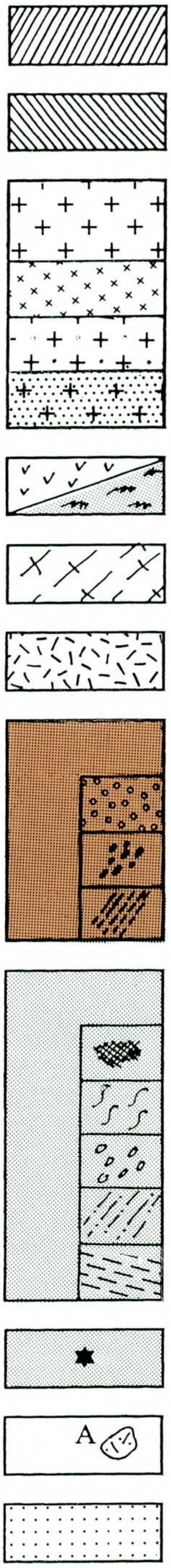
Text to maps in figures 2, 3, and 4:

The maps were compiled using published and unpublished maps from the sources given below and own data. Areas with similar lithologies and metamorphic grade were combined in larger units. Such areas are taken as representing the same tectonic unit consisting of thick sedimentary series before being separated along Variscan and/or Alpine mylonites. By definition they are supposed to have undergone a similar metamorphic evolution before the intrusion of the Variscan granites. All areas consisting of rocks formed before the emplacement of the Variscan volcano-sedimentary series are given in light grey (= Variscan basement). Areas within this basement which predominantly consist of anatectic rocks (metatectic to diatectic migmatites) are given in colour.

Sources:

ABRECHT (unpublished data), BÖHM (1988), COLLET and PARÉJAS (1931), DOLIVO (1982), DOLLINGER (1990), EUGSTER (1951), GNOS (1988), HUBER (1922a), HUBER (1948), HUGI (1934), HUTTENLOCHER (1933), JENNY (1973), LABHART (1965), LABHART (1977), NIEDERER (1932), NIGGLI (1944), NIGGLI (1965), OSCHIDARI (1986), PFLUGSHAUPT (1927), RIESEN (1991), SCHINDLER (1972), SIGRIST (1947), STALDER (1964), STECK (1966), STECK (1984), SWIDERSKI (1919), VÖGELI (1988), WYSS (1932), ZBINDEN (1949).

Legend to "Interpretative petrotectonic maps"



Mesozoic cover sediments:Autochthonous and parautochthonous units of the Helvetic realm

Permo-Carboniferous sediments (South of Aar massif)

Upper Carboniferous intrusives:
Central Aar Granite (ZAGr), Mittagfluh Granite (MiGr),
Grimsel Granodiorite (GrGr)
Gastern Granite (GaGr)

Diorites (Düssistock D., Fruttstock D.)

Giuv Syenite

Carboniferous volcanics and volcanoclastic sediments
VG: Val Gliems Formation

Lower Carboniferous intrusives:
Baltschieder Granite (BaGr), Southern Aar Granite (E Aar massif, SAGr)

Pre-Variscan granitoid intrusives: Granitic to tonalitic gneisses with intrusive contacts, homogeneous augengneisses, muscovite-gneisses

Migmatitic rocks: Granitic to tonalitic gneisses (metatexites to diatexites):
Cordierite-bearing migmatites of the ILC

Rich in amphibolitic inclusions ("Schollen amphibolites"), often in leucocratic matrix
With frequent amphibolite layers
(transitions to "Schollen amphibolites")

Pre-Variscan gneisses in general: (layered) Biotite-plagioclase gneisses, biotite gneisses, with amphibolite and calc-silicate lenses
Banded amphibolites, meta-gabbros

Muscovite-(Chl-Bio-Ser) gneisses.

Heterogeneous augengneisses, metasedimentary and metagranitic rocks, sometimes intrusive
Strongly retrograded gneisses: Biotite-sericite gneisses and -schists, biotite-chlorite gneisses and - schists, chlorite schists and-gneisses.
With interlayered Variscan volcanics and volcaniclastic sediments
("Gneis-Schiefer-Zwischenzone" between Grimselpass and Oberaar)

Ultramafic inclusions

Pre-Variscan granitic to aplitic stocks within migmatitic gneisses

Tavetsch massif, undifferentiated

Tab. 2 Lithologies and mineral assemblages of the Erstfeld Gneiss Zone.

Rock type	Susten area, Erstfeld	Oberhasli, Gauli area
Layered biotite-plagioclase gneisses	*"Primary" assemblages:* Plag, Qtz, Kf, Bio ± (Sill, Ky) *Retrograde assemblages:* Qtz, Chl, Ser, Plag, "Pinite" ± (Calc, Clz, Tit, Rut, Stilp)	*"Primary" assemblages:* Plag, Qtz, Kf, Bio ± Gt *Retrograde assemblages:* Qtz, Chl, Ser, Plag, "Pinite" ± (Calc, Clz, Tit, Rut, Stilp) Pseudomorphs after sillimanite
Biotite-plagioclase gneisses	Plag, Qtz, Bio ± (Kf, Gt, Tourm, Sill, Hbl, Tit)	Plag, Qtz, Bio ± (Kf, Gt, Tourm, Sill, Hbl, Tit, Stilp)
Calc-silicate rocks and marbles	*"Primary" assemblages:* Calc, Qtz, Diops, Ves, Gt, Woll, Ep, Plag (Opa, Ap) *Retrograde assemblages:* Pre, Clz, Ser, Tc, Tr, Ab, Calc, Qtz	*"Primary" assemblages:* Calc, Qtz, Diops, Ves, Gt, Woll, Ep, Plag (Opa, Ap)
Ultramafics	Chrys, Liz, Chl, Op With black walls against surrounding amphibolites (Anth, Cr-Tr, Tc)	
Amphibolites	*"Primary" assemblages:* (1) Hbl, Act, Plag (felses) (2) Gt-Amphibolites: Hbl, Gt, Cpx, Plag, Rutile, Clz	Strongly retrograded (Hbl often replaced by Bio and Chl; Gt replaced by Bio, Plag, Clz, Opa)
Metagranite		*"Primary" assemblages:* Plag, Kf, Qtz, Bio ± (Ap, Sphe) *Retrograde assemblages:* Chl, Serp, Stilp, Clz, Tit

the gneiss, but rather considered the gneisses to be metasediments which were strongly transformed and "differentiated" by partial melting. The sedimentary character of most of the lithologies is indicated by the presence of large marble or calc-silicate lenses.

The dominant rock type of this zone ("Erstfeld gneiss" s.str.) is a rather inhomogeneous, often intensely layered gneiss with a granodioritic modal composition. More pelitic members are characterized by the presence of sillimanite (Tab. 2). Often the gneiss shows microfolds, concordant or slightly discordant leucocratic veins or layers which are rimmed by biotite-rich selvages. At the type locality near Erstfeld (695 000 / 185 000) the gneiss has a distinct anatectic appearance (Fig. 9). Rocks with a gneissic texture pass into diatexites within short distance. Aplitic melts with idiomorphic garnet are quite common. Fibrolitic sillimanite, probably formed at the expense of biotite, is usually present and cordierite is preserved as pseudomorph in discordant leucosomes. Prismatic sillimanite rimmed by muscovite and kyanite are occasionally included in plagioclase or alkali feldspar. Here close to their eastern end the EGZ-gneisses are overlain by parautochthonous sediments lying conformably on the gneiss surface eroded during the Permian. The primary sedimentary contact is seen at several localities (e.g. at the famous "Scheidnössli" locality, 692 300 / 187 700).

Fig. 5 Anatectic migmatite of the *Innertkirchen-Lauterbrunnen Crystalline Zone* (Tschingelgletscher, Lauterbrunnental). Partly mobilized banded gneiss in granodioritic matrix. Photograph by R. Rutishauser.

SCHALTEGGER (1984) described the migmatitic character of these rocks in the Susten area (677 300 / 177 300; stromatitic migmatite), but they are also widespread in the Gauli area (659 000 / 164 000) and especially in the Erstfeld

Tab. 3 Comparison of the subdivisions of the central Aar massif (Grimsel road section) and eastern Aar massif (Reusstal section). Names used by the authors are given in brackets.

Reusstal (PFLUGSHAUPT, 1927; SIGRIST, 1947):	Grimsel road (ABRECHT and SCHALTEGGER, 1988):
(Contact zone of the Erstfeldgneis)	Metasedimentary rocks of the EGZ
Sericite gneiss and schists	Greenschist rocks of the GU
Metavolcanic rocks (pyroclastics) (Quartz porphyries and tuffaceous rocks)	Metasedimentary and pyroclastic rocks (SCHENKER, 1986)
Sericite gneiss and schists	Greenschist rocks of the GU
Amphibolites and migmatitic gneisses (Contact zone of the Aar granite)	High-grade gneisses of the OSU (see text)
Pyroclastic rocks (Quartz porphyries)	Metasedimentary and pyroclastic rocks (SCHENKER, 1986)
Aar granite	Aar granite

area. This author pointed out their strong Variscan and Alpine retrogression and deformation which produced grey to greenish chlorite-sericite schists or gneisses (Tab. 2).

A sequence of metasedimentary rocks from the Susten area with gneisses, calc-silicate rocks, marbles, and interlayered banded amphibolites, gabbroic amphibolites, garnet amphibolites, and

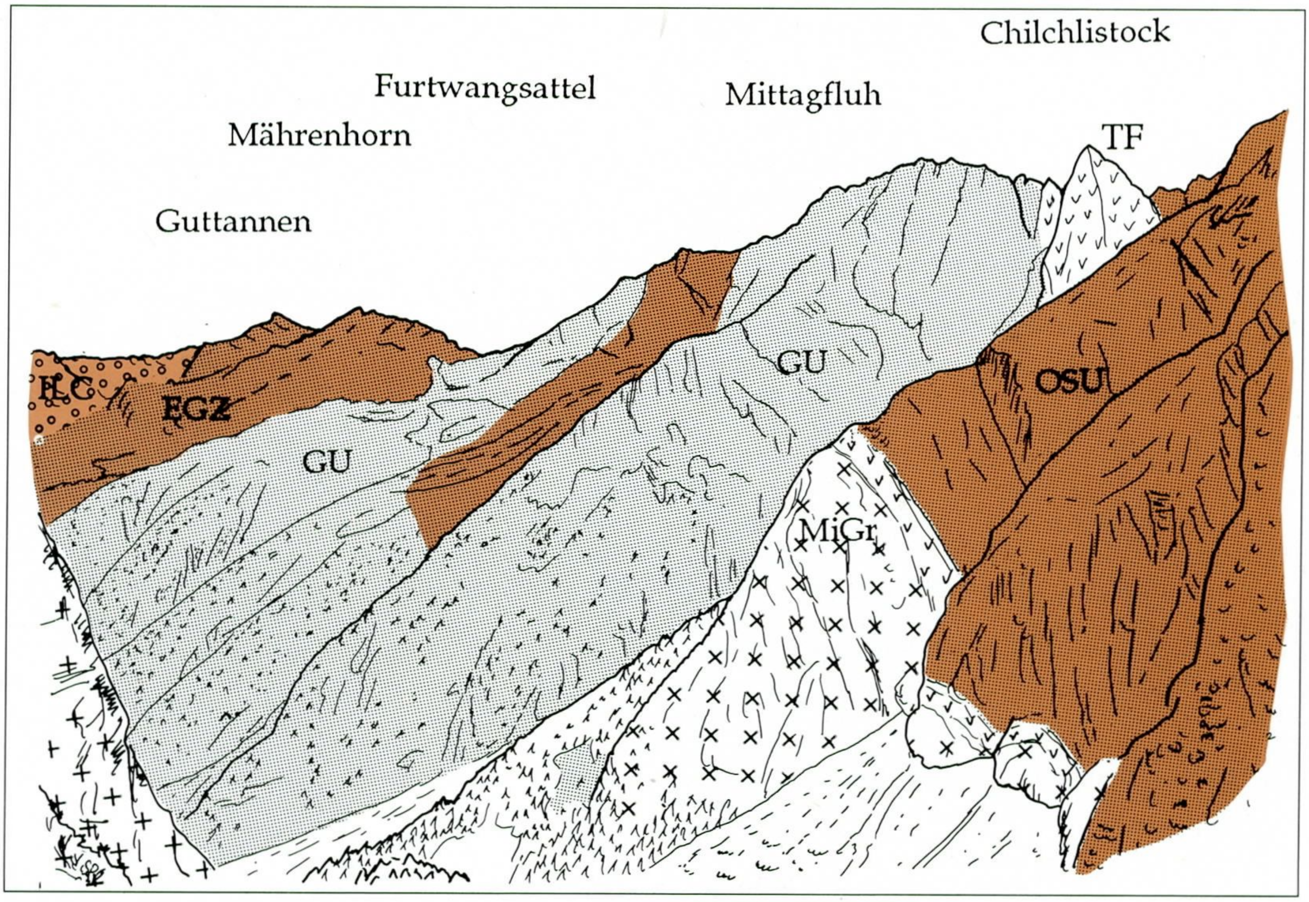


Fig. 6 View of the eastern slope of the Oberhasli Valley near Guttannen seen from the Grubengletscher. Geologic units from N (left) to S (right): *Innertkirchen-Lauterbrunnen Crystalline Zone* (ILC), *Erstfeld Gneiss Zone* (EGZ), *Guttannen Unit* (GU), volcanic rocks of Trift Formation (TF), Mittagfluh Granit (MiGr), *Ofenhorn-Stampfhorn Unit* (OSU).

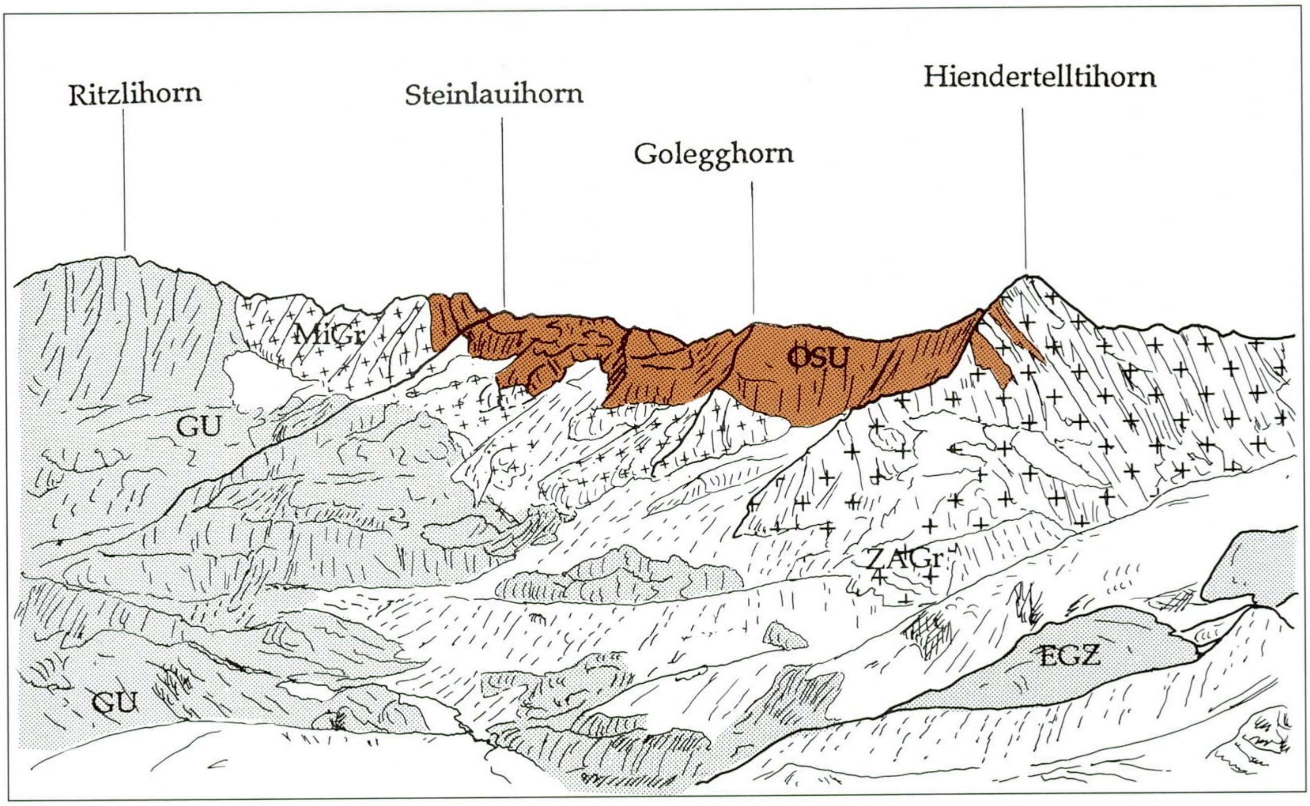


Fig. 7 View of the range between Hiendertelltihorn and Ritzlihorn seen from West (Gaulihütte). Geologic units from N (left) to S (right): *Guttannen Unit* (GU), Mittagfluh Granit (MiGr), *Ofenhorn-Stampfhorn Unit* (OSU), Central Aar granite (ZaGr).

related ultramafics was already described by LOTZE (1914) and more recently by SCHALTEGGER (1984). These rocks (*Silberberg series*) show a pre-Alpine deformation style and well-preserved high-grade metamorphic assemblages (Tab. 2). They were interpreted by SCHALTEGGER (1984) as the psammitic to conglomeratic members of a sedimentary-volcanoclastic rock pile. The possible origin of the amphibolite-ultramafic-sediment sequence as an ophiolitic olistostrome in a flyschoid environment has been pointed out by ABRECHT et al. (1991).

In the Oberhasli Valley the gneisses have a characteristic migmatitic appearance with transitions from metatectic banded structures to rather homogeneous diatexites (e.g. Wannisbordsee, 666 000 / 170 500). Approaching the Alpine mylonite zone that forms the cleft of the Furtwangsattel (667 200 / 170 200) the deformation is increasing and biotite-sericite schists, biotite-chlorite gneisses, and chlorite gneisses with retrograde greenschist facies assemblages predominate (Figs 5 and 6). The strong deformation and retrogression of rocks on either side of the mylonite zone often prevent their unequivocal distinction. Occasionally micaceous pseudomorphs after sillimanite and cordierite are observed in the metasedimentary rocks.

The western end of the EGZ in the Fiescherhorn-Trugberg-Mönch area (644 000 / 155 000) needs still to be defined. The rocks that build up the top of the Mönch and the Jungfrau were either attributed to the "Nördliche Schieferhülle", to the EGZ or to the ILC (summarized in RUTISHAUSER, 1975). RUTISHAUSER concludes that both peaks belong to the ILC. In a sketch map published by RUTISHAUSER and HÜGI (1978) the contact is situated between Rottalhorn (640 500 / 155 500) and Gletscherhorn. With the present knowledge the western boundary of the EGZ-type gneisses cannot be defined definitely, however, an extension to the West of the Kranzberg (642 000 / 152 000) seems unlikely (Fig. 2).

While the majority of the rocks of the EGZ is of sedimentary origin, some gneisses may be of magmatic origin. An orthogneiss has been reported by HUBER (1922). It extends from the bottom of the Haslital (900 m) up to Holzhüs (664 500 / 169 500; 1900 m). This metagranite is distinguished from the surrounding biotite-plagioclase gneisses by its distinct augen gneiss texture and its granitic composition. No intrusive contacts with the surrounding metasediments have been observed so far.

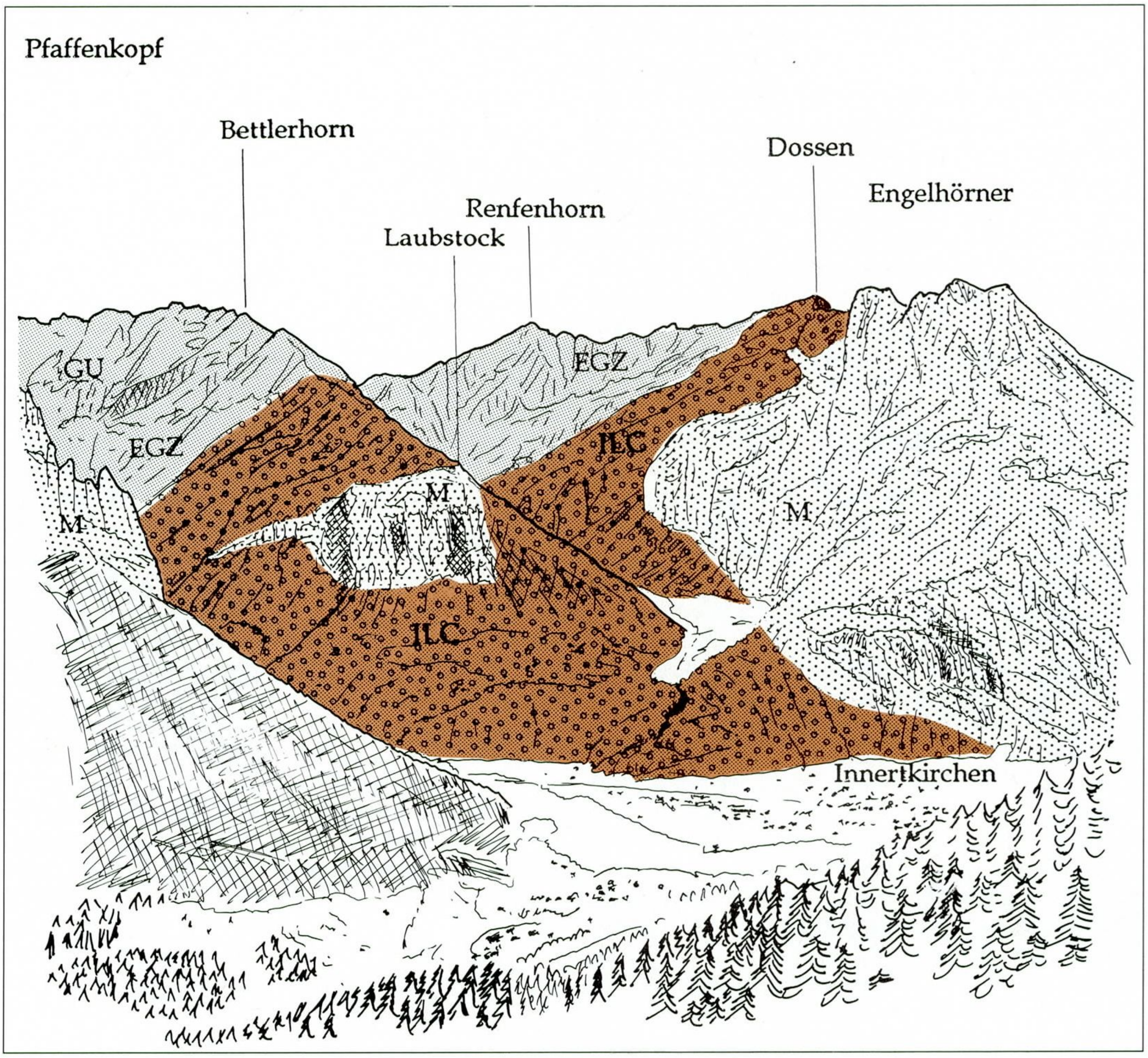


Fig. 8 View from northeast of the Urbachtal with Mesozoic wedges (M) of the Laubstock (center) and Pfaffenkopf (left). Autochthonous Mesozoic sequence of the Engelhörner is followed by the *Innertkirchen-Lauterbrunnen Crystalline Zone* (ILC), *Erstfeld Gneiss Zone* (EGZ) and *Guttannen Unit* (GU).

In the Susten area the deformation is characterized by isoclinal folds and the later "Schlingentektonik". SCHALTEGGER (1984) proposes the following pre-Alpine tectonic evolution:

1. Planar texture with flat lying fold axes in ultramafic and mafic rocks (s1).

2. Isoclinal folding of gneisses (s2). Formation of the layering and the dominant schistosity parallel to the compositional banding.

3. Refolding of (s2) by folds with steep NE-plunging fold axes. Formation of a crenulation cleavage in incompetent lithologies.

Deformation at stages 2 and 3 occurred at amphibolite facies conditions.

SOUTHERN PART: SERICITE-CHLORITE SCHISTS, GUTTANNEN UNIT, MIGMATITES, "SCHOLLEN AMPHIBOLITES", OFENHORN-STAMPFHORN UNIT

Many workers have described the gradual transition between EGZ gneisses and the more southern gneisses which were summarized as "Zone of the sericitic phyllites and gneisses" (Zone der Sericitschiefer und Sericitgneisse) by BALTZER (1888). In the eastern and more central parts of the massif this zone in fact consists of a variety of rocks which are characterized by their intense deformation and their greenschist facies mineral assemblages. LOTZE (1914) emphasized the interlayering of metamorphosed igneous, sedimentary and volcanic rocks in the Reuss Valley between Erstfeld and Gurtnellen (692 000/178 000). Along this section and in the Maderanertal PFLUGSHAUPT (1927) and SIGRIST (1947) recognized an increase in metamorphic grade from N to S and attributed it to the contact metamorphic effect of the Aar granite intrusion (Tab. 3; Fig. 4). The same sequence of low-grade rocks with quartz-muscovite (sericite)-chlorite-epidote-titanite assemblages and high-grade rocks with plagioclase-quartz (± alkali feldspar)-biotite-garnet assemblages occurs between Urweid (662 000 /170 000) and Guttannen along the Grimsel road section and also in the Gauli area. Occasionally gneisses with sericite pseudomorphs after fibrolitic sillimanite are observed within bio-plag-gneisses of the *Guttannen Unit* (GU). This zone was defined by ABRECHT and SCHALTEGGER (1988) in the Oberhasli Valley as a gneiss intermediate between EGZ-type gneisses and the amphibolite-rich banded gneisses dominated by migmatitic textures summarized as *Ofenhorn-Stampfhorn Unit* which is described at the end of this chapter.

East of the Oberalpstock (702 200 / 178 000) EUGSTER (1951) described an eastern continuation of the low-grade rocks into the Val Russein area (711 000 / 178 000) where a heterogeneous series of metasedimentary biotite-plagioclase gneisses with subordinate alkali feldspar ("Südliche Mischgesteinsserie") has been retrogressed to greenschist facies assemblages (quartz-sericite-chlorite) comparable to the rocks of the *Guttannen Unit*. To the North they are followed by a metagranite ("Nördlicher Granitgneis") related on chemical grounds by EUGSTER to the granitoid rocks of the *Innertkirchen-Lauterbrunnen Crystalline Zone*. However, the cordierite pseudomorphs typical for the ILC are missing and no spatial relationships between the two units can be constructed. This pre-Aar granite intrusion is flanked on its northern side by migmatitic banded gneisses with abundant gneissic and amphibolitic inclusions. Disregarding the orthogneiss ("Nördlicher Granitgneis"), the sequence from low-grade rocks in the North to high-grade rocks in the South as observed in the Lötschental (628 000 / 140 000), the Grimsel section, and the Maderanertal seems to be reversed in the Val Russein.

However, we believe that most of these low-grade assemblages are of retrograde origin as textures strongly indicate pseudomorphic replacement of high-T phases by low-grade assemblages. Based on such secondary alterations BALTZER (1888) clearly distinguished this zone from the "Northern gneisses" including the ILC and parts of the EGZ. Most prominent retrograde reactions include the pseudomorphic replacement of biotite by muscovite (especially in the EGZ) and chlorite. Sericite is widely formed at the expense of plagioclase and alkali feldspar and concentrated along shear zones. In strongly deformed gneisses plagioclase and biotite indeed may be totally replaced by sericite and muscovite giving the rock a phyllitic appearance. In fact some of these rocks were later interpreted as a mylonite separating the EGZ from the more southern GU ("Grenzmylonit" of KAMMER, 1985). At the Furtwangsattel the deformation involves Triassic sediments (dolomite and quartzite). This mylonite zone can be followed to the W as well as to the E where it also involves Upper Carboniferous volcano-sedimentary series and Mesozoic sediments. However, in the E (Maderanertal) this tectonic line does not coincide with the southern boundary of EGZ-type gneisses, but rather cuts it discordantly within rock series more typical for the GU or even the more southern *Ofenhorn-Stampfhorn Unit* (OSU) of the central part of the massif (see below).

Between the Gauli area (Fig. 7) and the Trift area (670 000 / 170 000) isoclinally folded bio-plag-gneisses and schists with a primary sedimentary bedding generally display retrograde greenschist facies assemblages. Within short distance they pass into layered high-grade gneisses with incipient melting and even gneisses with distinct migmatite textures. Calc-silicate lenses may be abundant in some areas (Guttannen, Gauli).

HÜGI et al. (1988) give a detailed account of the lithologies in the Lötschental area. Unlike in the Guttannen area, here leucocratic gneisses with muscovite as a major mineral are abundant. But to the south a sequence consisting of chlorite schists, biotite gneisses, and migmatitic gneisses resemble the lithologic composition of the GU as defined in the Guttannen area. Therefore the conspicuous succession of rocks exhibiting greenschist facies assemblages (N) with amphibolite facies assemblages or even anatectic gneisses (S) seems to be a large scale phenomenon observed in the Lötschental as well as in the Oberhasli and the Maderanertal (Tab. 3; see section on Metamorphism). Lenses of amphibolites and small bodies of serpentinized ultramafic rocks, chiefly in the Lötschental and in the Maderanertal, are quite widespread. Small boudins of calc-silicate rocks are frequently found in the Lötschental and near Guttannen but seem to be rare in the eastern Aar massif.

The *Ofenhorn-Stampfhorn Unit* (OSU) was defined by ABRECHT and SCHALTEGGER (1988) as a

Fig. 9 Anatectic migmatite of the *Erstfeld Gneiss Zone*. Partly mobilized banded gneiss in granodioritic to granitic matrix (Öfital, Reuss Valley).

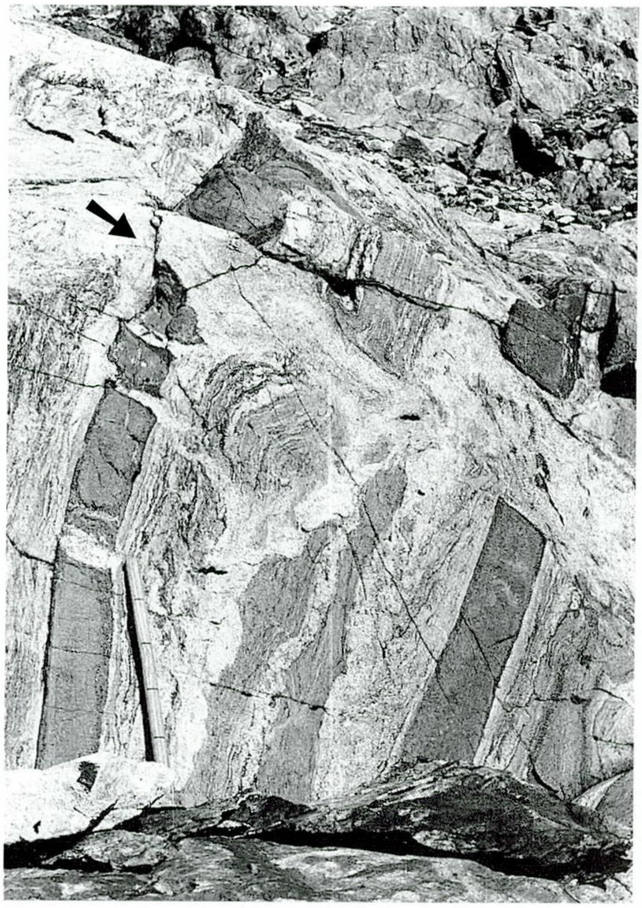


Fig. 10 Anatectic melting in banded gneisses of the *Ofenhorn-Stampfhorn Unit*. Note the amphibolite boudins (dark) with biotitized hornblendes along the rims. Melting is favoured along a shear zone (arrow). Gneiss displays different stages of dissolution. Grubengletscher (Oberhasli Valley).

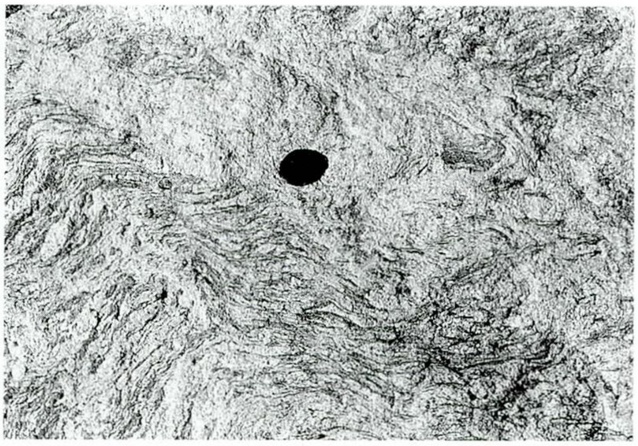


Fig. 11 Anatectic melting in biotite-plagioclase gneiss of the *Ofenhorn-Stampfhorn Unit*. Banded texture of the gneiss is still recognizable by relic biotite (dark). Melting is favoured in shear zones and fold hinges. Grubengletscher (Oberhasli Valley).

Fig. 12 Anatectic migmatite of the Southern Gneiss Zone (SGZ). Inclusions of amphibolites (dark) and gneisses in different stages of dissolution. Burg below Fieschergletscher.

variable series of high-grade to anatectic bio-plag gneisses with abundant mafic and occasional ultramafic inclusions (agmatites, "schollen amphibolites"; ABRECHT, 1980; Figs 10 and 11). Typically, the alkali feldspar content of these gneisses is very low. In many respects they resemble the migmatitic banded gneisses of the EGZ. To the West of the Grimsel section the zone is increasingly dominated by amphibolites which is up to 1500 m thick at the Finsteraarhorn (652 700 / 154 200) between the Grünhornlücke (649 500 / 151 500) and the Scheuchzerjoch (658 500/155 000; WYSS, 1932). Of interest are large inclusions of OSU-type gneisses of up to 200 m length found within the Aar granite in the Lauteraar and in the Oberaar area (660 000 / 154 000).

In the western Aar massif the OSU is probably represented by the layered series between the Sattelhorn and the lower Lötschen Valley where it disappears under the Mesozoic parautochthonous cover (HÜGI et al., 1988).

To the East the zone extends to the Sustenhorn (677 700/172 500) and then seems to fade out at the Stucklistock (680 200 / 174 500; LABHART, personal comm.). Amphibolites displaying the characteristic agmatite structures reappear in the Maderanertal ("Geschel" area, 699 000 / 181 000, and Brunnital, 704 500 / 180 000) where they contain occasional ultramafic lenses (PFLUGSHAUPT, 1927; SIGRIST, 1947). Typical agmatitic amphibolites ("Schollen amphibolites") then again occur along the contact with the Mesozoic at the Heimstock (709 200 / 184 900) at the northwestern end of the Aar massif (EUGSTER, 1951).

A thin basement zone consisting of metasediments, migmatitic gneisses, amphibolites associated with Variscan metavolcanics extends from the Rhone glacier over the Grimselpass to the Oberaarjoch (Gneis-Schiefer-Zwischenzone = GSZ, STALDER, 1964; DOLLINGER, 1990). This zone separates the Variscan Grimsel granodiorite (GrGr) from a granite body probably related to the Central Aar granite (Fig. 3).

Basement rocks south of the Aar granite body

The Aar granite body divides the basement into a northern and a southern part. Only in the Aletschhorn area (642 500 / 146 300) basement rocks bridge over the granite and connect northern and southern half (VON FELLENBERG, 1893; ROSIER, 1931; Fig. 2). Thus, the old subdivision into a northern and a southern "Schieferhülle" or into northern and southern "Gneiss zone", respectively, is an artifical one, based only onto the later intrusion of the Variscan granite. Indeed, many rock units on the southern side can easily be related to the northern units as described before. However, there are some differences that justify the definition of a "Southern Gneiss zone" (Südliche Gneiszone = SGZ) as suggested by earlier workers (e.g. HEIM, 1919; HUGI, 1934). The major difference between northern and southern rocks lies in the higher proportion of metamorphic rocks of magmatic origin in the SGZ. These orthogneisses form the mainly coarse-grained augengneisses which are widespread between the western end of the massif and Gletsch (671 000 / 157 000). The rocks of the SGZ have been studied in detail by (from West to East) SWIDERSKI (1919), HUTTENLOCHER (1921a, 1921b, 1933), LABHART (1965), STECK (1966), ROSIER (1931), ZBINDEN (1949), NIGGLI (1956), OSCHIDARI (1986), FEHR (1922), HUBER (1948), WEBER (1904), NIEDERER (1932). Unlike the units north of the Aar batholith where similar lithologies can be followed sometimes over several kilometers and therefore be combined in units, the SGZ is best defined by its extreme heterogeneity.

The zone has been described in detail by LABHART (1965) and STECK (1966, 1984) in the western Aar massif between the Gredetschtal (638 000 / 134 000) and the Eggishorn (650 400 / 142 400). The abundant bio-plag-gneisses (± gt ± hbl) often are banded and display complex plastic deformation features. Due to partial melting the amount of alkali feldspar is increasing and eventually two-feldspar gneisses are formed. Transitions into typical augengneisses also exist which even occur as small-scale intrusions cutting the migmatitic gneisses. According to LABHART (1965, 1969) augengneisses of both magmatic and metamorphic origin occur and the same augengneiss may show intrusive as well as gradual contacts with the surrounding gneisses. They occasionally contain inclusions of agmatitic amphibolites and were therefore assumed to be of post-migmatitic origin (LABHART, 1965). The same felsic rock associations have been described by ZBINDEN (1949) as porphyric granitic gneisses and as part of the "Mischgneise" ("mixed gneisses") from the area more to the north-east. Here also the gneiss series are characterized by the presence of migmatites characterized by a rather homogeneous granitic to granodioritic matrix with gneissic or mafic inclusions in different stages of dissolution (Fig. 12). These migmatites resemble those from the Lauterbrunnen Valley described in detail by RUTISHAUSER (e.g. 1973c). In the Belalp-Blatten area mafic rocks (amphibolites, metagabbros) generally occur as schollen amphibolites in a migmatitic matrix or, more seldom, as larger, more or less continuous bodies (e.g. SE of Blatten; LABHART, 1965). Smaller inclusions of ultramafic rocks have been reported by LABHART (1965, 1969) and STECK (1966). They give the following assemblages: serpentine (antigorite), talc, carbonate and actinolite and brown biotite as reaction product between ultramafic rock and surrounding quartzo-feldspatic rocks. Occasional gabbroic rocks occur as sill-like intrusions associated with amphibolites (STECK, 1966). The magmatic and metamorphic evolution of these rocks was tentatively presented by LABHART (1965) and STECK (1966). They both assume a Paleozoic high-grade metamorphic event prior to the migmatization phase. Their scheme is essentially in agreement with the one proposed by SCHENKER and ABRECHT (1988) for the rocks of the OSU. In fact, pronounced similarities exist between the OSU and the high-grade rocks in the Blatten-Belalp area (641 000 / 136 000).

LABHART (1966) reports the presence of variably schistose biotite-sericite-gneisses along the contact to the Permotriassic rocks in the South. The gneisses can be followed northeastwards up to Fiesch (ZBINDEN, 1949). This author summarizes these rocks together with bio-chl-gneisses, bioschists, chl-ser-schists, hbl-ep-gneisses, bio-ep-gneisses, bio-gneisses and aplitic gneisses as "Mischgneise". LABHART (1965) points out the strong Alpine deformation of these gneisses as well as of the augengneisses. These rocks most likely represent the retrograde equivalents of the bio-plag-gneisses described above. The same is suggested for the chlorite- and sericite-rich rocks extending up to Fiesch (653 000 / 139 000; ZBINDEN, 1949). The green and strongly foliated rocks rich in epidote and actinolitic amphiboles most likely represent retrograded amphibolites and the former hornblendites were altered to epidote-felses.

The area between the Grimsel Pass and Oberwald (670 000 / 154 000) has been well known for its spectacular rock associations (FEHR, 1922; NIGGLI, 1965; OSCHIDARI, 1986). Different genetic interpretations have been given by these authors. Basically they may be interpreted as the equivalent of the rocks described from the western end of the Aar massif (Fig. 2). Gneissic granitoids (augengneisses) are predominant and surround migmatitic rocks. Two zones of migmatitic rocks have been defined by NIGGLI (1965). The northern one mainly consists of amphibolitic to dioritic rocks crosscut by granitic material related to an intrusion of probable Early Variscan age (Gletsch migmatite zone). The southern zone is a metatectic in-situ migmatite with inclusions of gneisses, amphibolites and gabbros (St. Niklaus migmatite zone). The metasedimentary bio-plag gneisses typical for most areas in the Aar massif seem to be missing. In a more recent study most gneisses were interpreted to be of igneous origin (OSCHIDARI, 1986).

Though the area between the Oberalp Pass (694 400 / 168 500) and Val Russein has been investigated by several workers (WEBER, 1904; NIEDERER, 1932; HUBER, 1948; EUGSTER, 1951; VÖGELI, 1988; GNOS, 1988), the tectonic affiliation and origin of the numerous mapped rock units is still not satisfactorily resolved. East of the Oberalpstock the Aar granite rapidly thins out. Only at the Tödi (713 000 / 186 000) it reappears in a small window below the Mesozoic of the Helvetic nappes. Whether the Southern Aar granite (SAGr) is contemporaneous with the Central Aar granite (HUBER, 1948) or older has been tested by U–Pb analyses on zircons by SCHALTEGGER and CORFU (1992). Though their data are not conclusive the authors favour a 350 Ma age of the intrusion. A genetic relationship between the SAGr and the more western Baltschieder granite therefore is possible.

From the different descriptions of basement rocks it becomes evident that a zonation is strongly hampered by Alpine retrogression and mineral formation. Especially along the slopes of the Tavetsch Valley (= Tujetsch, 700 000 / 170 000) the degree of deformation is such that the distinction between granitic basement gneisses and later granitoid intrusive rocks is not readily made. To the South the SAGr is followed by the "southern granite gneiss" (HUBER, 1948), however, no distinct contacts are observed. The gneisses are distinguished from the SAGr by their increased deformation and metamorphic alteration. The "southern granite gneisses" have been subdivided by HUBER (1948) into a northern half mainly consisting of orthogneisses (strongly deformed SAGr?), and a southern half made up by heterogeneous metasediments. The latter are strongly deformed and SW–NE striking zones rich in inclusions of different composition occur within or along the gneisses. The inclusions often show a variety of compositions ranging from granodiorites to syenites. Dioritic to gabbroic rocks are quite frequent. These rocks may represent the eastern continuation of the similar but less deformed rocks in the Gletsch-Oberwald area (HUBER, 1948). HUBER already stressed the fact that many lithological differences are mainly due to different degrees of retrograde deformation. Relic mineral assemblages indicate the former high-grade nature of the schists and gneisses.

Typically gneisses of sedimentary origin are interlayered with orthogneisses. Occasional lenses of strongly altered ultramafic rocks are reported by GNOS (1988). Despite the fact that migmatitic rocks seem to be present only in minor quantities there exist similarities with the heterogeneous gneiss series in the south-western Aar massif (see above). Of some interest is the elongate zone along the northern boundary of the SAGr described by HUBER (1948) as a granitic matrix with numerous inclusions of different rock types. However, unlike in the migmatites in the Lauterbrunnen Valley or the Fiesch Valley here the intrusive nature of the granitoid matrix is evident. This zone most likely represents the contact zone between the SAGr and its country rock at rather shallow depths.

Pre-Alpine metamorphism and tectonics

The metamorphic zonation of the Helvetic nappes and its basement is well known since the studies by NIGGLI and NIGGLI (1965). In the Aar massif the rocks have been metamorphosed up to medium greenschist facies with increasing grade from North to South. This prograde recrystallization of the polymetamorphic basement on the one hand and the lack of adequate lithologies on the other hand hinder the determination of metamorphic conditions for pre-Tertiary orogenic events. Alpine overprint is weakest in the northernmost units including the ILC and the gneiss series to the South ("Erstfeld Gneisses"). Accordingly, pre-Alpine mineral assemblages are best preserved in these areas. RUTISHAUSER (1972) reports widespread cordierite in the granitoid matrix of the migmatites. Textures indicate a formation during partial melting of the metasedimentary gneisses. Sandy to arkosic sediments predominate and therefore qtz-plag-or-bio ± gt ± cord are the characteristic assemblage stable at conditions not exceeding 600 °C and 4 kbar (GULSON and RUTISHAUSER, 1976).

Several authors have tried to correlate the cordierite-bearing migmatites and intrusive rocks (*"Série de Fully"*, Vallorcine granite) in the External massifs to the cordierite-migmatites in the ILC of the Aar massif (KRUMMENACHER et al., 1965; VON RAUMER, 1976, 1984, 1987). In the light of the more recent age determinations by SCHALTEGGER (1993a, 1993b) who reports a Late Caledonian age (~ 445 Ma) for the ILC migmatites the assumed Devonian age (VON RAUMER et al., 1992) of the cordierite-migmatites (*"Série de Fully")* has to be questioned. However, recent isotopic investigations on the Vallorcine granite (Aiguilles Rouges massif) indicate a Variscan emplacement (SCHALTEGGER, personal communication).

In the metasedimentary *Silberberg Series* in the Susten area similar cordierite-bearing leucosomes crosscut pelitic gneisses with abundant sillimanite which therefore predates the 445 Ma migmatization phase affecting the ILC rocks (SCHALTEGGER, 1986). This author estimated the prevailing temperatures to 600–700 °C with qtz-plag(An_{20-60})-bio-or-sill ± tourm ± gt ± brown hbl ± tit as the stable assemblage. U–Pb age determinations on zircons from a migmatitic layered EGZ gneiss yielded an age of 456 ± 2 Ma (SCHALTEGGER, 1993a) for this amphibolite-facies metamorphism with incipient partial melting. Medium-scale structures of the EGZ in this area are characterized by steep fold axes ("Schlingenbau") related to amphibolite-facies conditions. However, mafic and some meta-sedimentary rocks display even older structures which are related to a pre-migmatization metamorphism and folding (LABHART and SCHALTEGGER, 1983; SCHALTEGGER, 1986). The same pre-migmatization structural features were reported from the Southwestern Aar massif by LABHART (1965, 1977). There is also evidence for a possible "Schlingenbau" type deformation in the Gletsch-Oberwald area where such structures are crosscut by pre-Aar granite granodioritic intrusions.

The garnet-amphibolite lenses with conspicuous symplectic and coronitic textures within a banded amphibolite complex in the *Erstfeld Gneiss Zone* near the Sustenpass could be interpreted as relics of an early high-P phase. Unlike in the Gotthard massif where high-P minerals have been preserved, the Aar massif rocks underwent extensive amphibolite-facies and anatectic events that completely erased earlier high-P assemblages in mafic rocks. Indications of a high-P metamorphic event may be represented by symplectites (plag + Na-cpx) in gabbroic rocks of the Susten area and kyanite as armoured relic within feldspars in granitic pods in migmatitic gneisses of the Erstfeld type (own data). The latter rocks also contain relics of prismatic sillimanite and abundant fibrolitic sillimanite. It is suggested that the kyanite was formed during an early high-P phase preceding the amphibolite-facies metamorphism in which sillimanite was a stable phase (kfsp + plag + qtz + sill + bio).

High-T mineral assemblages are also found in migmatitic gneisses following EGZ to the South (*Guttannen Unit* in the Oberhasli Valley) with quartz-plagioclase-biotite ± garnet ± alkali feldspar ± sillimanite (pseudomorphs) as predominating assemblage. However, here sillimanite is rare and completely altered to micaceous retrograde assemblages. Textural features indicate that cordierite formed during the partial melting from sillimanite-bearing bio-plag(± kfsp) gneisses. This is evident in laminated metasediments of the Gauli area where concordant or discordant leucosomes, preferentially formed in fold hinges or along shear zones, often contain cordierite (± quartz; = "pinite"). However, in the migmatitic gneisses of the OSU having similar compositions cordierite is not present which may indicate a different P-T evolution path for this unit.

The basement of the Aar massif continues below the Swiss molasse basin and reappears only in the Variscan orogen of the Black Forest. It has been penetrated by several drillholes in northern Switzerland. On much less retrograded pelitic samples from deep drillholes MAZUREK (1988, 1992) determined P-T conditions of 5.5–7 kbar, and 610–640 °C for the pre-migmatitic metamorphism (qtz, olig, bio, gt, sill). For the migmatitic phase he estimated pressures of 3–4.5 kbar and temperatures of 650–700 °C. P-T conditions for the Pre-Alpine(!) retrograde phase with variable alteration of the high-grade assemblages due to hydration processes were estimated to 1–2 kbar and 450–550 °C. His P-T estimates for the migmatization appear more likely than the rather low estimates by GULSON and RUTISHAUSER (1976). In the more southern migmatite zones of the Aar massif (OSU and SGZ) so far neither cordierite nor sillimanite have been observed. We tentatively suggest that the high-grade metamorphism and subsequent partial melting of the ILC and the northern gneisses ("Erstfeld gneisses" and gneisses of the GU) are contemporaneous and of Late Caledonian age (SCHALTEGGER, 1993a, 1993b). The large blocks of EGZ-type gneisses preserved within the ILC (Susten area, central Aar massif) were interpreted by LABHART and SCHALTEGGER (1983) as relic precursors of the ILC migmatites.

From the eastern part of the massif sillimanite and cordierite are reported from the pelitic rocks in the Etzlital (698 000 / 176 000) and were interpreted by WEBER (1904) as product of the contact-metamorphism caused by the Variscan Giuf syenite intrusion. HÜGI et al. (1988) report staurolite and kyanite from micaschists in the northern Lötschental (Western Aar massif).

So far most data on pre-Alpine metamorphism relate to the northern parts of the Aar massif. Detailed studies of relic high-grade mineral assemblages in rocks of the SGZ are not available. The more intense Alpine (and Variscan?) recrystallization may have destroyed most of such mineral assemblages. To answer the question as whether the anatectic event in the SGZ is contemporaneous with the formation of the ILC migmatites isotopic age data are needed.

At present, petrologic data are not sufficient for establishing a P-T-t path for the pre-Variscan evolution of the Aar massif as has been done for the Aiguilles Rouges and the Mont Blanc massifs (VON RAUMER, 1987). In these external massifs the high-P assemblage ky-stau-gt was assumed by this author to be of Ordovician to Devonian age and the high-T assemblage sill-bio-gt of Devonian to Lower Carboniferous age.

The conspicuous alignment of ultramafic rocks along rather narrow zones parallel to the strike of the main tectonic structures in the Aar massif has been pointed out before (LABHART, 1977; ABRECHT et al., 1991). In such ultramafic rocks within amphibolitic migmatites of the OSU in the central Aar massif or in serpentinites within mafic/ultramafic associations in the Maderanertal (eastern Aar massif; STAUB, 1911) olivine ± Cr spinel are occasionally preserved. The age of their high-T metamorphic origin remains unclear. SCHENKER and ABRECHT (1987) point out the presence of ultramafic inclusions in microcline pegmatite dikes within the migmatitic gneisses and assume a Caledonian age for their emplacement.

Metamorphic assemblages of undoubtful Variscan age are of contact-metamorphic origin. In the south-eastern Aar massif EUGSTER (1951) reported andalusite in the pre-Upper Carbonifeous volcano-sedimentary sequences (Val Gliems Formation) intruded by the Central Aar granite. And FRANKS (1968) attributed musc-qtz-opaque assemblages in the meta-sedimentary Bifertenfirn Formation in the Eastern Aar massif to the contact-metamorphic effect of the intrusive Tödi granite. SCHENKER (1986) and SCHENKER and ABRECHT (1987) described the formation of andalusite, garnet, muscovite, and biotite in meta-volcano-sedimentary rocks along the Central Aar granite intrusive contact between the Grimsel road and the Trift area (central Aar massif). Apart from these minerals due to contact metamorphism, Variscan regional metamorphism seems to account for mainly retrograde assemblages (e.g. SCHALTEGGER, 1986, 1993b). Such retromorphism is represented by the alteration of the sillimanite- and cordierite-bearing parageneses to ab + mus + chl + clz as stable assemblage.

We have already stressed the fact that in the rock units between ILC and the Aar granite there is a rather immediate transition from greenschist facies rocks into high-grade rocks exhibiting even partial melting. Because relics of high-grade mineral assemblages are also observed in the greenschist-facies rocks we believe that this difference in metamorphic grade is due to Variscan retromorphism which especially affected more northern units. This metamorphic zonation cannot be due to the Alpine metamorphism which is responsible for the recrystallization or neo-formation of green biotite preferentially in Variscan metagranites and the growth of stilpnomelane in metagranites and EGZ-type gneisses (NIGGLI, 1970; GNOS, 1988; own data). In the gneisses N of the Aar granite plagioclases were not affected by the Alpine rehomogenization and An-contents up to 40 mole-% (EGZ-type gneisses) or 50 mole-% (ILC) are preserved (own data).

The fact that Lower Carboniferous volcanics and sediments were deformed and recrystallized through the intrusion of the calc-alkaline Central Aar granite at greenschist-facies conditions led OBERHÄNSLI et al. (1988) to assume Upper Paleozoic compressional tectonics related to a destructive continental margin. Based on the distribution of the pre-Westphalian pyroclastic volcanic rocks and related meta-sediments they proposed a model of Variscan faulting and nappe tectonics. The burying of surface-rocks of volcanic and sedimentary origin shortly after their deposition indeed indicates compressional tectonics but its timing is unclear. However, so far no direct evidence for large-scale nappe-type structures has been presented. While most authors agree on the likelyhood of Variscan thrust zones (mylonite zones) rejuvenated during the Alpine orogeny (Kammer, 1985) the possibility of even older structures reactivated during the Variscan has not been discussed so far.

Summary

The zonation of the Aar massif has been a matter of debate since the beginning of the century. Basically all workers who presented a map of the massif agreed more or less on the boundaries of the different geologic or tectono-stratigraphic units. But even recent studies suggesting large scale Variscan thrust tectonics (Schenker, 1987) or even nappe tectonics (Oberhänsli et al., 1988) relied on the zonation proposed some fifty years ago by Hugi (1934). Krummenacher et al. (1965) used the classical zonation for their attempts to correlate such units from the External massifs and even from the Penninic realm. They, however, do not sufficiently take into consideration metamorphic effects that may have obliterated original similarities or created obvious but misleading differences that are based upon the present (Alpine) tectonic situation and secondary metamorphic retrogression. Therefore rock assemblages with a different tectonic and metamorphic evolution may erroneously be combined. This has to be considered when correlations are made between units of different external massifs.

The purpose of the present study was to present the main features of the pre-Alpine Aar massif and to emphasize the extensive similarities found between certain lithologic units. In the maps (Figs 2, 3, and 4) areas with large scale common features are summarized and small scale lithologic differences have widely been omitted. Consequently the maps represent attempts to interpret the pre-Alpine rock assemblages of the Aar massif by taking into consideration the retrogressive alteration of pre-Variscan mineral assemblages and the Alpine recrystallization especially south of the Aar granite (Southern Gneiss Zone). By doing so five major geologic elements can be recognized in the pre-Variscan Aar massif:

(1 and 2) Two large areas of anatectic migmatites with chiefly metasedimentary protoliths: the *Innertkirchen-Lauterbrunnen Crystalline Zone* of Late Caledonian age (ILC) in the North and an important part of the Southern Gneiss Zone (SGZ) of unknown age south of the Aar granite. The two migmatite zones display some common characteristics but also differences which indicate different P-T-conditions. The ILC migmatites are characterized by low-pressure assemblages with cordierite which is not present in the SGZ migmatites. Migmatization was probably due to decompression with only a slight increase in temperature. The SGZ migmatites have much larger portions of mafic rocks of probable magmatic origin and probably represent a separate tectonometamorphic environment. Unlike the ILC the southern migmatites are related to or intruded by intrusive granitoids (augengneisses) which are abundant in the SGZ. The SGZ migmatites represent rocks with a large amount of melt generated from quartzofeldspatic gneisses which are generally preserved only as inclusions or ghost structures (diatexites). The two migmatite terranes are important in the western and central Aar massif but are not exposed in the eastern part. The migmatization is assumed to be Ordovician and the affected rocks were already metamorphosed to amphibolite facies. The precursors of the mainly detrital sedimentary rocks with intercalated volcanics may well represent Precambrian sequences.

(3) Between these two large migmatite areas a belt of predominantly metasedimentary and granitic gneisses occurs which have been metamorphosed to amphibolite facies conditions or have suffered from partial melting. Zones with large amounts of migmatites occur in the *Erstfeld Gneiss Zone*, the *Guttannen Unit*, and the *Ofenhorn-Stampfhorn Unit*. They are mainly found in the internal parts of the massif and often contain mafic inclusions ("Schollen amphibolites" in the OSU). There exist extensive similarities in their lithologies and in their metamorphic evolution. This indicates a common pre-Variscan evolution of a crustal section separated only later by Variscan and Alpine thrusting, although the disappearance of cordierite in the more southern units may infer a different P-T evolution. This also implies that high-grade metamorphism and partial melting of the mainly sedimentary protoliths is contemporaneous with the beginning of migmatization in the adjoining migmatite terranes, i.e. probably around 456 Ma.

As long as there are no chemical data (major and trace elements, isotopes) for the important rock types, especially mafic and ultramafic assemblages, any paleogeographic interpretation is speculative. But some noticeable similarities in the occurrence of mafic-ultramafic assemblages within a metasedimentary gneiss terrane in the Gotthard massif (Abrecht et al., 1991) and the Aar massif might indicate a similar evolutional path. Garnet-amphibolites from the EGZ with symplectic and coronitic textures may record an early high-pressure phase also in the Aar massif. These more internal rock series probably represent the same Precambrian sedimentary sequences with locally abundant intercalations of mafic to ultramafic magmatic and volcanic rocks (serpentinites, gabbros, amphibolites). Pre-Variscan granitic intrusive rocks are rare. Several geologic units can be defined based on primary lithologic variations and a large scale retrogression which occurred during the Variscan. The units are especially retrograded along shear zones and were interpreted by some authors as nappes created during the Variscan (OBERHÄNSLI, et al., 1988).

(4 and 5) After rise and erosion during the Lower Carboniferous volcanoclastic sediments and subaerial volcanics were deposited on the exposed high-grade terrane already intruded by shoshonitic-ultrapotassic diorites to granitoids (SCHALTEGGER and CORFU, 1992). The basement and volcano-sedimentary rocks were then included in the Carboniferous mountain building processes and eventually intruded by further pulses of dioritic to granitic rocks during the Carboniferous. The breakdown of early high-grade mineral assemblages is possibly related to Carboniferous to Triassic (?) hydrothermal activities (ABRECHT and SCHALTEGGER, 1988).

The metamorphic overprint during the Tertiary is of moderate grade in the Aar massif and does not exceed lower greenschist facies conditions. To what extent the deformation of the basement rocks and the Variscan intrusives is due to Variscan or to Alpine tectonics is still a matter of debate (KAMMER, 1985).

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The lithostratigraphy of the pre-Mesozoic basement of the Gotthard massif: a review

by *Ivan Mercolli*[1], *Giuseppe G. Biino*[1,2] and *Jürgen Abrecht*[1,3]

Abstract

The Gotthard massif shows a coherent lithostratigraphy and can be subdivided into units, which can be traced across the entire massif. Indications of possible protholiths, relics of metamorphic parageneses, and magmatic events permit to classify the units chronologically and to distinguish major orogenic cycles. We propose the following revised lithostratigraphic subdivision of the Gotthard massif:

- Uppermost Carboniferous, Permian and Mesozoic sedimentary covers (with some outcrops of Permo-Carboniferous volcanic rocks)
- Late Variscan granitoids (divided into two cycles by a deformation phase)
- Middle Paleozoic metasedimentary rocks
- Late Ordovician metagranitoids
- Proto Gotthard (pre-Late Ordovician):
  - Migmatitic gneisses
  - Metagabbros, with island arc affinity
  - Metabasalts, metagabbros and meta-ultramafics, with ophiolitic affinity
  - Metasedimentary gneisses

Keywords: basement, granitoid, orogenic cycle, pre-Mesozoic, Gotthard massif, Central Alps.

Introduction

The Gotthard pass, one of the privileged North-South connections across the Alps, has been crossed by many famous naturalists during the past centuries. Many of them report geological descriptions of the area (Cotti et al., 1991). The gigantic venture of the railroad tunnel at the end of the 19th century led to the remarkable geological description by Stapff (1880) along the railway cross section.

At the beginning of the 20th century, the petrography school of Zürich guided by Paul Niggli, started a long tradition of detailed geological investigations in the Gotthard massif which ended in the sixties. An exhaustive bibliography was presented by Labhart (1977) and Cotti et al. (1991). These works were mainly done in times when fossils were the only chronological support to geologists, and geophysics was an unknown discipline. Nevertheless, earlier authors clearly recognized in the Gotthard massif (Fig. 1 and Tab. 1), despite its Alpine deformation and metamorphism (greenschist to lower amphibolite facies), some records of at least two major pre-Alpine tectonometamorphic (orogenic) events.

The purpose of this paper is to review the literature on the Gotthard massif. The review is not based on a rigorous literature survey but on the authors' subjective selection of papers that, in the their opinion, are of broad interest, that were particularly novel, or that represented substantial advances in the knowledge of the lithostratigraphy and tectonometamorphic relationships between the different rocks making up the Gotthard massif. In this sense, the so called geological field evidences provided by the old authors (but not only...) are useful and important. Nevertheless

[1] Mineralogisch-petrographisches Institut, Universität Bern, Baltzerstrasse 1, CH-3012 Bern, Switzerland.
[2] Present address: Institut de Minéralogie et de Pétrographie, Université de Fribourg, Pérolles, CH-1700 Fribourg, Switzerland.
[3] Present address: GEOTEST AG, Birkenstrasse 15, CH-3052 Zollikofen, Switzerland.

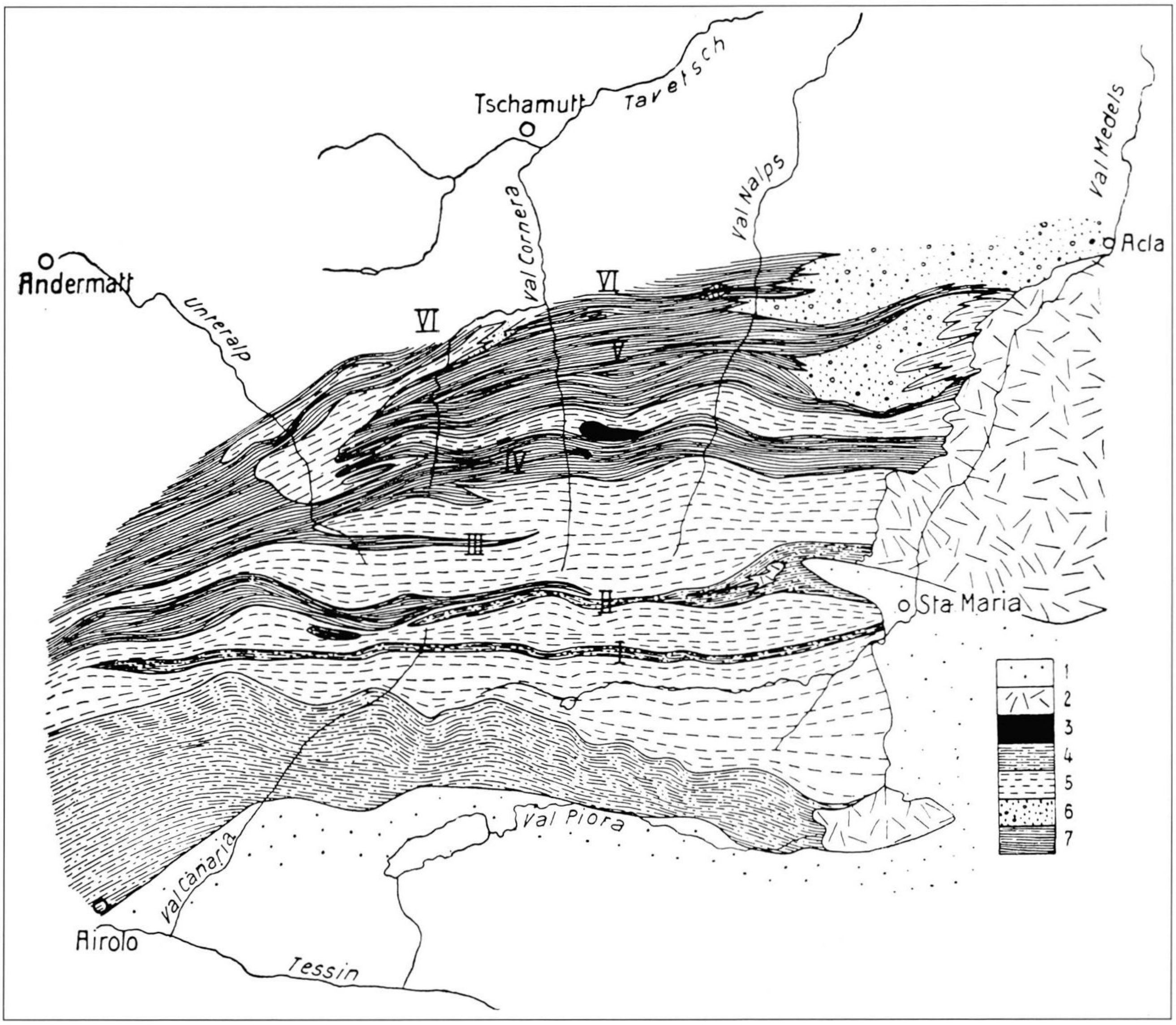

Fig. 1 Tectonic subdivision of the south-eastern Gotthard massif. 1. Mesozoic schists; 2. Late Paleozoic granite bodies; 3. peridotite bodies; 4. younger trough zones (Tremola-Tenelin-Borel); 5. "Streifengneise"; 6. "Mischgneise"; 7. older trough zones with basic layers. Reproduction of the original figure of HUBER 1943, figure 6, page 93.

some caution must always be applied since the dominant theory at that time could considerably have conditioned the field observations: many of the earlier authors described thermal effects produced by the serpentinite magma (considered a Late Paleozoic intrusive), and the contact between Streifengneis and migmatitic gneiss is always quite controversially described (the dominant theory at the beginning of the century suggested migmatitization by lit-par-lit intrusion).

In this contribution we summarize in a coherent model (at a regional scale) the observations of previous authors. This model may represent a simplification in many respects, and misinterpretation of former authors' interpretations cannot be excluded. However, despite or because of such shortcomings we hope to stimulate a discussion of this important chapter of the geology of the Central Alps.

Rock types and lithostratigraphy

The pre-Mesozoic basement of the Gotthard massif is made up by paragneiss and micaschist with embedded mafic, ultramafic and calc-silicate rocks. This sequence was intruded during Late Ordovician and Late Carboniferous by granitoids.

A characterization of the rock types and the used formational names are presented in tables 1 and 2.

HUBER (1943) and NIGGLI (1944) have proposed to use two major magmatic events as lithostratigraphic markers for the evolution of the

Tab. 1 Rock series belonging to the sedimentary portion of the crystalline basement of the Gotthard massif. Translated from NIGGLI (1944), table V, page 128.

	Series I	Series II	Series III	Series IV	Series V	Series VI
Typical localities in the central Gotthard massif	Garves da Nual Piz Cavradi Six Madun Piz Tegliola Unteralptal (Spannmatt, Glockenspitz)	Eastern Val Nalps Piz Paradis Guspistal	Motta Naira zone (H.M. HUBER) central Val Curnera and Val Nalps	Tremola series southern border of the massif	Piz Tenelin Piz Borel Val Rondadura	Northern and ? eastern border of the massif
Main rock type	**Andesine/labradorite gneisses** (Bt, Hbl, Grt), with inclusion of calc-si-licate and Bt-Act-fels; Sil gneiss; associated with albite/oligoclase gneiss and rare amphibolite	**Mica albite/oligoclase gneiss** (Bt, Ms, Grt), hornfelsitic or fine banded or fine "augig"; associated with minor amphibolite	Amphibolite; minor mica-albite/ oligoclase gneiss and andesine/ labradorite gneisses	Grt-mica schist; Hbl-garben schist; Cal-mica schist; amphibolite; Zo amphibolite; quartzitic gneis; quartzite; coal bearing schist; Bt quartzite; cross-Bt gneiss	Mica gneiss; Hbl-Grt-mica schist; Hbl-Cal-mica schist; quartzite; amphibolite	Sericite-Bt gneiss; phyllite; quartzite; graphitic schist
Guide rock	Calc-silicate			Quartzite	Quartzite	Quartzite
Pre-Alpine metamorphic grade	Meso to catazone			Meso to epizone		
Age refered to the Streifengneis and Hercynian granite	Pre Streifengneis			Post Streifengneis	but pre-Hercynian	granite (? ± coeval)
Likely primary sedimentary facies	Shale to carbonaceous marl, partly sandy; layers of calcareous sandstone in the shale	Sandy shale; minor dolomitic marl; relatively monotonous sedimentation	Dolomitic marl, sandy shale; with intercalatons of ? "ophiolite"; deep basin?	Shale to dolomitic marl with single quartz sandstone layers	Shale to dolomitic marl with thick quartz sandstone layers	Shale ? and sandy shale quartz sandstone

massif. The first marker of the basement evolution is the intrusion of the Streifengneis (Late Ordovician granitoids), the second is represented by the Late Variscan intrusives (Tab. 1 and 2).

In the central part of the massif (Fig. 2) HUBER (1943) and NIGGLI (1944) proposed the following subdivision of the crystalline basement:

- Pre Streifengneis gneisses and amphibolites
- Streifengneis
- Middle Paleozoic metasedimentary rocks, mainly mica schists and quartzites (post-Streifengneis sedimentation age, first metamorphism and deformation pre-Upper Paleozoic granitoids ?)
- Late Variscan granitoids (Upper Carboniferous-Permian)
- Permo-Carboniferous and Mesozoic sediments.

In this review we used the remarkable lithostratigraphic synthesis of NIGGLI (1944, Tab. V, page 128, here reported as Tab. 1) as starting point for our reconstruction. We reorganized them (Tab. 2) according to the evolution model proposed by ABRECHT et al. (1991a) and summarized in table 3. Table 2 reports further a synopsis of the geological terms occurring in the past literature.

Pre-Streifengneis gneisses and amphibolites are in the following considered as being a member of a unit called Proto Gotthard (Tab. 2).

In order to simplify matters for the readers, we have subdived the Gotthard massif in three geographical areas. This subdivision has no geologic ground.

The central part of the Gotthard massif

THE MAFIC AND ULTRAMAFIC ROCKS

The mafic and ultramafic rocks are embedded in metasedimentary rocks. As already suggested by NIGGLI (1944), some of the amphibolites in series I, II, and III (Tab. 1) show an ophiolitic affinity and belong to the oldest part of the basement (Proto Gotthard). Isotopic and chemical investigations show that part of the mafics derived from former MOR basalts (ABRECHT et al., 1991a; BIINO and MEISEL (1993) have suggested that the meta-ultramafics are mainly abyssal peridotites. The mafics and ultramafics are clearly associated in the field. Therefore, mafics and ultramafics can be related to an ophiolitic sequence. The Sm–Nd isotope systematics suggest a formation age of approximately 950 Ma (BIINO et al., 1994). The

Tab. 2 Characterization of the lithostratigraphic units of the pre-Mesozoic basement of the Gotthard massif.

	Proto Gotthard			Late Ordovician granitoids	Palaezoic metasedimentary unit	Late Carboniferous granitoids
	Metasedimentary meta-ophiolitic unit	Metagabbro unit	Migmatic gneiss unit			
Correlation with unit names already existing in the literature	"Nördliche Paragneise", "Gurschengneise", Guspisgneise", "Prato Serie", "Distelgrat Zone" Series I, and II of NIGGLI		"Mischgneise", "Homogene Mischgneise", "Injektionsgneise", "Schmitzengneise", "Paradisgneis", "Sorescia gneis", wester part of the "Giubine Serie" Series II of NIGGLI	"Streifengneis", "Orthogneis"	"Tremola Serie", "Zone des Piz Borel", "Zone des Piz Tenelin", eastern part of the "Giubine Serie" Series IV, V and VI of NIGGLI	Medelser granite, Cristallina granodiorite, Uffien diorite, "Gamsboden-Granit-gneis", "Fibbia-Granit-gneis", "Winterhorn-Granitaplit", Cacciola granite, Rotondo granite, Prosa granite, Sedelhorn diorite
Guide rocks	Bio-andesine/ labradorite gneiss, Grt-amphibolite, serpentinite and calc silicate	Metagabbro	migmatite, banded gneiss, chorismatic and stromatic gneisses	Two mica gneiss	Quartzite, Hbl-Grt-mica schist, Hbl garben schist, Sericite-phyllite	Undeformed to weak foliated granitoid
Protholith	Clastic sediment and dismembered ophiolitic rocks	Gabbros with island arc affinity	Clastic sediments	Granite	Clastic sediments	Calc-alkaline granitoid
Age of the protholith	Proterozoic to Cambrian	Proterozoic to Lower Ordovician	Proterozoic to Cambrian	Late Ordovician (440 Ma)	Silurian to Devonian	Late Carboniferous
Pre Late Ordovician metamorphisms	Eclogite facies Granulite facies	Eclogite facies Granulite facies	Eclogite facies Granulite facies anatexis			
Variscan metamorphism	Amphibolite facies	Amphibolite facies	Amphibolite facies	Amphibolite facies	Greenschist facies ?	

metasedimentary and meta-ophiolitic rocks are interpreted by ABRECHT et al. (1991a) as an accretionary prism.

Until recent (ABRECHT et al., 1991a,b; ABRECHT and BIINO, 1994), metagabbros were not recognized in the Gotthard massif. The Kastelhorn metagabbro was only dubiously considered a former orthogenic rock of upper Carboniferous age (AMBÜHL, 1929). Two generations of gabbros can be defined. Some metagabbros (e.g. Fuorcla Paradis) clearly belong to the ophiolite sequence, but other metagabbros (e.g. Kastelhorn, Unteralptal) are intrusive into the metasedimentary and meta-ophiolitic series. These younger metagabbros, possibly of Lower Ordovician age (OBERLI et al., 1993), show island arc affinities.

All these rocks have suffered at least two major metamorphic overprints prior to the intrusion of the Streifengneis (Late Ordovician granitoids); the first one at eclogite facies conditions and the second one at granulite facies conditions (ARNOLD, 1970).

THE PRE-STREIFENGNEIS BASEMENT AND THE MIGMATITE PROBLEM

The wedge sequence is made up by a variety of gneisses. Some of these gneisses show, to different degrees, migmatitic-looking textures ("Mischgneise", "chorismatische Gneise", "Injektionsgneise", "feldspatreiche Gneise", "Migmatitgneise" and "Paradisgneis" according to AMBÜHL, 1929; HUBER, 1943; NIGGLI, 1944; ARNOLD, 1970).

The interpretation of the relationship between these gneisses, the Streifengneis, and the evolution of the older basement is quite controversial. AMBÜHL (1929), HUBER (1943) and NIGGLI (1944) used different names for these gneisses, such as "Mischgneise", "Homogene Mischgneise", "chorismatische Gneise", "Injektionsgneise", "feldspatreiche Gneise", but never explicitly called them migmatites. Nevertheless, they always used the classical migmatite terminology (chorismatic, micro chorismatic, stromatic, nebulitic, phlebitic) in their descriptions. It is important to keep in mind that ptygmatic folds or melt migration in axial planes are seldom described (in contrast to the migmatitic terrains outcropping in the Aar massif). All these authors describe the rocks as neither clearly paragenetic nor orthogenetic. They stressed the non homogeneous character at microscopic and hand specimen scale, but the relative homogeneity at megascopic scale.

HUBER (1943) observed that the "Mischgneise" were always cropping out along the contact of Late Ordovician granitoids to the basement. He pointed out the close spatial relationships, and

Tab. 3 Schematic summary of the geological history of the Gotthard massif, after ABRECHT et al. (1991a).

Time	*Tectonic event*	*Process of crustal growth*	*Metamorphism*
~ 1000 Ma	– Opening of an oceanic basin		
		– Formation of oceanic crust	
			– Sea water-rock reaction
~ 900 ? Ma	– Subduction of the oceanic crust		
		– Formation of an accretionary prism	
		– Juxtaposition of oceanic and continental series	
		– Intrusion of gabbros in the accretionary prism	
~ 470 Ma	– Subduction of the accretionary prism due to collision		
			– Eclogite facies (Ky)
			– Granulite facies (Ky)
			– Anatexis (Sil)
			– Grt-amphibolite facies
~ 440 Ma	– Uplift	– Intrusion of granitoid (Streifengneis)	
	– Erosion	– Sedimentation of clastic series	
~ 350 Ma	– Compression		– Amphibolite facies
315–300 Ma		– Intrusion of the first generation of granitoids	
~ 300 Ma	– Deformation phase		
300–250 Ma	– Uplift	– Intrusion of the second generation of granitoids	
		– Formation of volcanic and volcanoclastic series	

interpreted the "Mischgneise" as the product of the impregnation of the metasedimentary gneisses by melt or fluids during the intrusion of the Late Ordovician granitoids. NIGGLI (1944) partly agreed with Huber's interpretation. However, he

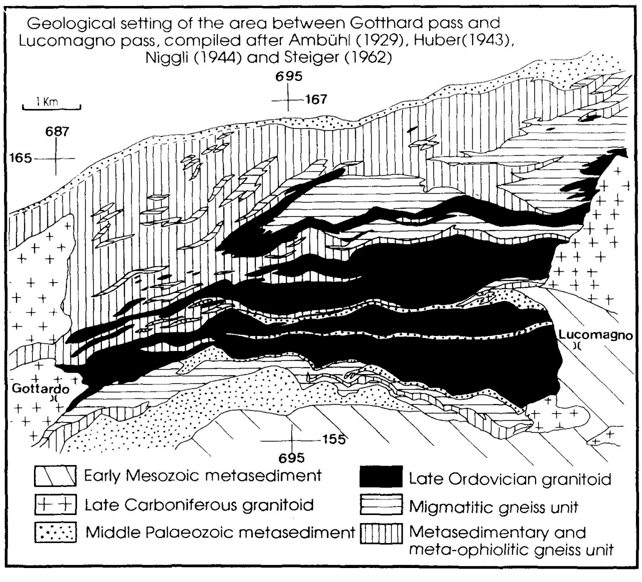

Fig. 2 Geological setting of the area between Gotthard pass and Lucomagno pass, compiled after AMBÜHL (1929), HUBER (1943), NIGGLI (1944) and STEIGER (1962).

observed "Mischgneise" with no obvious spatial relationship with the Late Ordovician granitoids. AMBÜHL (1929) described sharp contacts between ortho- and paragneisses, and he observed discordant dikes cutting the country rocks. ARNOLD (1970) described true migmatites occurring mainly as border facies of the "Mischgneise" along the contact either with the Late Ordovician granitoids or the metasedimentary gneisses. He could not establish a precise age relationship between migmatites, "Mischgneise" and Late Ordovician granitoids, but he supported the conclusion of HUBER (1943) that the anatectic phase was related to the intrusion of the granitoids at least in time.

In the following, we propose to consider the "Mischgneise", "chorismatische Gneise", "Injektionsgneise", "feldspatreiche Gneise" and "Migmatitgneise" of AMBÜHL (1929), HUBER (1943), NIGGLI (1944) and ARNOLD (1970) as a single complex of rocks of sedimentary origin having been transformed to different degrees by migmatitic processes. We will refer to these rock types as migmatitic gneisses (Tab. 2, Fig. 2).

A particular type of gneiss, associated with the migmatitic gneisses has been reported by HUBER (1943) as "Paradisgneis". It is a rather massive mica-plagioclase gneiss, showing only a weak foliation and containing centimetric to decimetric inclusions of gneisses, amphibolites, quartz nodules and calc-silicate rocks. Similar rock types are described by AMBÜHL (1929) and NIGGLI (1944, 1948) in Val Maighels. In contrast to the syn-Streifengneis impregnation hypothesis proposed by HUBER (1943), ARNOLD (1970) has suggested a pre-Streifengneis anatectic origin of this rock (pp. 41, 44). The mica-plagioclase gneiss represents the anatectic melt and the inclusions are considered to be restites. The presence of granulite-facies assemblages in the "Schollen" clearly indicates an anatectic event between the high temperature metamorphic event and the intrusion of the Streifengneis (Late Ordovician in age). Whether the "Mischgneise" were formed during this anatectic event is still a matter of debate. A continuous transition from the non migmatitic paragneiss to "Paradisgneis" is shown in HUBER (1943), NIGGLI (1944), and ARNOLD (1970), and the transitional contact is discordant to older structures (e.g. lineaments of mafic lenses). A similar observation is also true for the transition between the non migmatitic paragneiss and the migmatitic gneiss. The contact between Paradisgneis and migmatitic gneiss is described by HUBER (1943) as transitional and by ARNOLD (1970) as tectonic. All these authors point out the difficulty of establishing clear field relationships between migmatitic gneiss and Paradisgneis.

Thus, two different scenarios may be proposed:

1. The "Mischgneise", "chorismatische Gneise", "Injektionsgneise", "feldspatreiche Gneise", "Migmatitgneise" and the Paradisgneis were formed by the same anatectic event. In this case the anatexis must be pre-Streifengneis but younger than granulite facies metamorphism.

2. Two separate anatectic events have occurred. As a consequence, a first migmatization phase of unknown age has to be assumed for the migmatitic gneisses, while a second one of presumably Lower Ordovician age is responsible for the Paradisgneis. In this case the migmatitic gneisses represent the oldest rocks of the basement and are relics of a continental crust on which the protolith of the Paradisgneis has been deposited or overthrusted. The second event (Paradisgneis) is considered to be only a minor one with local geological importance.

The first scenario would indicate a widespread migmatitic event of at least Late Ordovician age, which affected large masses of the older metasedimentary to meta-ophiolitic series. The field relationships between paragneiss-migmatitic gneisses and between paragneiss-Paradisgneis strongly support this interpretation, and the tectonic contact between Paradisgneis and migmatitic gneisses may be due to a local and minor event. On the other hand, several arguments are not fitting the second scenario. Paradisgneis and Migmatitgneis show the same type of inclusions (mafics, ultramafics, calc-silicate fels), and it was not possible to demonstrate any difference in the metamorphic evolution. At present, this second scenario must be only considered as a working hypothesis. Hence we propose to consider the Paradisgneis as part of the migmatitic gneiss. New field observations led us to conclude that the contact between Streifengneis and metasediments (already migmatitized) is discordant and intrusive. Dikes and apophyses emanating from the Late Ordovician metagranitoids discordantly cut the metamorphic structures of the Upper Proterozoic metasedimentary and metaophiolite rocks, indicating an Ordovician to Upper Proterozoic tectonometamorphic event (or events) recorded only in the oldest part of the basement. A post migmatite deformation in garnet amphibolite facies occurred before the Streifengneis intrusion (BIINO, unpubl. data), while Streifengneis and migmatitic gneisses were deformed together during the Variscan (Schlingen phase).

The term Streifengneis is well established in the Alpine literature. Nevertheless, it contains ambiguities since it is constrained by a peculiar texture more than by genetic or chronological criteria. The Streifengneises are locally less deformed and, therefore, are not banded orthogneisses but augengneisses, or even at outcrop scale they have preserved igneous textures. Another quite common feature is the presence of a finer grained marginal facies that is transitional to the augengneisses. These clearly plutonic textural and structural variations are not easily integrated in a classification based on a later tectonic fabric. In the present review as in the older literature the chronological criteria seem to be the overwhelming characteristic. These rocks yield an absolute chronological age of ca. 440 Ma (ARNOLD, 1970; BOSSART et al., 1986; SERGEEV and STEIGER, 1993), and we therefore suggest to replace the term Streifengneis by Late Ordovician metagranitoids, although they consist of granites, granodiorites, quartz monzodiorites and quartz monzonites.

MIDDLE PALEOZOIC METASEDIMENTS

An interesting rock unit, including sericite-biotite-gneisses, phyllites, quartzites and graphitic schists, borders the northern margin of the crystalline basement in the central and eastern part of the massif. NIGGLI (1944) considers these rocks to be Middle Paleozoic metasediments (series VI in Tab. 1). According to AMBÜHL (1929) the sericite-

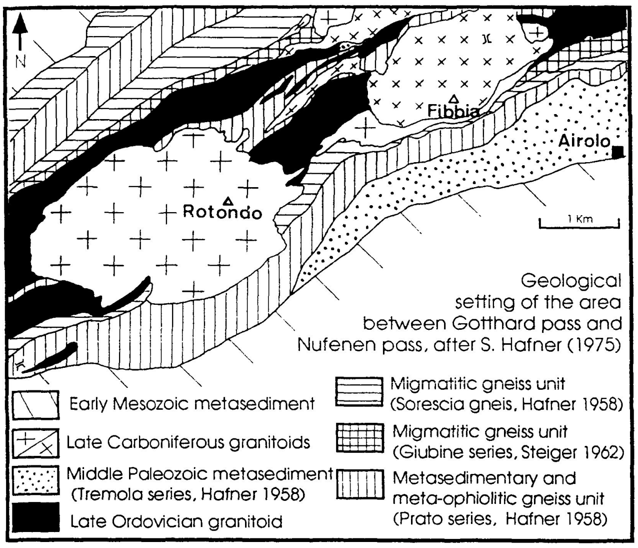

Fig. 3 Geological setting of the area between Gotthard pass and Nufenen pass, modified after HAFNER (1975, 1:25 000 Swiss Geological map, Val Bedretto, Blatt 68, LK1251).

biotite-gneisses and phyllites are formed due to retrograde alteration of the paragneisses along the contact with the Permo-Carboniferous sediments.

Although admitting a strong Alpine (or Late Variscan) deformation and recrystallization, in accordance with ARNOLD (1970), we prefer Niggli's interpretation of a Middle Paleozoic sedimentary sequence and consider it to be a separate lithological unit (Fig. 2). Similar rocks outcrop in the Piz Tenelin and Piz Borel slices (Fig. 4). AMBÜHL (1929) clearly described "Garbenschiefer" identical with those from the Tremola zone (see below) in the Piz Borel zone (Pizzo Centrale, Fig. 4). In the western termination of the massif, OBERHOLZER (1955) reports an alignment of quartzitic rocks of several kilometers in length interlayered with the "Zweiglimmer-Na-K-Feldspatgneise" (Fig. 5). We tentatively assign these rocks to the same Middle Paleozoic metasediments.

The southern and western parts of the Gotthard massif

HAFNER (1958) and STEIGER (1962) have investigated the southern margin of the massif (Figs 2 and 3). From the descriptions of the units mapped by these authors we can derive the following relationships with the previously defined units.

The "Prato Serie" (HAFNER, 1958, p. 277) is an unequivocal equivalent of the metasedimentary gneisses (accretionary wedge sequence) with embedded ophiolitic metabasalt and meta-ultramafic rocks. In this series HAFNER (1958) observed migmatitic structures.

The "Soresciagneis" (HAFNER, 1958, p. 274) is described as biotite-plagioclase gneiss. The contact with the "Streifengneis" is a pre-Late Variscan thrust plane (HAFNER, 1958, p. 273). The gneiss is very homogeneous and with seldom stromatic, ophthalmitic and microchorismatic structures. STEIGER (1962, p. 482) considered the "Soresciagneis" as a sedimentary cover of the Prato series. HAFNER (1958, p. 315) pointed out a possible correlation between "Soresciagneis" and "Mischgneis". In our reconstruction, the "Soresciagneis" is considered as migmatitic gneiss and, therefore, belongs to the Proto Gotthard.

The "Giubine Serie" (STEIGER, 1962, p. 506 and so forth) contains three lithotypes:

– The "Schmitzengneis". From Steiger's descriptions and from a comment by ARNOLD (1970, p. 38) the "Schmitzengneis" appears to be identical with the Paradisgneis.

– The stromatic gneiss seems to correspond to the "Mischgneise".

– The garnet micaschist, as already stated by STEIGER (1962, p. 515), shows a clear affinity to the micaschists of series IV, V, VI of NIGGLI (1944; Tab. 1).

STEIGER (1962) pointed out the possible age differences of the rocks of the "Giubine Serie" and the difficulties to map the contact between "Schmitzengneis", stromatic gneiss and "Soresciagneis". Steiger's observations suggest that only one migmatitic event occurred (but at different degrees of partial melting).

The garnet micaschists are intruded by the Late Variscan granitoids (e.g.: north of the Passo dell'Uomo after STEIGER, 1962).

The "Giubine Serie" is composed of poly- and mono(Variscan)-metamorphic rocks, but it is not an independent nappe. Hence we propose to discard the unit name "Giubine serie" (Tab. 2 and Fig. 2) and to assign the "Schmitzengneis" and stromatic gneiss to the migmatitic gneisses and the garnet micaschist to the Middle Paleozoic metasediments.

The "Tremola Serie" is formed by marine metasediments (shales, carbonates with minor sandstone), and in only one locality metaconglomerate layers crop out (HEZNER, 1909, pp. 164, 186). HAFNER (1958) described discordant contacts between Prato and Tremola series (p. 321). The "Tremola Serie" and its subunits have been studied in detail by HEZNER (1909) and STEIGER (1962). This unit shows neither the high-grade pre-Alpine metamorphism nor any intrusive contact with the Late Ordovician granitoids. Apparentely, it is not refolded by the Variscan Schlingen tectonic. A separate slice of "Tremola Serie" (map by HAFNER, 1:25 000 Swiss Geological map, Val Bedretto, Blatt 68, LK1251) is possibly intruded by the Gamsboden granite (Fig. 3). Therefore, the "Tremola Serie" has been deposited or tectonically juxtapposed on the Gotthard basement during the Middle Palaeozoic. In accordance with the subdivision by NIGGLI (1944) and with the field observations of AMBÜHL (1929), we assign the "Tremola Serie" to the Middle Paleozoic metasediments.

The western Gotthard massif has been investigated by OBERHOLZER (1955). His lithological classification permits a correlation with our proposed lithostratigraphic subdivision. Mica-plagioclase gneisses, amphibolites, garnet amphibolites and serpentinites represent the metasedimentary gneisses, ophiolitic metabasalt and metaultramafics unit (Series I, II, III, NIGGLI 1944; reported in Tab. 1). The "Mischgneise" belong to the migmatitic gneisses and the "Zweiglimmer-Na-K-Feldspatgneise" to the Late Ordovician metagranitoids. OBERHOLZER discussed the possible correlations of these rocks with the central part of the massif and arrived, despite of some local lithological differences, at similar conclusions.

The eastern part of the Gotthard massif

Somewhat more problematic is the extrapolation of our lithostratigraphic subdivision to the eastern end of the massif. WEBER (1924) distinguishes on his map two main units, the "Paragesteine" and the "Ältere kristalline Schiefer (teils Ortho-, teils Paragesteine)". The main part of the "Paragesteine" clearly belongs to the Proto Gotthard, while some lithotypes such as "Konglomeratgneiss, Serizitgneisse, -schiefer -phyllite und -quarzite" could be assigned to the Middle Paleozoic metasediments. The "Ältere kristalline Schiefer (teils Ortho-, teils Paragesteine)" include migmatitic gneisses and Late Ordovician granitoids.

WINTERHALTER (1930) did not map the "Orthogneiss" (Late Ordovician granitoids) and the "Injektionsgneis" (migmatitic gneisses) separately. It was, therefore, impossible to define on figure 5 the limits of these two units in the area north of the Medelser-Cristallina granitoid complex. In WINTERHALTER's map (1930) a phyllite zone marks the Late Ordovician granitoids-paragneiss contact. He interprets these phyllites as strongly deformed paragneisses and discusses a possible link with the wedging of Permo-Carboniferous sediments within the paragneisses. On the other hand, the mineralogy of these phyllites is the same as the sericite-phyllite that NIGGLI (1944) assigned to series VI (Tab. 1). Lacking new facts on this subject, it is impossible to decide if these phyllites belong to the Middle Palezoic metasediments or to the Proto Gotthard.

FEHR (1956) has tried to distinguish different gneiss domains at the eastern end of the massif. Unfortunately, it is difficult to relate his gneiss nomenclature to our subdivision, this concerns particularly the distinction between Late Ordovician granitoids and migmatitic gneisses. Further, the map by FEHR (1956) differs in some points from the one by WEBER (1924) preventing clear correlations.

It is, nevertheless, evident that the eastern end of the massif does not show any important lithological changes. Rocks only present in this area, are meta-rhyolitic volcanics and rhyolitic dikes ("Quarzporphyre") of Late Paleozoic age (frequentely associated with black schists and tourmaline fels) which crop out within the crystalline basement. Together with the abundant Permo-Carboniferous sediments on top of the crystalline basement (Verrucano of Ilanz), the presence of the these volcanics indicates that at least this part of the massif was denuded in Late Paleozoic times.

Structural evolution

The polyorogenic tectonic reworking of the Gotthard massif and the lack of systematic modern structural studies, presently prevent a clear assignment of structures to single deformation events. As the emphasis of our study was clearly on the petrographic characterization of the rock units, it was beyond its purpose to summarize in a modern and coherent frame the structural observations dispersed in the literature. Nevertheless, some general remarks can be made. The best way to investigate the main structures is by establishing the structural evolution within the three major intrusive bodies: the Late Ordovician granitoids, the first and the second suites of Late Variscan granitoids, and to compare them with the structures in the old basement. This same strategy has been followed by earlier geologists but the theoretical progress in structural geology will lead to new results. The help of isotope geology is also decisive in order to geometrically distinguish similar but diachronous phases of deformation, and to better constrain the age of the structural markers. A good example of such strategy is found in the central Gotthard massif. The Rotondo granite

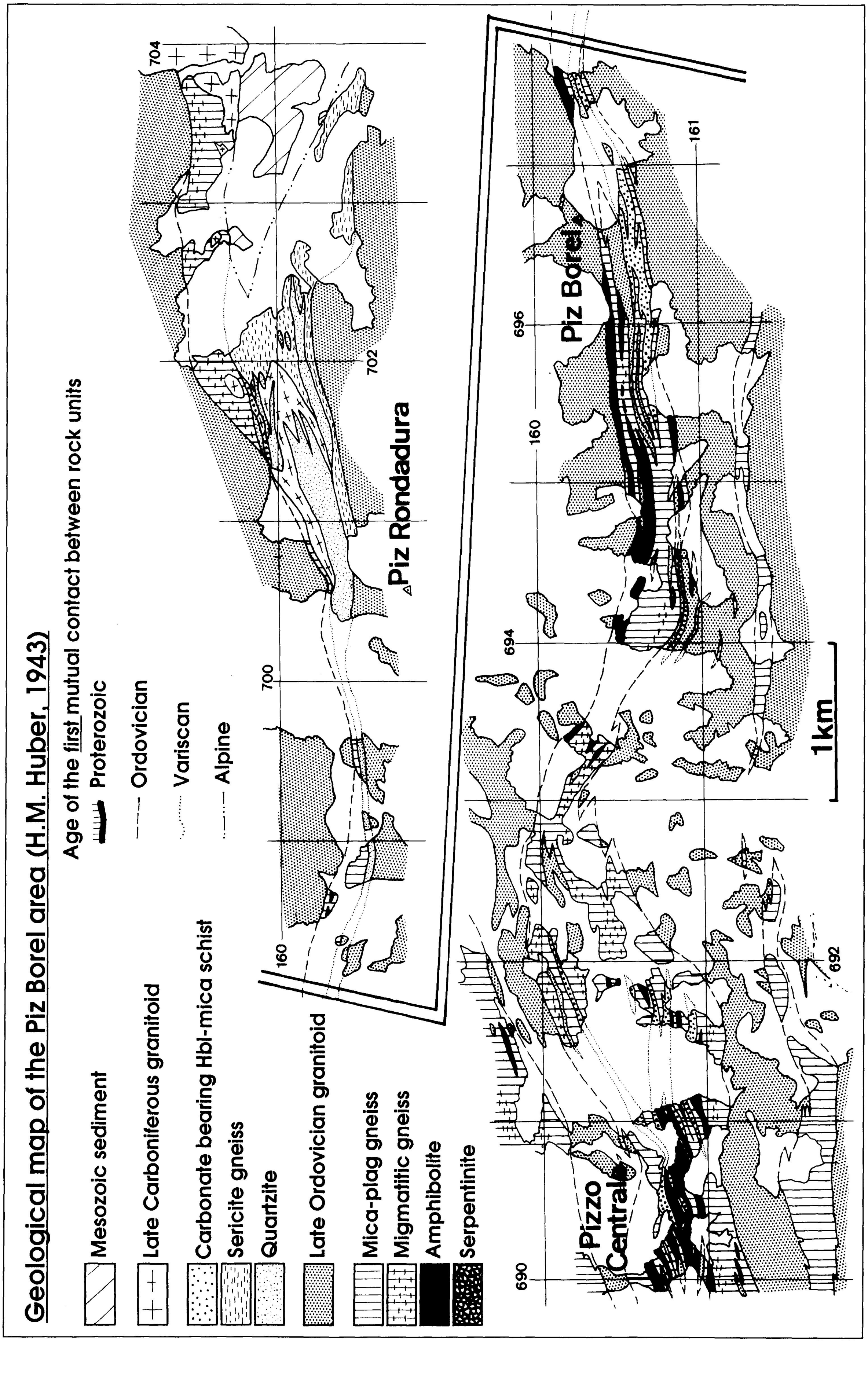

Fig. 4 Geological map of the Piz Borel zone, after HUBER (1943).

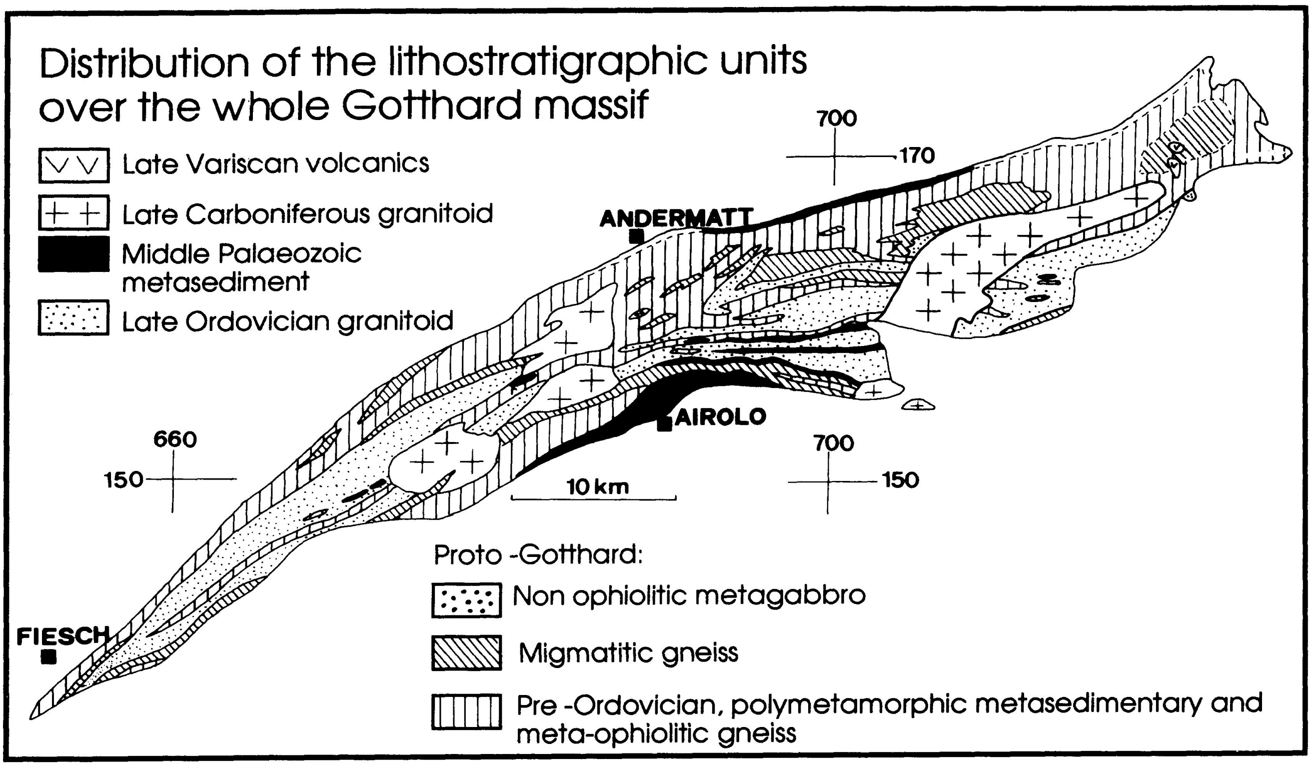

Fig. 5 Distribution of the lithostratigraphic units over the whole Gotthard massif. Drawn after the Geological Map of Switzerland 1:500 000, 1980.

shows significant differences in deformation patterns when compared to the Fibbia-Gamsboden orthogneisses (HAFNER, 1958; STEIGER, 1962; GRÜNENFELDER and HAFNER 1962; KVALE, 1966; MARQUER, 1990). New chronological data suggest that a phase of deformation occurred within a relatively limited time span at the end of the Variscan cycle (GUERROT and STEIGER, 1991; SERGEEV and STEIGER, 1993). This phase is probably responsible for the differences in deformation of the Variscan plutons. A Late Variscan tectonic phase was also suggested for the Aar massif by OBERHÄNSLI et al. (1988).

Conclusions and open problems on the Gotthard massif structuration

The proposed lithostratigraphy helps us to understand the structuration of the Gotthard massif, but poses new questions too. In the following, some of these problems are briefly outlined.

THE VARISCAN PALEOGEOGRAPHY

The pre-Triassic evolution is a good criteria in order to understand the old structuration of the Alpine basement. The Gotthard massif shows a pre-Alpine metamorphic evolution similar to that of the Tavetsch (BIINO, 1994), Silvretta (MAGGETTI and FLISCH, 1993) and Strona Ceneri (as already suggested by NIGGLI, 1944). They possibly formed a coherent basement, later on disrupted by Alpine tectonics.

More problematic is the correlation with the Aar massif (ABRECHT, 1994). Some differences (lack of extensive Ordovician intrusion, presence of "Schollenamphibolite", widespread occurrence of low pressure migmatites, and strong retrogression of the high temperature assemblages) suggest a different Paleozoic evolution. The presence in both terranes of slightly diachronous and, in a wider sense, cogenetic intrusives (Late Carboniferous granitoids) may help to constrain the timing of the Late Variscan rearrangement of the different blocks.

THE NATURE OF THE CONTACT BETWEEN THE BASEMENT AND THE MIDDLE PALEOZOIC METASEDIMENTS

The Late Ordovician granitoids were themselves folded together with the older basement, as indicated by their pervasive foliation and the large scale open fold ("Schlingen" tectonic, Fig. 2). The time of this deformation is loosely constrained by the Upper Devonian – Lower Carboniferous

(Variscan) tectonics. If the Middle Paleozoic metasediments represent the cover of the basement, then they should be folded with the basement during this tectonic stage. From the literature it is hard to prove such a conclusion. The other possibility is that the Middle Paleozoic metasediments may represent a Variscan nappe from a higher structural level, tectonically juxtaposed with the basement after the Schlingen tectonic phase. In any case the Middle Paleozoic metasediment-basement contact must be of Carboniferous age. In fact, the Upper Carboniferous intrusives clearly crosscut these structures and locally produced a contact metamorphism in the Middle Paleozoic metasediments (e.g. Medel intrusive in the Rondadura Valley, Fig. 4).

In the Tremola series, Steiger (1962) described two metamorphic events. The first prograde event is characterized by a metamorphic grade increasing towards the north. The later metamorphic phase is responsible for the formation of the garben texture, and the metamorphic grade increases towards the south. The thermal gradient of the first event is quite problematic and difficult to explain in terms of the Alpine metamorphic evolution only. The correlation of the first metamorphism with a Late Variscan event, presumably the phase of deformation observed in the older Late Variscan plutons (Fibbia, Gamsboden and Medelser), would coherently explain Steiger's observations.

THE COVER SYNCLINES

The Piz Borel zone (Huber, 1943) is a small east-west trending complex slice between two bodies of Late Ordovician metagranitoids, and is well developed between the Pizzo Centrale and the Lucomagno pass (Fig. 4). From west to east it contains: Upper Proterozoic metasedimentary and meta-ophiolitic rocks, Middle Paleozoic metasediments (truncated and metamorphosed by the intrusion of a Late Variscan granitoid which was itself deformed by Alpine tectonics) and finally Mesozoic metasediments. Accordingly, three orogenic events are superimposed in this small zone. In pre-Late Ordovician times the ophiolitic material (metabasalt and meta-ultramafic) was folded and metamorphosed together with metasedimentary gneisses. After the intrusion of the Late Ordovician granitoids the active folding during the Variscan orogeny was superimposed on the pre-existing structures. The juxtaposition of the Middle Paleozoic metasediments predates the intrusion of the Upper Carboniferous granitoids. Finally, in Alpine times, the Mesozoic sedimentary cover was itself folded into the same previously folded structures (Lambert et al., 1992). It can, therefore, be expected that also other ancient structures have consecutively been reused during different tectonic phases from the Proterozoic until the present.

A logic continuation of the Piz Borel zone can be traced eastwards between the Fibbia and Gamsboden bodies and, after the break of the Rotondo granite, until the Rappental (Fig. 5).

Similar zones represent intrabasement (both Alpine and older) thrust planes. Without sedimentary markers, the importance of these thrust planes may be underestimated. Metamorphic petrology points out a complex tectonic setting with imbrication of basement slices in the Gotthard massif as suggested by anomalous Alpine pressure gradients (Lucomagno pass after Ridley, 1989) and Alpine temperature gradient (Nufenen pass after Kamber, 1993).

Summary

The Gotthard massif shows a coherent lithostratigraphy and can be subdivided into units (Tab. 2), which can be traced across the entire massif (Fig. 5). We propose the following revised lithostratigraphic subdivision of the Gotthard massif:

- Uppermost Carboniferous, Permian and Mesozoic sedimentary covers (with some outcrops of Permo-Carboniferous volcanics)
- Late Variscan granitoids (divided into two cycles by a deformation phase)
- Middle Palaeozoic metasediments
- Late Ordovician metagranitoids
- Proto Gotthard (pre Late Ordovician):
  - Migmatitic gneisses
  - Metagabbros, with island arc affinity
  - Metabasalts, metagabbros and meta-ultramafics, with ophiolitic affinity
  - Metasedimentary gneisses.

Within the pre-Mesozoic basement of the Gotthard massif, indications on possible protholiths, relics of metamorphic parageneses and magmatic events, permit to classify the units chronologically and to distinguish major orogenic cycles. The geological history proposed by Abrecht et al. (1991a) is summarized in table 3.

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