Zeitschrift: Eclogae Geologicae Helvetiae
Herausgeber: Schweizerische Geologische Gesellschaft
Band: 79 (1986)
Heft: 1

Artikel: Structural evolution and metamorphism of the Dent Blanche nappe and the Combin zone west of Zermatt (Switzerland)

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DOI: https://doi.org/10.5169/seals-165825

Eclogae geol. Helv.	Vol. 79	Nr. 1	Pages 41–56	Basel, April 1986

Structural evolution and metamorphism of the Dent Blanche nappe and the Combin zone west of Zermatt (Switzerland)

By MARTIN MAZUREK[1])

ABSTRACT

An area west of Zermatt exposing a profile through the Combin zone (Prépiémontais–Piémontais externe) and the lower part of the Arolla series (Dent Blanche nappe, Austroalpine basement) was studied in detail. The Dent Blanche rocks include orthogneisses of granitoid to gabbroic composition. They were strongly deformed and metamorphosed under Mesoalpine greenschist facies conditions during thrusting. No traces of older deformations or metamorphic events, either Eoalpine or Prealpine, were observed.

A structural comparison of the Dent Blanche nappe and the Combin zone including field and microstructural evidence yields the following model: Thrusting of the Dent Blanche nappe (D_1) leaves the strongest imprint on both tectonic units. It is accompanied by mylonitization and the development of the main schistosity (S_1) and a metamorphic banding. This banding is strictly parallel to the thrust plane. In a later stage of this deformation, isoclinal, NNE–SSW-trending folds indicate a compression oriented approximately ESE–WNW. Mesoalpine greenschist facies metamorphism is syn- and post-D_1. Its peak results in postkinematic anneal of the deformed fabrics and the growth of new biotite. A large-scale fold in the Dent Blanche nappe, labeled D_2, deforms the preexisting S_1 metamorphic banding and schistosity. It has an E–W orientation and may be related to a late northward movement. Backfolding (D_3) is well developed in the Combin zone but does not affect the Dent Blanche nappe. The thrust plane of the latter is not deformed by D_3. D_4 fractures and faults result from late differential uplift within the whole area.

ZUSAMMENFASSUNG

In einem Gebiet westlich von Zermatt, das ein Profil durch die Combin-Zone (Prépiémontais–Piémontais externe) und den unteren Teil der Arolla-Serie (Dent-Blanche-Decke, ostalpines Kristallin) liefert, wurde die strukturelle Entwicklung dieser beiden Einheiten untersucht. Die Gesteine der Arolla-Serie enthalten Orthogneise granitoider bis gabbroider Zusammensetzung. Sie wurden im Zusammenhang mit der Dent-Blanche-Überschiebung stark deformiert und in mesoalpiner Grünschieferfazies metamorph überprägt. Es wurden keinerlei Anzeichen einer älteren Deformation oder Metamorphose (eoalpin, voralpin) beobachtet.

Ein struktureller Vergleich zwischen Dent-Blanche-Decke und Combin-Zone liefert folgendes Modell: Die Überschiebung der Dent-Blanche-Decke (D_1) ist in beiden tektonischen Einheiten gefügeprägend. Sie wird begleitet von Mylonitisierung und der Ausbildung der Hauptschieferung S_1 sowie einer Stoffbänderung, welche streng parallel zur Überschiebungsfläche stehen. In einer späteren Phase der Deformation D_1 entsteht eine isoklinale Faltung mit NNE–SSW-Achsen, welche eine etwa ESE–WNW gerichtete Kompression dokumentiert. Die mesoalpine Grünschiefer-Metamorphose ist syn- und post-D_1, ihr Höhepunkt bewirkt eine postkinematische Rekristallisation und das Wachstum neuen Biotits. Eine grossräumige Falte (D_2) in den Arolla-Gneisen deformiert die präexistierende S_1-Stoffbänderung und Schieferung. Sie ist E–W orientiert und dokumentiert die letzte gegen Norden gerichtete Bewegung. Die anschliessende Rückfaltung ist in der Combin-Zone intensiv ausgebildet, scheint die Dent-Blanche-Decke aber nicht zu beeinflussen. Die Dent-Blanche-Überschiebungsfläche wird durch D_3 nicht deformiert. Klüfte und grössere Brüche (D_4) sind eine Folge differentieller Hebung des ganzen Gebiets.

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1. Introduction

The area studied is located on the north slope of the Zmutt valley west of Zermatt at an altitude of 2100–3300 m a.s.l. (grid ref. 618–620/95–97, see Fig. 1). Due to the very rugged topography, this exposure yields a three-dimensional view of the structures. The profile exposes the whole Combin zone (700 m thick) and part of the overlying Dent Blanche nappe (500 m thick in the area studied). The tectonic map of the Zermatt region on Figure 1 displays the major units. As the area is located west of the Lepontine structural high, the general dip of all units is approximately to the west. About 4.5 km^2 were mapped on a scale 1:10000. The emphasis of the field work was to describe the various lithologies and to deduce the structural history.

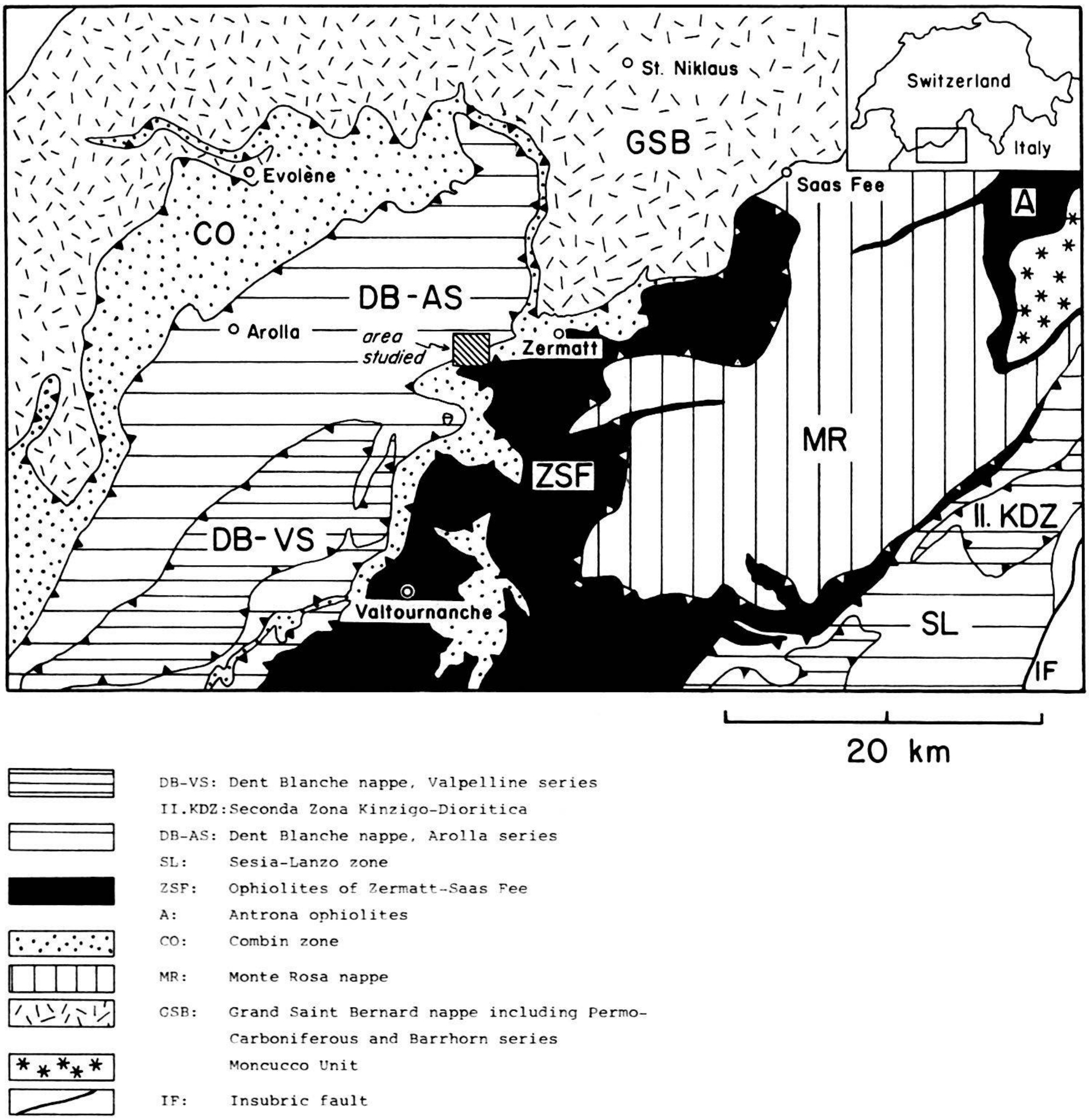

Fig. 1. Simplified tectonic map of the Zermatt region and location of the area studied. Smaller tectonic units are not distinguished. Compiled from BEARTH (1964), DAL PIAZ & ERNST (1978) and the Tectonic Map of Switzerland (Schweiz. geol. Komm. 1980).

Geological setting (see Fig. 1 and 2)

The *Combin zone* (ARGAND 1909) is a sequence of Mesozoic metasediments and metavolcanics which overlie the ophiolites of the Zermatt–Saas Fee zone (Piémontais basin) in the south (as in the area studied, see Fig. 2) and the Grand St-Bernard nappe with its parautochthonous sediments (Barrhorn series, Briançonnais) in the north. It is overlain either by the Tracuit zone (Piémontais basin) or, as in the area studied, directly by the Austroalpine Dent Blanche nappe. Its paleogeographic position is transitional between the Briançonnais high (Triassic, Liassic carbonate sequences including breccias) and the Piémontais basin (metavolcanics, some metagabbros) (BEARTH 1974). Detailed stratigraphic work by MARTHALER (1984) yields an origin from the "Prépiémontais" (basin) and "Piémontais externe" (a supposed relative high between the Prépiémontais and the Piémontais basins) realms. Thus the tectonic position of the Combin zone over the ophiolites is an inverted one. This reversal is explained either by Eoalpine southward thrusting (DAL PIAZ et al. 1972) or by post-Lepontine backfolding (MILNES et al. 1981, MÜLLER 1983b). The latter explanation is more plausible in the studied area. It does not, however, account satisfactorily for the emplacement of the southern parts of the Combin zone (e.g. east of Valtournanche, see Fig. 1).

The *Dent Blanche nappe,* a huge crystalline klippe, overlies the Combin zone (Fig. 2) and is situated in an axial depression between the Zermatt valley and the Val d'Aosta (Italy). It is the highest tectonic unit of the Valais Alps. The whole complex was first mapped and described by GERLACH (1869, 1871) and ARGAND (1908, 1909). It can be subdivided into the Arolla series (predominantly orthogneisses, gabbros) and the overlying Valpelline series (orthogneisses, paragneisses) (ARGAND 1909). The studied part of the Dent Blanche nappe is situated entirely in the Arolla series. Both due to its sedimentary cover (Mont Dolin; HAGEN 1948, WEIDMANN 1974) and to its lithologic similarity with the Sesia–Lanzo zone (see Fig. 1) (CARRARO et al. 1970, DAL PIAZ et al. 1972), the Arolla series is assigned an Austroalpine provenance.

Metamorphic conditions

The only sure traces of a Prealpine (presumably Variscan) metamorphism in the Dent Blanche nappe are reported from paragneisses (sillimanite–biotite–cordierite) and marbles (garnet–diopside) of the Valpelline series (ARGAND 1909, MASSON 1938). An Eoalpine high-pressure metamorphism is known from the Sesia–Lanzo zone and klippen to the northwest (e.g. Mt. Emilius, BEARTH et al. 1980 and DAL PIAZ et al. 1983) and is documented by the occurrence of eclogites and glaucophane-bearing rocks. Based on this evidence, many authors infer an Eoalpine high-pressure phase for the Dent Blanche nappe as well, though no conclusive data are available so far. DAL PIAZ et al. (1972) reported a northward decrease in pressure for the Eoalpine phase within the Sesia–Lanzo zone, the northern part of which is of greenschist grade. They distinguish this greenschist event from the younger Lepontine (= Mesoalpine) metamorphism. Thus, a possible Eoalpine metamorphism of the Dent Blanche nappe may be weak, lack high-pressure mineral parageneses and be largely overprinted by the younger event.

AYRTON et al. (1982) and THÉLIN et al. (1983) report blue amphiboles and clinopyroxenes both from the Arolla series and from the Combin zone in the region west of

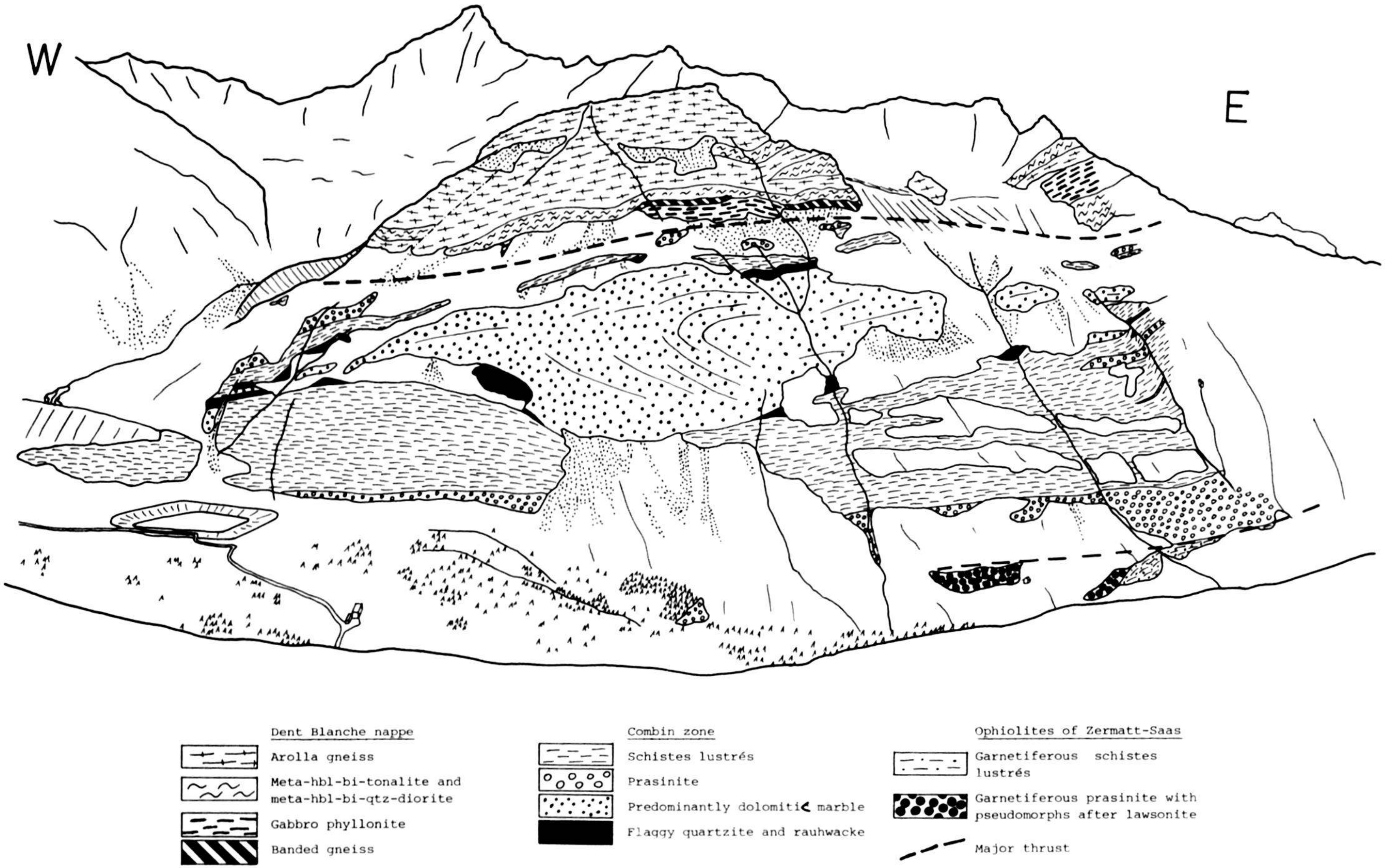

Fig. 2. View of the northern side of Zmutt valley as seen from the foot of Matterhorn glacier. The mountain in the background is the Obergabelhorn. The profile shows the uppermost portions of the Ophiolite zone of Zermatt–Saas Fee, the whole Combin zone and the lowermost 500 m of the Dent Blanche nappe.

Arolla, i.e. about 15–20 km west of the area investigated here. These minerals occur mainly in metabasic rocks (prasinites, metagabbros) but are also found in leucocratic gneisses of the Arolla series. Glaucophanitic amphibole and omphacitic clinopyroxene are generally regarded as indicators of higher-pressure metamorphic conditions, although no microprobe analyses of these minerals are given in the aforementioned papers. AYRTON et al. (1982) carried out age determinations of white micas in order to elucidate the age of the supposed high-pressure metamorphism. The samples, all from metasediments of the Combin zone, yielded ages of 55–30 my (K/Ar) and 44–30 my (Rb/Sr). These data are interpreted either as rejuvenated Eoalpine ages or ages belonging entirely to Mesoalpine metamorphism.

Thus, a high-pressure metamorphism of the Arolla series and the Combin zone is not well established, though it may very well be present at least in the Dent Blanche nappe.

Both in the Dent Blanche nappe and in the Combin zone the Lepontine greenschist facies metamorphism (38 my according to HUNZIKER 1969) is dominant, and, at least in the area studied by the author, the only recognizable event. No geothermo-barometry was carried out for the present study, but maximum Lepontine temperatures are estimated to be around 450 °C from available mineral parageneses. These are: chlorite + actinolite + epidote + albite (prasinites), paragonite + quartz + calcite (schistes lustrés), dolomite + quartz reacting to talc + calcite (schistes lustrés) and the presence of biotite. The presence of epidote + albite, sphene and talc indicate a high water activity in the fluid phase. There are no indications for a difference in Lepontine metamorphic conditions between the Combin zone and the Arolla series. Lepontine pressures are hard to establish, but can be estimated at around 4 kbar assuming a geothermal gradient of 30–40 °C/km.

2. The Arolla series

Petrographic description

The Arolla series of the Dent Blanche nappe consists of orthogneisses variously affected by deformation. They comprise the Arolla gneisses (GERLACH 1871) and overprinted hbl-bi-tonalites, hbl-bi-qtz-diorites and gabbros (for abbreviations, see caption of Fig. 6).

The *Arolla gneisses* are a collective term for primarily different types of metagranites with or without augen texture. They are by far the most important rock type of the Arolla series. The hornblende-bearing variety was named "arkesine" by GERLACH (1871). The magmatic minerals are biotite, sometimes hornblende, k-feldspar, plagioclase, quartz ± allanite, sphene, apatite and zircon. The rock types vary from hbl-bi-melagranites to bi-granites and bi-poor leucogranites. Lithologic contacts are indistinct and often obscured by recrystallized mylonite zones. Bands of leucogranitic gneiss ranging in thickness from 1 dm to several meters are common in all other lithologies.

The microfabric of the Arolla gneisses is mylonitic and shows extensive pseudomorphization and post-mylonitic, static recrystallization. The photographs on Figures 3–5 show the progressive deformation of a typical Arolla gneiss in hand-specimen and thin-section (note the very different scales of the two photographs on Fig. 4 and 5). The mesoscopic appearance of the rocks varies greatly as a function of progressive deformation.

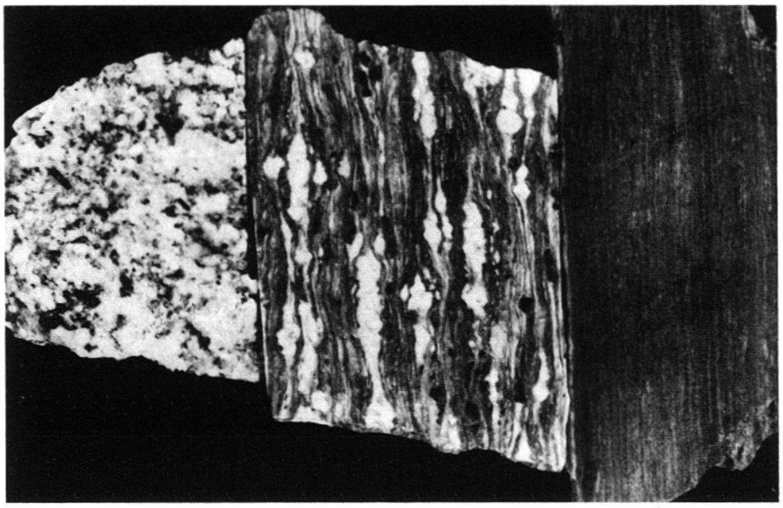

Fig. 3. Progressive deformation of an Arolla gneiss.

1. Left: Undeformed hbl-bi-granite from the Mont Collon area (grid ref. 605.3/93.2).
2. Centre: Typical Arolla gneiss with augen of chessboard albite (pseudomorphed microline). Plagioclase and biotite are completely altered.
3. Right: Ultramylonitic Arolla gneiss. No magmatic minerals or textures are preserved.

Width of picture 15 cm.

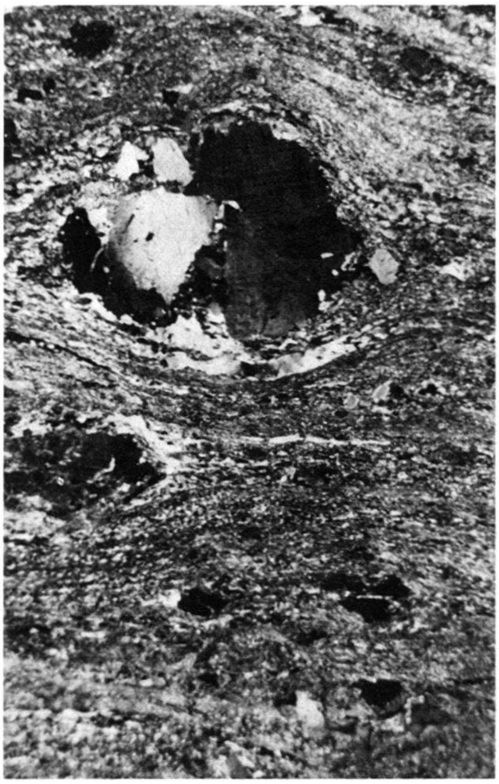

Fig. 4. Optical micrograph of handspecimen 2 in Figure 3. Porphyroclasts of albitized microcline (top) and hornblende (bottom half) in a fine-grained matrix of white mica, epidote, albite and quartz. Height of photograph 18 mm, crossed polarizers.

Fig. 5. Optical micrograph of the ultramylonitic handspecimen (No. 3 in Figure 3). Leucocratic bands consist of quartz and albite, melanocratic laminae consist of white mica and epidote. A hypidiomorphic garnet is seen in the upper right-hand corner. Height of photograph 0.6 mm, crossed polarizers.

In the small area studied in detail, all Dent Blanche rocks are strongly deformed. Weakly deformed and almost unaltered Arolla granites can be found only 10 km further west in the region Mont Collon–Bouquetins (grid ref. 605–608/90–94), where saussuritization of plagioclase is the only alteration.

The metamorphic overprint of all lithologies of the Arolla series occurred during a single event. It took place during and just after the mylonitic deformation D_1 (see below), which is related to the thrusting of the Dent Blanche nappe. It ended with a postkinematic recrystallization, which represents the peak of Lepontine metamorphism. There are no microstructural arguments that would point to an earlier metamorphic event, either Eoalpine or Prealpine.

The sedimentary cover of the Dent Blanche nappe preserved on Mont Dolin (20 km west, grid ref. 601.3/97.0) contains polygenic breccias, probably of Middle Jurassic age (Hagen 1948, Ayrton et al. 1982). The breccias include large components of foliated rock similar to leucocratic Arolla gneisses. Do these observations suggest a Prealpine (i.e. Pre-Middle Jurassic) deformation of Arolla gneisses? A close inspection reveals: 1) that the internal schistosity of the components is subparallel to the schistosity in the surrounding carbonaceous matrix and; 2) that the crystalline components are likely to represent a metamorphosed quartz porphyry. It is striking that the hypidiomorphic quartz phenocrysts are not very deformed. Most of the deformation must have been accommodated in the very fine-grained matrix. The point made here is that the dynamically recrystallizing matrix may have been sufficiently incompetent to allow an internal deformation of the breccious components in an Alpine deformation. Thus, it is not necessary to invoke a Prealpine deformation in order to explain these fabrics.

Relationship between deformation and mineral growth

The mineralogical evolution of an Arolla gneiss is shown on Figure 6. It is obvious that deformation (D_1) enhances mineral reactions, as the proportion of magmatic minerals strongly decreases with deformation.

The first transformations are saussuritization of plagioclase and formation of chlorite, epidote and sphene from biotite (see Fig. 7). Both plagioclase and biotite are preserved only as pseudomorphs except for samples from the Mont Collon–Bouquetins region. The latter show no indications of older deformation despite the relatively weak Lepontine overprint.

The alteration of hornblende to actinolite, epidote, sphene and chlorite (see Fig. 7) is in most cases confined to rims and cracks. K-feldspar is completely albitized in hornblende-bearing rocks (often resulting in chessboard albite, see Fig. 4), though it can be preserved in leucocratic gneisses.

Progressive deformation destroys the pseudomorphic textures of the aforementioned transformations and leads to a decrease in grain size, accompanied by the development of segregated, mylonitic laminae of mm width rich in quartz, albite and white mica, epidote, respectively (metamorphic differentiation). Examples of these textures are shown on Figures 4 and 5. Postkinematic recrystallization results in an increase of grain size. The highest-grade mineral is new undeformed biotite (intergrown with phengite). Garnet also occurs, but is rare and restricted to the ultramylonites. Due to this localized occurrence, garnet is interpreted to have grown during D_1 mylonitization.

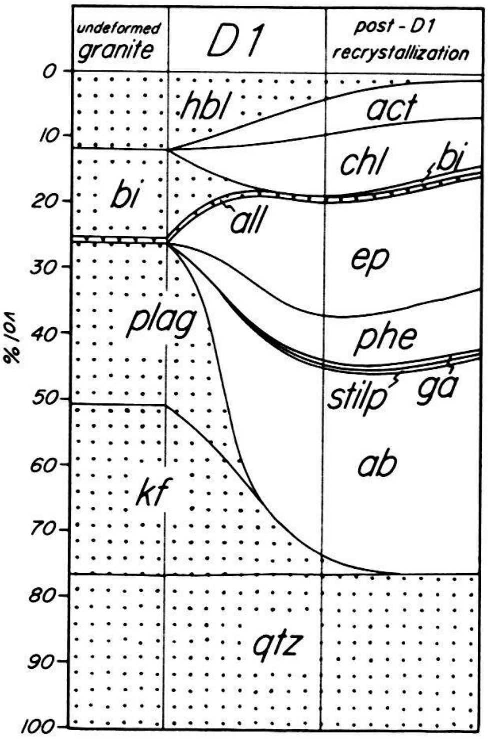

Fig. 6. Mineralogical evolution of an hornblende-bearing Arolla gneiss as a function of progressive deformation and recrystallization. Magmatic minerals are stippled. Their proportion strongly decreases during D_1 deformation. Abbreviations: ab = albite, act = actinolite, all = allanite, bi = biotite, cc = calcite, ep = epidote, ga = garnet, hbl = hornblende, kf = K-feldspar, phe = phengite, plag = plagioclase, qtz = quartz, sph = sphene, stilp = stilpnomelane.

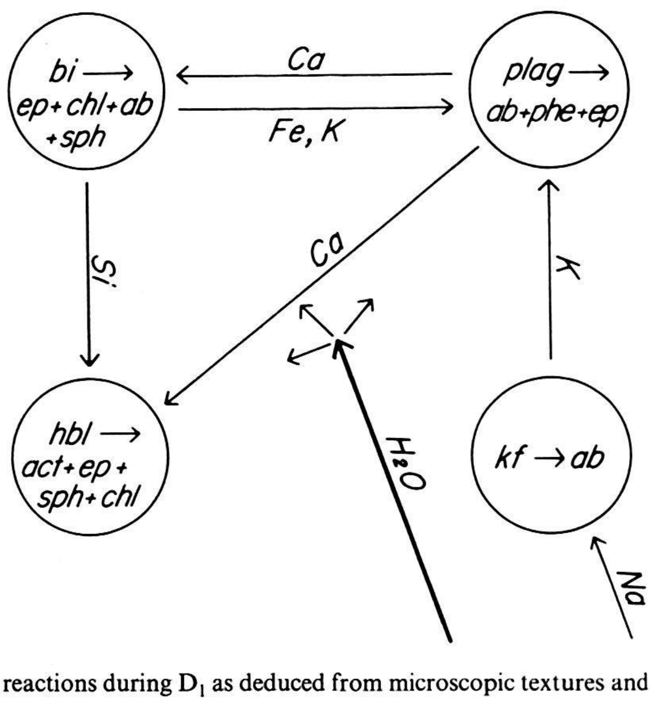

Fig. 7. Qualitative mineral reactions during D_1 as deduced from microscopic textures and their mass balance. H_2O and Na must be supplied to the rock to balance the reactions.

The hbl-bi-tonalites and hbl-bi-qtz-diorites are transformed to chl-ep-schists with progressive deformation. Metagabbros in the area studied are only found in the lowest parts of the Arolla series, close to the thrust plane (see Fig. 2), and therefore are transformed to a crumbly phyllonite. Relics of clinopyroxene in hornblende are only preserved in some small lenses that escaped penetrative deformation.

A striking feature is the extensive albitization of the rocks in the Zermatt area. So far, this phenomenon has been reported from various lithologies of the Monte Rosa nappe (BEARTH 1948), the Ophiolites of Zermatt–Saas Fee and the Combin zone (BEARTH 1967). Albite growth is syn- and post-D_1 in the Arolla gneisses and replaces k-feldspar and plagioclase. In many cases, this process required a Na source outside the deformed rock. Even basic lithologies (e.g. gabbros) may contain rock portions which have excessive amounts of albite and yield whole-rock analyses with up to 10 wt% Na_2O. The main phase of albite growth in the Combin zone is post-D_1 and may be correlated with the albitization in the Arolla series. Ovarditic textures are typical. Albite porphyroblasts replace deformed muscovite in the schistes lustrés and chlorite, actinolite ± muscovite in prasinites. As far as could be observed, the albitization was not restricted to fracture zones.

Large-scale and mesoscopic structures in the Arolla series

All structures measured (except for D_4 faulting) are summarized on the plate. The area was subdivided into 13 sectors due to small-scale variation in the structural development.

Mylonitization, main schistosity S_1, folding F_1

The oldest structure recognizable in the Arolla series is the penetrative schistosity S_1, which is associated with the intensive mylonitic deformation described in the last section. The degree of this deformation varies widely on the scale of meters and decameters. On the whole, it decreases with increasing distance from the Dent Blanche thrust, to which it is strictly parallel. Greenschist parageneses are associated with S_1. All lithologies are deformed in 10–100 m thick bands, which can be traced over distances more than 1 km parallel to the general strike of S_1 (see Fig. 2). Lithologic contacts are indistinct and usually gradational. Basic inclusions in Arolla gneisses yield axial ratios of up to 30:10:1.

The base of the Dent Blanche nappe consists either of a gabbro phyllonite or of a banded gneiss. This gneiss is comprised of alternating, decimeter-thick layers of leucogranitic gneiss and chl-ep-gneiss. In most cases, the thrust plane itself is hidden beneath grass. S_1 is constant close to the thrust plane and gently dips to the northwest (about 310/25, see the plate). In the upper sectors 3–4, S_1 dips more steeply (40–70°), is widely scattered, and becomes indistinct. The scatter of S_1 is a consequence both of the weakly developed foliation in the quartzo-feldspathic, mica-poor rocks of sectors 3–4 and, more importantly, of a later, inhomogeneous, semi-ductile to cataclastic deformation and folding.

Where S_1 is well developed, F_1 folds are very common. They formed in a later stage of D_1 in rocks where the banding was sufficiently well developed to accommodate deformation by buckling. They are of similar type and their size is in the centimeter range. Their axial planes are parallel to S_1. The fold axes plunge gently to the northeast (25/15), indicating compression oriented approximately ESE–WNW. As the same greenschist minerals are associated with F_1 and S_1, these two structures belong to the same phase. A stretching lineation of actinolite can be recognized parallel to the fold axes. Deformation phase D_1 is clearly related to the thrust of the Dent Blanche nappe. As the highest-grade minerals of the Lepontine upper greenschist metamorphism grew during a post-D_1, static, recrystallization (see above), the Dent Blanche thrust must be older than upper Eocene (38 my according to HUNZIKER 1969). An upper time bracket for the thrust is supplied by MARTHALER (1984) who dated Wildflysch of the Barrhorn sediments (which were overridden by the Dent Blanche nappe) as somewhere between Maastrichtian and Middle Eocene.

Large-scale fold F_2

Poles to S_1 form a girdle pattern in the northern sectors 1–4 (see the plate) and define a large-scale, open fold closing to the north (see sketch on Fig. 8). It can be traced throughout the area. On the Aebihorn (grid ref. 616.5/96.5), this fold is defined lithologically by a horizon of schistes lustrés folded into the surrounding crystalline rocks. The fold axis is horizontal and trends E–W. Smaller-scale D_2 deformation is cataclastic and typically concentrated along lithologic contacts, which consist of very sharp, polished

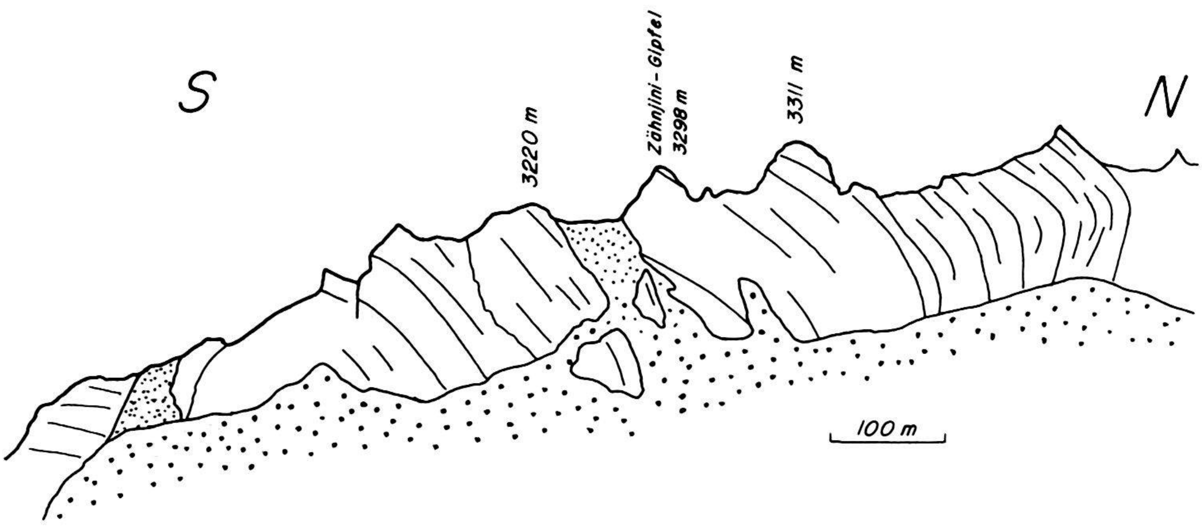

Fig. 8. Large F_2 fold in the Arolla gneisses as seen parallel to the fold axis, looking west from grid ref. 619.4/96.6.

surfaces (in contrast to the transitional lithological boundaries in sectors 5–8). These zones reflect bedding plane-slip associated with D_2 folding. Apparently, the lithologic contacts are inherited zones of weakness. In some places, bigger rock portions are reduced to a fine mortar, either along discrete shear zones or pervasively. Leucocratic, mica-poor rocks display cataclastic deformation. Very often, no minerals can be distinguished by the naked eye, and the rock is massive. Deformation of mica-rich rocks is semi-ductile and characterized by small-scale folds, whose limbs merge into shear zones. D_2 is not followed by static recrystallization and evolved at lower temperatures than D_1. There is limited growth of chlorite and calcite. D_2 is interpreted to be a late northward movement of the Dent Blanche nappe.

3. The Combin zone

As the Combin zone has received much attention in the past (e.g. ARGAND 1909, GÜLLER 1947, BEARTH 1953a, b, 1964a, b, 1974, 1976, DAL PIAZ et al. 1978), no petrographic description will be given here. In the area studied, it consists of Triassic quartzites and carbonates and of Jurassic–Cretaceous carbonaceous to argillaceous schists (schistes lustrés) and prasinites (chlorite–actinolite–epidote–albite rocks mostly derived from basic volcanics). No internal subdivision of the Combin zone into "Untere" and "Obere Zermatter Schuppenzone" (BEARTH 1953a, b) can be made in the area studied. A large-scale fold in the Combin zone closing to the southwest can be recognized from a distance (see Fig. 2). The fold-core consists of a synform of Triassic dolomites which comprise the striking 300 m high face seen on Figure 2. This fold-core is mantled by younger schistes lustrés and prasinites.

Structural relations

Main schistosity S_1

Greenschist facies parageneses comprise the S_1 foliation. This schistosity is penetrative and parallels the banding of schistes lustrés and prasinites. This banding is probably of sedimentary origin and was transposed parallel to the new planar structure. S_1 is constant in the upper sectors 10–11 and parallels the Dent Blanche thrust, i.e. it gently dips to the northwest. In the lower sectors 12–13 it is deformed and is distributed in a girdle pattern. Folds related to D_1 are rare and are best recognized in small quartz streaks as exemplified in Figure 9. They are refolded during D_3 and range from 1 cm to several dm in amplitude.

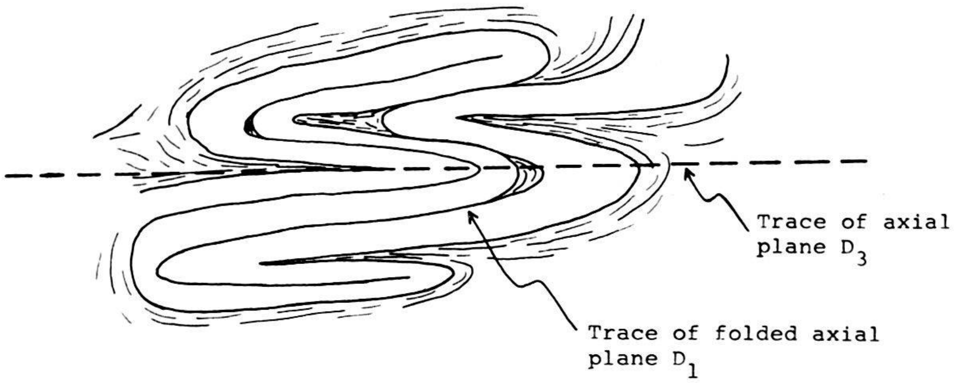

Fig. 9. Polyphase deformation of a quartz streak in schistes lustrés. A rootless and now isoclinal fold, presumably of D_1 age, was refolded during backfolding D_3. Width of sketch 15 cm.

D_1 tectonic mélange

The above-mentioned, Triassic fold-core in the Combin zone consists predominantly of dolomitic marbles. It is surrounded by a 0–20 m thick horizon of rauhwacke and flaggy quartzite (see Fig. 2). The quartzite is Lower Triassic, overlain by Middle Triassic rauhwacke and dolomite (BEARTH 1953b, 1964b, GÜLLER 1947). MARTHALER (1984) describes a similar stratigraphy from his "Frilihorn series" (Upper Combin zone). The stratigraphic succession quartzite–rauhwacke–marble is normal in the lower fold limb and reversed in the upper limb. Thus, the Triassic fold is a synform, and the contact with the enveloping younger schistes lustrés and prasinites must be tectonic. The quartzite-rauhwacke horizon is indeed highly tectonized. The rauhwacke consists of up to 50% breccious components of schistes lustrés and quartzite. The thickness of the horizon varies widely. There are multiple repetitions of rauhwacke and quartzite in some places, whereas the whole horizon is missing in other outcrops. This tectonic contact around the fold-core comprised of Triassic rocks documents an internal imbrication of the Combin zone and was refolded during backfolding (see below). It is parallel to S_1 and may thus be a D_1 event.

The very same relations were encountered by MÜLLER (1983a) in his larger-scale structural study. He found Triassic synforms surrounded by younger schistes lustrés (e.g. Chüeberge, 1–2 km north of Zermatt, and Täschalpen, 7 km north-east of Zermatt). In Müller's model, the Triassic of the Combin zone is thrust upon the schistes lustrés during an early deformation. He attributes this imbrication to major thrusting in the nappe pile. Moreover, he discusses some arguments for subsequent isoclinal, large-scale folding with fold axes trending approximately N–S. It is possible that these folds (not observed by the present author on a larger scale) could be correlated with D_1 folds in the Dent Blanche nappe described above.

Backfolding D_3

No structures can be recognized in the Combin zone that could be related to the D_2 phase in the Dent Blanche nappe. Either they are indistinguishable from D_1 or are disguised by D_3 deformation. The large-scale fold described above (see also Fig. 2) closes to the southwest and is related to backfolding. Its formation postdates the north-directed deformations and is labeled D_3. All linear structures of the Combin zone presented on the plate are related to D_3 and represent fold axes and stretching lineations defined mainly by actinolite. Small-scale D_3 structures and the big fold have a parallel orientation of about 320/20. This fits well with the regional pattern investigated by other authors. It is likely that the fold is the direct continuation of the Mischabel backfold 6 km to the northeast in the crystalline rocks of the Grand St-Bernard nappe. Backfolding phenomena in the Valais Alps have been investigated by MILNES (1974), MILNES et al. (1981), MÜLLER (1983a, b) and LACASSIN & MATTAUER (1985). The axial trace of the Mischabel fold as mapped by MILNES et al. (1981, Fig. 2) continues to the west directly into the Combin zone of the area studied. As MÜLLER (1983b) states, the fold becomes isoclinal beyond recognition in the Combin zone due to the large competence contrast between basement and cover rocks. The thick accumulation of Triassic dolomites is the probable reason for its good development in the area investigated here.

Parasitic D_3 folds are usually in the decimeter range. The fold types are parallel, similar or isoclinal depending on lithology. D_3 parasitic folds are absent in the thick dolomite but are prominent in the schistes lustrés and prasinites. The deformational style is semi-ductile on a microscopic scale. Micas are slightly bent or kinked. This is accompanied by the nucleation of secondary quartz, calcite and chlorite. D_3 is younger than the main static crystallization, and no penetrative schistosity is developed.

A new interpretation of structures so far attributed to backfolding is presented by LACASSIN & MATTAUER (1985). They describe the cross section of a supposed sheath fold in Triassic metasediments of the Monte Rosa nappe from Mattmark, Saas valley (grid ref. 638/97.5). Sheath folds are interpreted as products of a very strong, simple shear-dominated deformation mechanism, in which the fold axis and lineations are parallel to the direction of shear (QUINQUIS et al. 1978, COBBOLD et al. 1980). The stretching lineation of the Mattmark sheath fold trends SE–NW, i.e. it parallels lineations of the regional backfolding. Based on this evidence, LACASSIN & MATTAUER suggest that the regional lineation may be due to intense simple shear directed to the northwest. Such a shear movement is also described by LACASSIN (1983) from the Monte Rosa granite. It is my opinion that this deformation may be related to thrusting prior to backfolding. The parallelity of the lineations may be due to passive rotation of older lineations (e.g. D_1?) during backfolding. Rotated lineations have also been described by MÜLLER (1983a). MARTIN (1982) was able to correlate folds and lineations that are clearly parasitic to the Mischabel backfold with the regional lineation over a wide area between Täsch and Villadossola.

The structural relation of the Combin zone to the Dent Blanche nappe (see Table)

The main schistosity S_1 is particularly well developed close to the Dent Blanche thrust and parallel to the latter. Greenschist facies parageneses are related to S_1 in both units. The peak of Lepontine metamorphism is slightly younger than S_1, as biotite is postkinematic in both units. The conclusion is that the Dent Blanche thrust over the Combin zone is related to D_1.

There are no structures related to backfolding in the Dent Blanche nappe, which apparently moved southward as a more or less rigid block. All the deformation was accommodated within the underlying, incompetent Combin zone (consistent with MÜLLER 1983a). The structural evolution of the Combin zone and the Dent Blanche nappe deduced from this study is summarized on the Table.

The structural history presented here is different from the interpretation of AYRTON et al. (1982) for the Arolla region. These authors attribute large-scale structures trending ENE–WSW and a crenulation cleavage within the Arolla series to backfolding. In the Zermatt area, however, backfolding structures within the Combin zone cannot be correlated in style or orientation with any of the structures observed in the Arolla series. The Dent Blanche thrust plane is not deformed by backfolding (AYRTON & RAMSAY 1974).

The structural study in the Combin zone by WILSON (1978) led to the distinction of three deformations and is nicely correlatable with phases D_1, D_3 and D_4 of the present study. The only difference is the interpretation of D_1, which in Wilson's study is correlated with thrusting of the Combin zone upon the Ophiolite zone of Zermatt–Saas Fee. The timing of this south-directed movement is different according to other authors, as discussed above. Wilson does not account for the Dent Blanche thrust, which must have left an imprint on the incompetent sediments.

The latest deformation, labeled D_4, is of brittle character and is developed both in the Arolla series and the Combin zone. It consists of subvertical systems of fractures and faults. A major system of N–S-trending faults displaces the eastern side upward by several meters along each fault. Minor joints are sometimes open. Especially in the Combin zone, they are healed with calcite.

Table: *Summary and interpretation of the structural evolution of the Dent Blanche nappe and the Combin zone determined from this study.*

	DENT BLANCHE NAPPE				COMBIN ZONE			
	EVENT	STYLE OF DEFORM.	RELATED STRUCTURE	MINERAL GROWTH	EVENT	STYLE OF DEFORM.	RELATED STRUCTURE	MINERAL GROWTH
D_1	thrusting	mylonitic	main schistosity S_1 folding F_1 stretching lineat. L_1	crystallization of greenschist parageneses	thrusting of Dent Blanche nappe or other nappe movements	ductile, isoclinal	main schistosity S_1 folding F_1	crystallization of greenschist parageneses
	quiescent stage	--	--	recrystallization peak of Lepontine metamorph.	quiescent stage	--	--	recrystallization peak of Lepontine metamorph.
D_2	last northward movement	semiductile - cataclastic	big fold F_2	qtz, cc, chl	?			
D_3	back-folding	southward movement as a ± rigid block	--	--	back-folding	semi-ductile	backfolding F_3 stretching lineat. L_3	qtz, ab, cc
D_4	differential uplift	brittle	fractures and faults	(cc)	differential uplift	brittle	fractures and faults	cc

4. Conclusions

All deformations are of Alpine age. The strongest tectonic imprint is the development of the main schistosity and subsequent folding. This deformation, D_1, is common to the Arolla series and the Combin zone and developed during thrusting of the Dent Blanche nappe under Mesoalpine greenschist facies conditions. A characteristic metamorphic banding develops in the Arolla gneisses and is strongest close to the thrust plane. The bands are parallel to the latter. The NNE–SSW-trending, isoclinal folds developed later during the same deformational event. This folding is interpreted to result from intense shortening oriented ESE–WNW. The internal imbrication of the Combin zone and the development of Argand's "Würmlizüge" may have formed during this phase. The finite strain must be enormous both in the Dent Blanche nappe and the Combin zone. The presence of a Tertiary flysch beneath the Dent Blanche nappe documents major movements in the Alpine nappe pile during the Tertiary.

Subsequent development of large-scale folds (F_2) in the Dent Blanche nappe indicates that thrusting was not a single event but occurred at different times and under different physical conditions.

Backfolding (D_3) was, at least in the area studied, confined to the Combin zone. The direct continuation of the Mischabel backfold of the Grand St-Bernard nappe can be identified in the Combin zone. The Dent Blanche thrust plane is not deformed in the Zermatt region.

Acknowledgment

I wish to thank Prof. S. Ayrton (Lausanne), Prof. K. Bucher (Oslo), Prof. M. Frey (Basel), M. Handy (Basel), Prof. A. G. Milnes (Trondheim) and Dr. R. Oberhänsli (Berne) for comments and careful reviews of the paper. I am grateful to Prof. Bucher and Dr. Oberhänsli for making their well-documented collection of rocks and thin-sections available to me.

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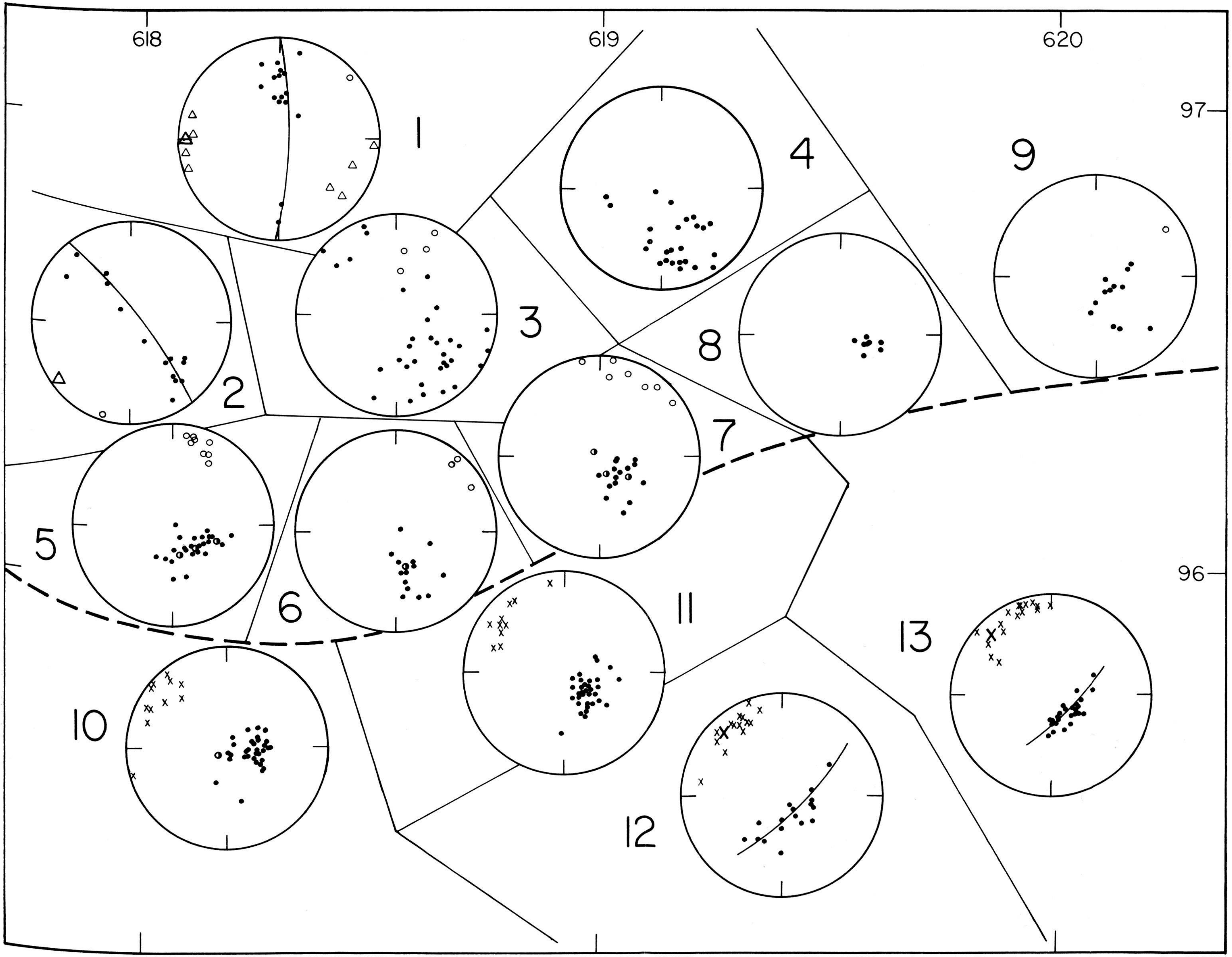
Manuscript received 19 June 1985
Revision accepted 25 November 1985

Plate

Equal-area plots of structures in the area studied (map view). Projection is of the lower hemisphere. Heavy line represents the Dent Blanche thrust. The area covered by the plate is 2.6 km × 2 km.



	D_1	D_2	D_3
S	●		
AP	◑		
L	○	△	×
FA		▲	✕

S = schistosity

AP = axial plane of folds

L = Fold axis and stretching lineation

FA = Fold axis constructed from girdle patterns