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Objekttyp: **Article**

Zeitschrift: **Schweizerische mineralogische und petrographische Mitteilungen = Bulletin suisse de minéralogie et pétrographie**

Band (Jahr): **48 (1968)**

Heft 3

PDF erstellt am: **21.07.2024**

Persistenter Link: https://doi.org/10.5169/seals-37789

The pre-Westphalian (Hercynian) Metamorphism and Structures of the Tödi Area (Aar Massif)

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With 14 figures in the text

Summary

The small areas of pre-Upper Carboniferous sediments of the eastern Aar Massif show folds and contact metamorphism of pre-Westphalian (possibly mid-Carboniferous) age. A preliminary static metamorphism was succeeded by stress-accompanied metamorphism at about the same temperature. Structures of the Bifertenfirn and Val Gliems areas show close similarities and are unrelated to the folds of the Upper Carboniferous of the Bifertengrätli Formation. The cause of the metamorphism was presumably the intrusion of the Tödi granite and a related igneous body in the southern igneous complex of the Massif which is now separated from the northern areas by the important tectonic line of the Val Gliems.

Zusammenfassung

Die geringen Vorkommen vor-oberkarbonischer Sedimente des östlichen Aar-Massivs lassen eine Faltung und eine Kontaktmetamorphose vor-westphälischen (möglicherweise mittelkarbonischen) Alters erkennen. Auf eine erste statische Kontaktmetamorphose folgte eine druckbegleitete Phase mit ungefähr gleicher Temperatur. Die Strukturen von Bifertenfirn und Val Gliems weisen starke Ähnlichkeiten miteinander auf und sind nicht mit der Faltung des Bifertengrätli-Oberkarbons in Zusammenhang zu bringen. Die Metamorphose entstand vermutlich als Folge der Intrusion des Tödigranites und eines verwandten Intrusivkörpers des südlichen Eruptivgesteinskomplexes, der nun vom nördlichen Teil des Massivs durch die wichtige tektonische Linie des Val Gliems getrennt ist.

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I. FOREWORD

This study of the oldest recognisable sediments of the eastern Aar Massif was done as part of a comparative study of the occurrences of rocks which have been described as Upper Carboniferous in age. The Upper Carboniferous sediments, in fact, overlie the older metamarphosed sediments and form a single principal belt along the northern part of the Massif which was described in a thesis of the E.T.H., Zürich (Franks, 1968); the older rocks occurring south of the Upper Carboniferous belt were studied at the same time (1963—1965) because they had in the past been looked upon as equivalent in age (Widmer 1949, Eugster 1955). Since these sediments throw some light on an important early stage in the history of the Massif, the two small field areas, the Bifertenfirn and the Val Gliems, were studied in detail and are here briefly described.

It is a pleasure for me to thank Professor A. Gansser and Professor R. Trümpy for the supervision of this study, their critical suggestions, and for reading an early draft of this paper.

II. INTRODUCTION

The two areas discussed, the Bifertenfirn area and Val Gliems, lie at the eastern end of the Aar Massif, wedged in between more extensive crystalline blocks, just as the Massif disappears beneath the autochthonous Mesozoic mantle and the overthrust sheets of the Helvetic nappes. The old structures of the pre-Triassic sediments have been tightened by the Alpine movements, mainly by continued shearing on the near-vertical cleavage, although the overlying carbonate rocks of the Mesozoic signs of repeated and intense deformation.

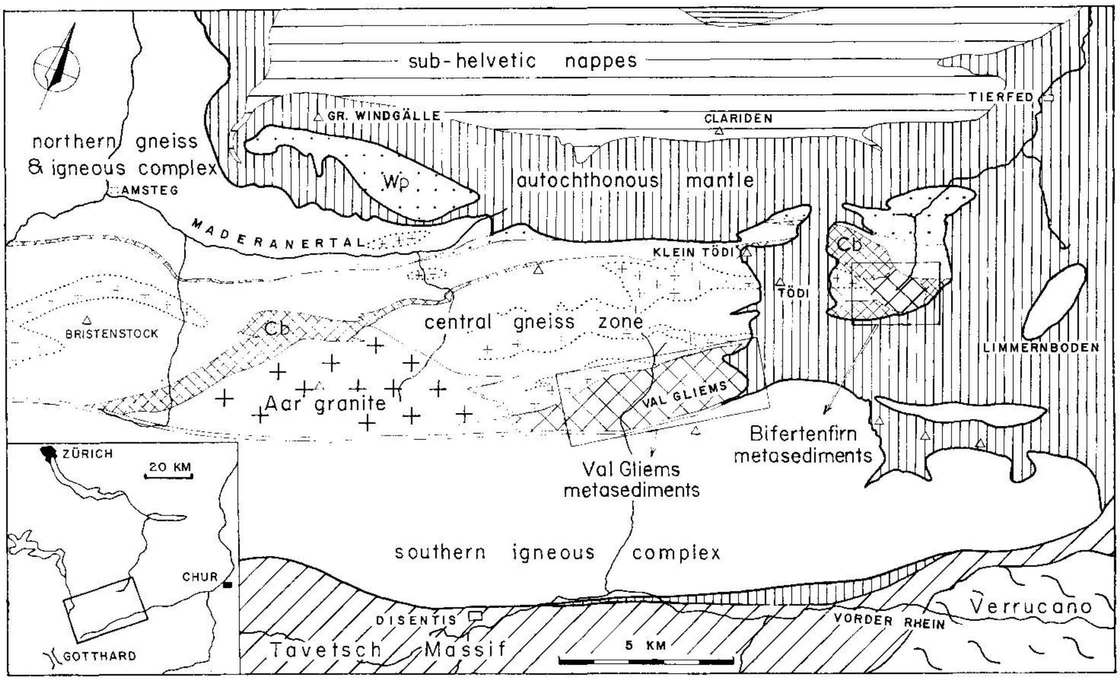

Fig. 1. Simplified geological location map of the eastern Aar Massif. (Cb, Upper Carboniferous sediments; Wp, Windgällen "porphyries" and ignimbrites.)

The two areas, the one lying to the north of Tödi, the other to the south (Fig. 1) are separated by a strong zone of dislocation where the Mesozoic rocks are pinched into a tight syncline. This zone is seen in the basement as a zone of sericitic schists and strongly deformed gneisses. A stronger dislocation to the south of the Val Gliems metasediments contains mylonitic Jurassic sediments

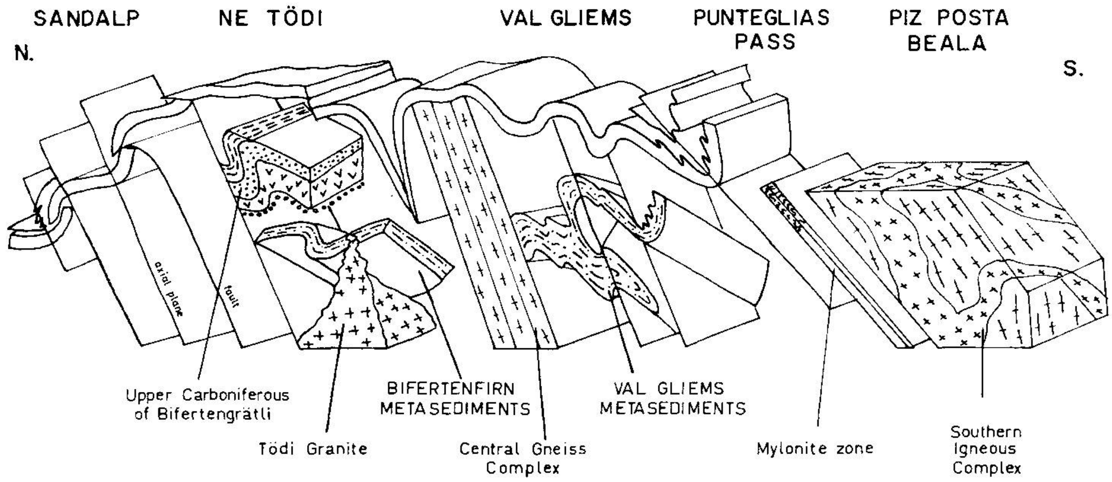

Fig. 2. Schematic block diagram of the pre-Triassic sediments and folding of the Triassic unconformity in the Tödi area. (Triassic Röti Dolomite indicated as the folded layer above the unconformity.)

as calcareous schists and marks an important boundary within the Aar Massif (Fig. 2). The differences of the rocks south of this line with those to the north suggest that it was already a pronounced feature in pre-Alpine times; against it the southern sedimentary belt narrows to the west and the central Aar granites appear to be cut off.

III. THE BIFERTENFIRN METASEDIMENTS

1. Field relations and lithology

Low grade contact metamorphic rocks cover an area of 2½ sq km around the northern end of the Bifertenfirn. The retreat of the glacier in the last 50 years has opened new exposures which were not available to B. G. Escher (1911) or Fr. Weber, although Weber (in Heim, 1922) had already separated an older group of sediments, to which these metamorphic rocks belong, from the overlying Upper Carboniferous. Hügi (1941) gave their first petrographical description. The opinion of Widmer (1949) that the metasediments are the same as the Carboniferous sediments on Bifertengrätli is not tenable.

Many of the sedimentary details of the rocks are preserved, although the individual grains are entirely recrystallized and new minerals are developed in places. The original composition of the rocks must have approached that of lime-free mudstones, siltstones and fine-grained sandstones. Bedding features show that deposition of the fine sand, silt and mud took place in relatively calm water. Coarser material is rare and only one isolated pebble bed with rounded quartzite components up to 3 cm has been observed (N Bifertenfirn), in contrast to Val Gliems where pebble beds are important. No accurate estimate of the true total thickness of this sequence can be given; from cross-sections about 400 m are recognized, but neither the top nor the bottom is exposed.

The field appearance of the rocks is usually hornfelsic, greenish grey in colour, with prominent regular bands varying between 0.5 and 5 cm of lighter coloured fine-grained meta-sandstones and meta-siltstones. Lens-shaped bodies of coarser material, fine cross-bedding and cut-off bands are seen locally. Darker hornfels bands are frequently spotted with dark spherical or oval porphyroblasts up to 1.5 mm diameter, which are seen even in the field to contain small mica flakes. The bedding planes are also marked by a weak growth of mica.

The outcrops north of the Bifertenfirn are easily accessible and show clearly the metamorphic character of the sediments and their intrusion by granitic veins and quartz diorite and granodiorite sills. The beds here are almost vertical and maintain a constant lithology for about 250 m across the strike. Igneous sills make up about 25% of this thickness. Small scale faults with displacements of 1 cm to 1 m are common, especially on the margins of the igneous sills which are believed to have intruded during the volcanic episode of the Upper Carboniferous.

Higher on the east side of the Bifertenfirn the lithology of the sediments is similar, but there is much less evidence of recrystallization, and spotted rocks are absent. Cross-bedding shows that these beds lie normally, and higher in the cliffs they are overlain, commonly with tectonic contacts, by conglomerates and breccias of the Volcanic Member of the Upper Carboniferous. The mudstones appear to be a less metamorphic equivalent of the hornfelses and knotenschiefer found lower in the valley; the boundary between lower and higher grade metamorphic rocks, marking the outer limit of a contact aureole, has been disturbed by post-Stephanian movements and cannot be mapped accurately.

The intermixing of non-metamorphic shale fragments and knotenschiefer in the overlying conglomerates shows that the pre-Westphalian/Stephanian unconformity cut across this outer margin of the contact aureole, and the abundance of biotite and the occasional presence of garnet and higher grade metamorphic rock fragments shows that a higher grade zone of metamorphic sediments was present nearby.

2. Petrography of the Bifertenfirn metasediments

Petrographically the rock types present are hornfelses and knotenschiefer, and were appropraitely named by Hügi (1941). Variations in the original chemical composition of the sediments are clearly shown by the types of hornfels produced; the coarser bands, originally argillaceous siltstones and fine-grained sandstones, show the clearest microscopic evidence of readjustment to equilibrium conditions, and the more argillaceous bands show only little enlargement of the matrix grain-size. Many of the more argillaceous types have developed rounded spots, but certain darker fine-grained beds, sometimes markedly iron-stained, pyrite-bearing and probably graphitic, show very little effect of recrystallization. Shearing of the rocks took place after the metamorphism and formed local belts which show cleavage with a slight growth of sericite on the surfaces.

In thin-section the spots of the typical banded hornfelses from the outcrops directly north of the Bifertenfirn are seen as large poeciloblastic flakes of muscovite (0.5—1.0 mm), either single or in groups, which enclose smaller grains of chlorite and quartz (fig. 3b). These are primary porphyroblasts and do not show evidence of replacing earlier andalusite or cordierite. The matrix of the hornfelses is composed of a mosaic of quartz (0.1—0.5 mm), albite (0.1—0.2 mm) and white mica in which some larger quartz grains of 0.5 mm retain detrial shapes. Small growths of chlorite are sometimes seen in the matrix,

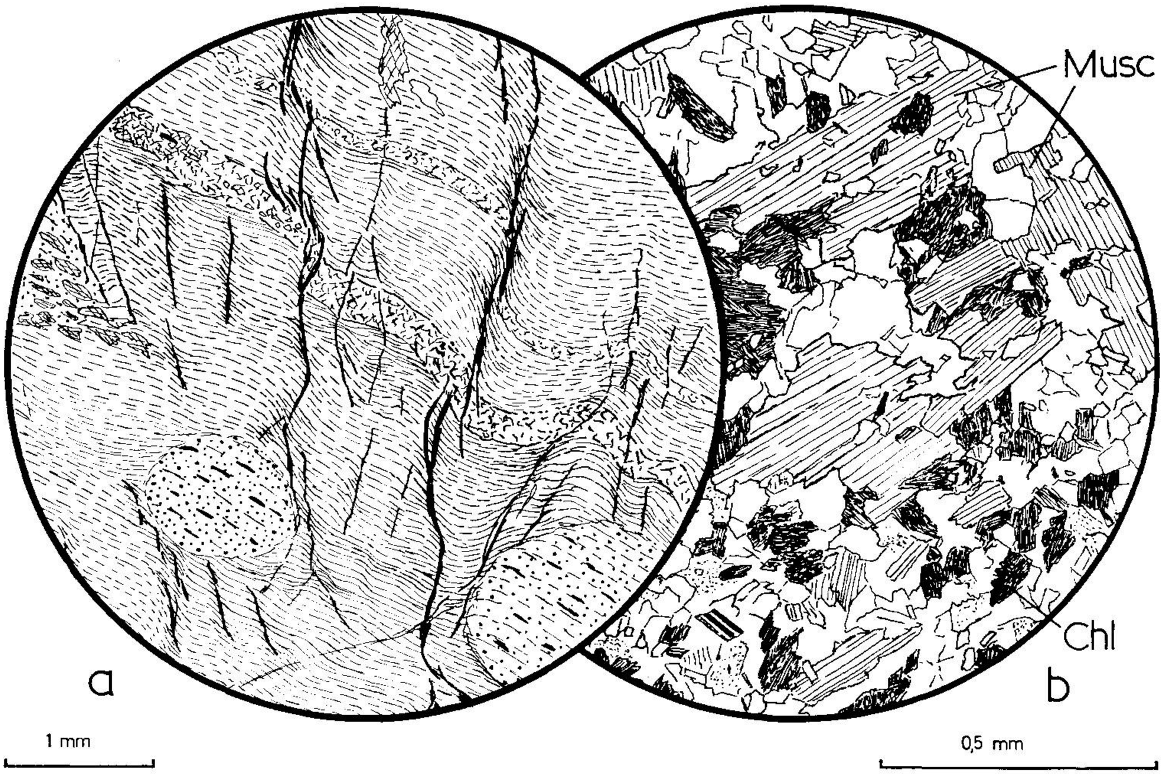

Fig. 3. Thin-section drawings of hornfelses from the Bifertenfirn area: a, spotted slate (Knotenschiefer) with altered porphyroblasts and cut by later cleavage; b, mica-hornfels with muscovite, chlorite, albite and quartz.

but more normally this mineral forms irregular patches up to 2 mm across around the mica aggregates.

The spots of the darker argillaceous beds are seen in thin-section as rounded or irregular areas up to 1 mm which are composed of small flakes of white mica, some quartz and numerous small opaque grains, sometimes as octahedra, presumably of magnetite (Fig. 3a). The mica of these spots is smaller and less strongly foliated than the mica of the groundmass, and the quartz and mica are less segregated into distinct layers. They may be areas in which the original groundmass fabric is preserved, as in the knotenglimmerschiefer of ROSENBUSCH (1877, p. 191), or they may be altered andalusite or cordierite porphyroblasts, formed at this low grade of metamorphism because of a high kaolin content of the sediments (HARKER, 1939, p. 49).

Calcite is seen in some of the hornfelses as small rhombs or as restricted layers with micas. It was probably present in the original sediments in small amounts, but as it does not enter into reaction with the quartz and as it cuts the margins of the spots it is probably mainly a later exogene addition. Apatite is abundant in some of the carbonate-bearing hornfelses. Less abundant but widespread metamorphic minerals in certain rock types are epidote, clinozoisite, an almost colourless spinel (in types lacking large muscovite plates) and a little biotite (in more argillaceous types).

The grade of the metamorphism is indicated by the presence of chlorite together with white mica (muscovite) and albite. Andalusite or cordierite may have been present, and the alteration has not progressed far enough to produce abundant biotite in place of the chlorite and sericite. There is very little orientation of micas in the fine sandy beds and the mineral foliation in more argillaceous beds is parallel to the bedding; the metamorphism is thus a result of the thermal effects of a contact aureole with very little influence of stress. The mineral assemblage places these rocks in the lower grades of the albite-epidote-hornfels facies of contact metamorphism (TURNER and VERHOOGEN, 1960). The reactions appear to have reached an equilibrium, as is suggested by the straight recrystallized boundaries between the quartz grains, the lack of reaction around the muscovite plates and the constant development of the same assemblage (TURNER, 1948, p. 56). A temperature of between 400° and 500° C is suggested in the light of recent experimental studies (WINKLER, 1965, p. 59). The large size of some of the minerals suggests that the conditions remained constant for a considerable time, and it is postulated that these rocks lie on the outer margin of a formerly more extensive contact aureole.

3. Intrusive igneous rocks in the metamorphic sediments

The history of magmatic intrusions in the pre-Triassic sediments is divided into three episodes:

1. Granite intrusion. Intrusion of the main Tödi granite as a large body with related granitic, aplite and pegmatite veins. This was probably the cause of the metamorphism of the pre-Upper Carboniferous sediments.
2. Granodiorite, micro-granodiorite and quartz-diorite intrusion, mainly as sills. Some of the sills are cut by the Upper Carboniferous unconformity; also similar rocks are closely associated with the Upper Carboniferous volcanics. The rocks are thought to have been intruded during a volcanic episode which reached its maximum immediately before the onset of Westphalian D-Stephanian sedimentation.
3. Granite dyke intrusion; post-volcanic. In the Bifertenfirn area these dykes are not senn to cut the Upper Carboniferous sediments, but they are seen to cut the breccias and tuffs of the Klein Tödi.

HÜGI (1941) described five varieties of the Tödi granite and postulated a genetic relationship between them. His porphyritic Tödi granite, fine-grained Tödi granite, deformed varieties of the Tödi granite and possibly the granodioritic facies of the Tödi granite would belong to the early granite intrusion of the present classification, and his "Granitporphyr" marginal facies of the

Tödi granite would mostly belong to the intrusions of the volcanic episode. The present study confirms the time relationship assumed by HÜGI—the porphyritic Tödi granite being followed by the "Granitporphyr".

A. Tödi Granite

The relations NE of the Hintere Rötifirn, where the largest outcrops of Tödi granite are exposed, are complex, and in the field the finer-grained porphyritic granite is sometimes difficult to discern from the granodiorite of the second intrusive episode. The most characteristic porphyritic granite exhibits large hypidiomorphic feldspars which in places are strongly oriented, with their long axes roughly horizontal in an E-W direction. As this granite appears only over a restricted area no further details of the structure of the intrusive body are to be obtained.

The petrographical descriptions of HÜGI retain their validity and may be summarized for completeness. In composition the rock is a normal granite. Plagioclase is somewhat more abundant than potash feldspar and normally occurs as euhedral crystals up to 4 mm. Potash feldspar (perthite and microcline(forms large phenocrysts up to 2 cm in length, but it is now largely altered and shows only local remnants of microcline lamellae. Quartz makes up about 30% of the rock; it shows irregular, fractured outlines and commonly strained extinction, and many of the internal boundaries are fractured. Sericite occurs as large individual crystals or as small laths in the groundmass; sericite and chlorite replace the original biotite. Some ore minerals, zircon and epidote are present as accessories.

Chemical analyses of this rock have been given by ESCHER (1911), NIGGLI et al. (1930), HÜGI (1941), DE QUERVAIN et al. (1942) and summarized by HÜGI (1956).

B. Granodiorites etc. of the second intrusive episode

The younger intrusive rocks which are found as sills in the metamorphic sediments are variable in composition. They are greenish grey hemicrystalline or holocrystalline porphyritic rocks of medium to fine grain-size. They occur as sills 2 to 10 m thick which sometimes cross the bedding of the metamorphic rocks. They vary in thickness along their trend, and their margins are strongly faulted (Fig. 4). The small-scale faults have both normal and reverse displacements and affect the bordering sediments more than the igneous rock, suggesting that the igneous rock was still plastic at the time of faulting, or that the faulting began before the emplacement of the sills. The intrusion probably took place at shallow depths, accompanied by strong earth movements which caused the fracturing.

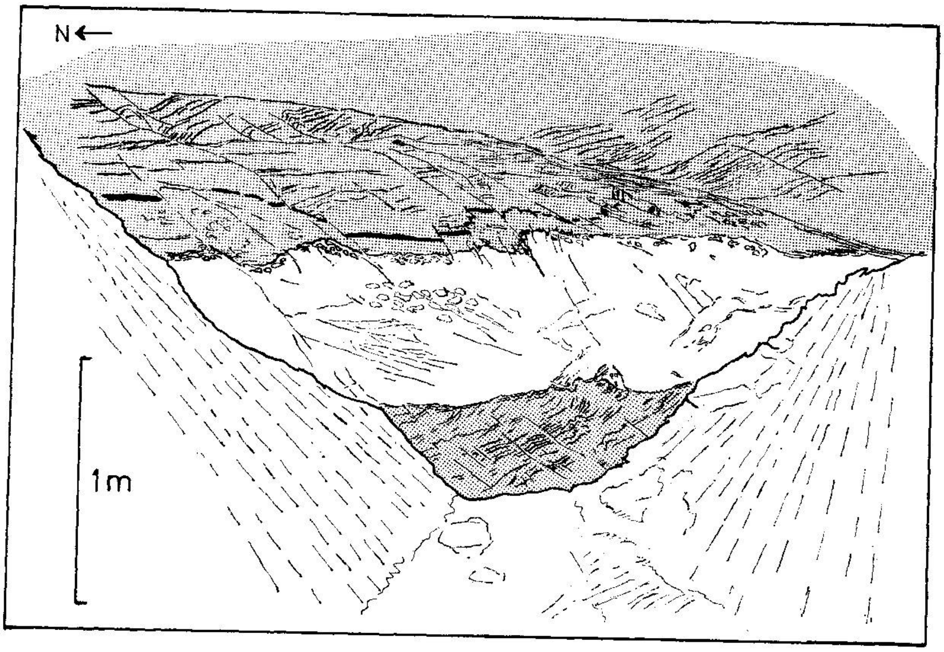

Fig. 4. Quartz-diorite dyke in the Bifertenfirn metasediments with syngenetically faulted margins (NE of Bifertenfirn).

In hand-specimens abundant plagioclase phenocrysts up to 2 mm set in a fine-grained to microcrystalline matrix are clearly visible in most of the varieties, sometimes showing fluidal arrangement near the margins of the sills. Small dark shale fragments are locally abundant in the sills, and occasional basic schlieren up to 10 cm are seen. Chlorite pseudomorphs and quartz phenocrysts are sometimes visible.

Microscopically the rock consists of plagioclase, quartz in variable amounts and chlorite pseudomorphs after hornblende and augite. Apatite, sericite, calcite, epidote, sphene and ores are common accessories. Plagioclase forms euhedral crystalls up to 2 mm in length in the porphyritic varieties or anhedral crystals in the more uniform varieties (Fig. 5). Where determined on the universal stage its composition is albite (An_{0-10}), but it always shows strong alteration. Rounded and corroded quartz grains may make up 5% of all the phenocrysts; normally quartz forms about 30% of the rock as a fine-grained to microcrystalline groundmass (0.2 to 0.05 mm). The shapes of the chlorite pseudomorphs suggest that both augite and hornblende were present.

The majority of the rocks found as sills are porphyritic granodiorites or microdiorites; the term quartz-diorite is applied only to those types with very small amounts (10—15%) of visible quartz. These are found amongst the sills north of the Bifertenfirn, in Schiebenruns and north of Bifertengrätli. The diabase stock of Hügi (1941) is a quartz-bearing porphyritic microdiorite, and is thought to belong to this suite of igneous rocks.

Rocks of similar composition are abundant in the volcanic breccias of the

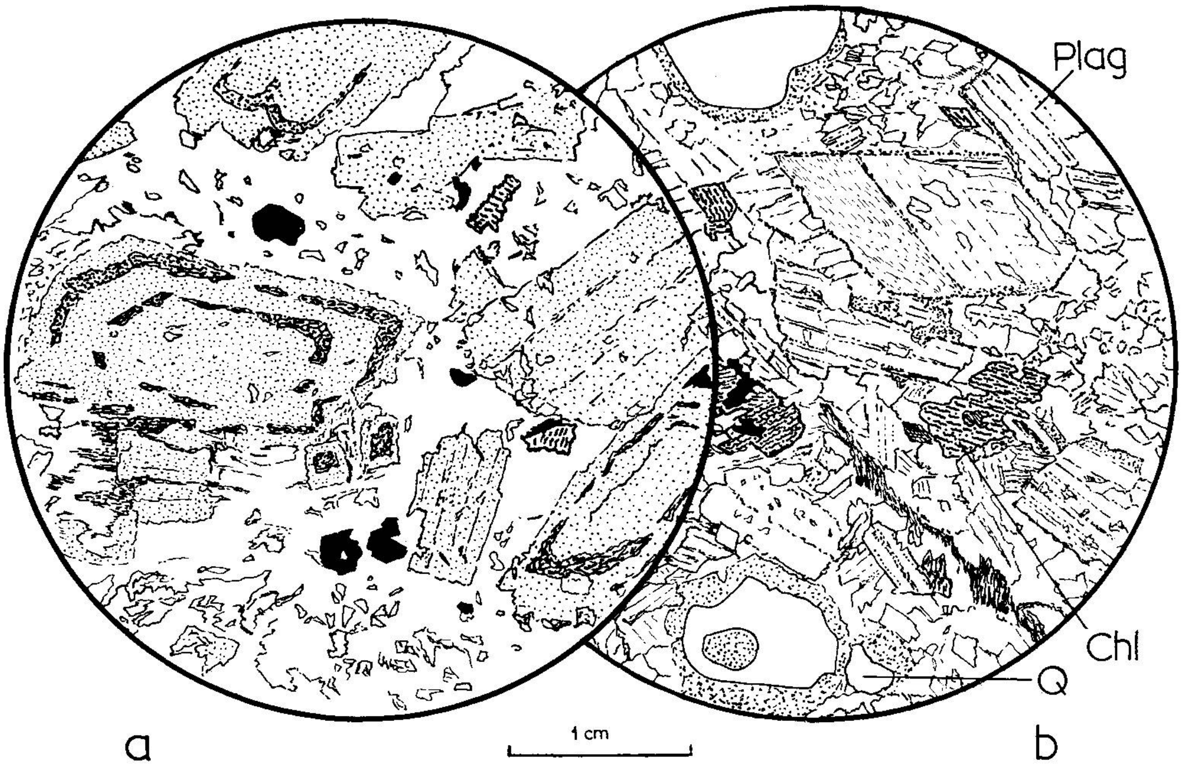

Fig. 5. Intrusive dykes in the Bifertenfirn metasediments; a, porphyritic diorite (strongly altered) with relics of zoned plagioclase; b, porphyritic granodiorite with resorbed quartz.

Upper Carboniferous, and are associated with rhyodacites, dacites and altered andesites of more obviously extrusive origin.

C. Discussion of chemical analyses of the igneous rocks

Chemical analyses of the intrusive rocks of the NE Tödi area have been compiled and discussed by Hügi (1956). Rocks here distinguished as the true Tödi granite and the volcanic suite have been considered together in this and earlier works, and a number of magma-types have been allotted to the sum of the igneous rocks found in the area. The value of this procedure in a non-genetic discussion of rock-types is not doubted, but as it gives no assistance in understanding the history of the rocks it is not pursued further here. Hügi (1956, p. 16—17) is aware of the limits of validity of chemical classification, and goes no further than the strict definition of Burri and Niggli (1945), which states, that the allotted magma-types are but a simple arrangement of magmatic rocks as they are found at the earth's surface according to their chemical composition. Hügi is also aware that the names tasnagranitic, soda-rapakivitic, leucoquartzdioritic and granosyenitic magmatypes, which have been used for igneous rocks of the E Aar Massif are simply descriptions of the chemical composition of the rocks and are not applicable to the magmas from which the various rocks are assumed to have been derived (1956 loc. cit). Furthermore, the high degree of alteration of most of the rocks places some of the analyses in doubt.

IV. THE VAL GLIEMS METASEDIMENTS

1. Lithology and problems

Pre-Triassic sediments south of Tödi form a narrow ENE-WSE belt 10 km in length and at the most 2 km broad. Val Gliems, where the greatest variety of lithological types is seen, lies at the eastern end of the belt. The northern and southern contacts with the surrounding igneous and metamorphic rocks are faulted, and the overlying Triassic and Jurassic rocks to the east are tightly folded.

Heim (1878) was the first to describe the sedimentary rocks and mention carbonaceous rocks and anthracitic beds in the neighbourhood of Piz Gliems. Weber's description of the area, given in Heim (1922, p. 933) is very short but accurate; the rocks of Val Gliems are placed in the lower group of the Carboniferous consisting of slates, quartzites and conglomerates which are older than the plant-bearing Carboniferous of Bifertengrätli. Eugster (1951), however,

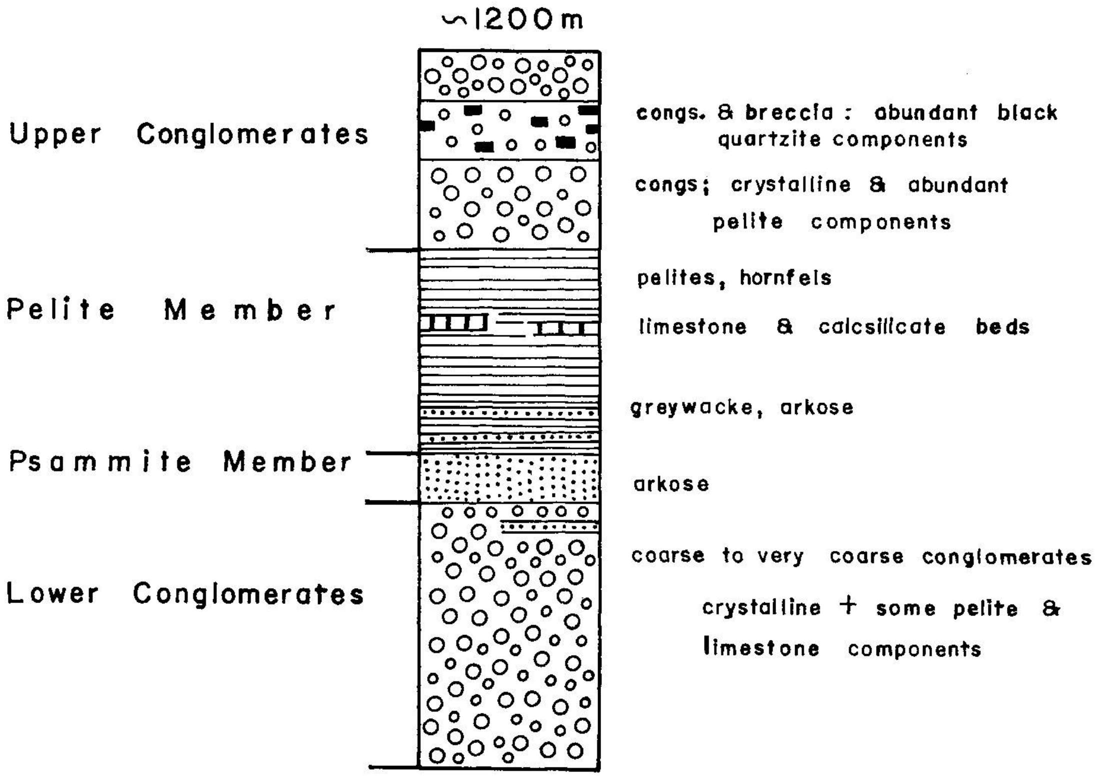

Fig. 6. Schematic stratigraphical section of the Val Gliems metasediments.

correlated the rocks of this southern "Paragesteinskomplex" with the Upper Carboniferous of Bifertengrätli. This correlation, which is now discarded, was based on a supposed analogy with the facies of the section described by WIDMER, who, as has been shown in the discussion of the Bifertenfirn metasediments, failed to separate the earlier Bifertenfirn metasediments from the dated Upper Carboniferous. A single plant fragment of very boubtful character was described, but no further specimens have since been found; the local, slightly carbonaceous beds described by EUGSTER bear no similarity with the Upper Carboniferous beds.

It is now believed that the rocks of the southern sedimentary belt of this part of the Aar Massif are roughly the equivalent of the Bifertenfirn metasediments; they show a distinctly more complex structural and metamorphic history than the dated Upper Carboniferous sediments, and fragments of comparable rocks have been found in the Upper Carboniferous conglomerates.

The rock-types and the rough stratigraphical succession are shown in Fig. 6.

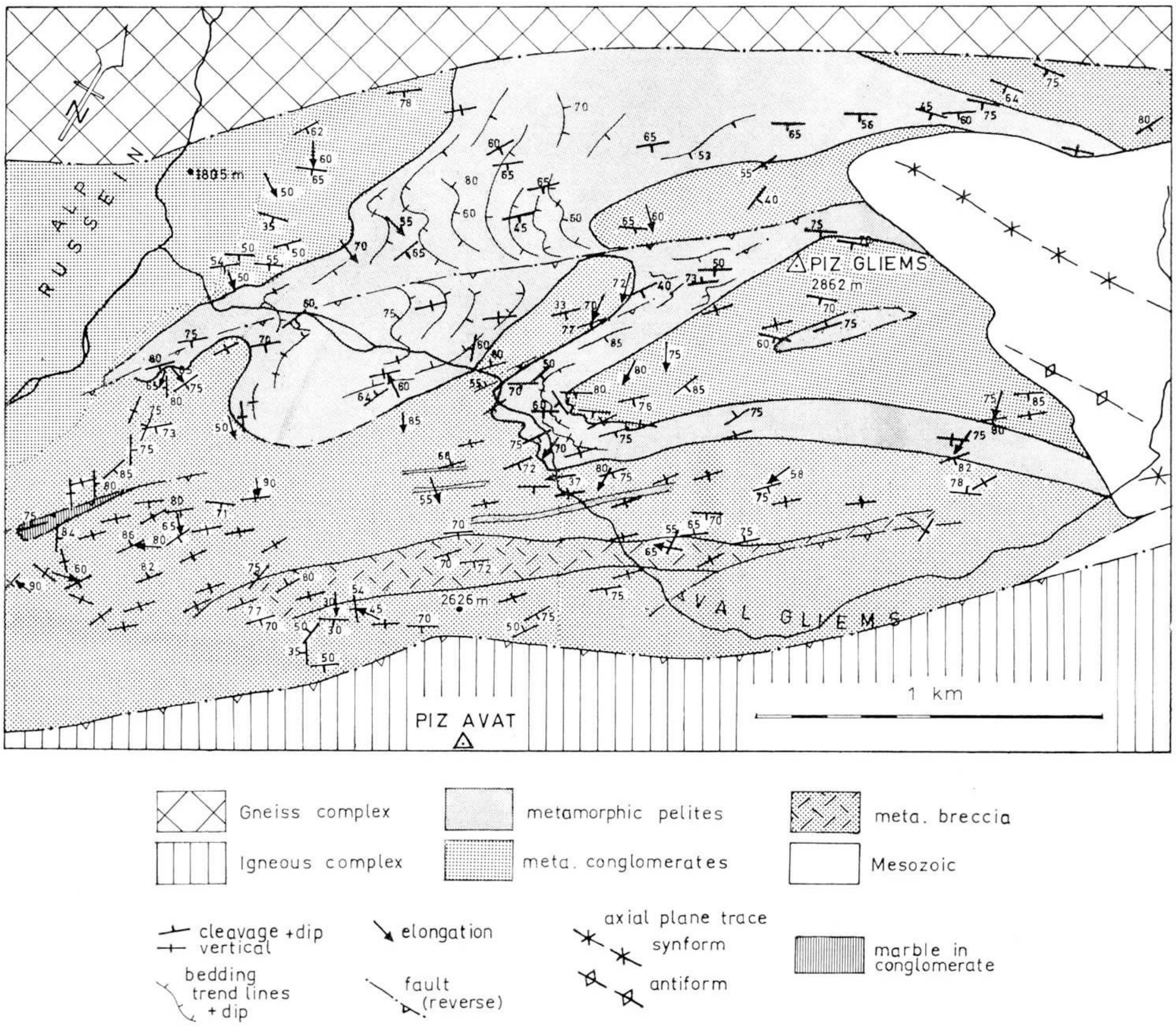

Fig. 7. Structural sketch map of the Val Gliems area.

The sediments lie in complex fold structures and are cut by strongly developed cleavage planes (Fig. 7). Most of the rocks show a clear development of new minerals which places them in the amphibolite hornfels facies. The large mass of conglomerates is the most outstanding feature of the area, and good exposures of these rocks are seen at the mouth of Val Gliems and west of Val Russein on the Cuolmet de Mustèr. The conglomerates generally lack bedding planes and are both strongly deformed internally and cut by a number of disturbance zones of unknown displacement, so that the thickness estimates are very uncertain. The finer-grained beds are best seen in Val Gliems and in a smaller exposure on Alp Cavrein.

A. The Lower Conglomerates

The upper boundary of the Lower Conglomerates is formed by a mappable unit of light-coloured sandstones and arkoses which pass upwards into the pelitic succession. The lower boundary of the sediments is not exposed. The field appearance of the Lower Conglomerates is similar to that of the conglomerates that succeed the pelitic sediments, and in the western and southern areas, where no continuous pelitic sediments are exposed, the higher and lower units cannot be separated. It is likely that much of the area of conglomerates to the west of Val Gliems belongs to the lower conglomeratic section, and the higher unit is not present.

The characteristic field appearance is a polygenic unsorted conglomerate with an abundant sand-sized matrix. The fragments are normally lighter in colour than the greenish amphibole-bearing matrix; the rock is well indurated and individual components are recrystallized with the matrix. The following components are present:

Sedimentary components	*Igneous components*	*Metamorphic components*
meta-mudstones	granite	amphibolite
meta-siltstones	granodiorite	
marbles	monzonite (quartz monzonite)	
quartzites		

The predominant components in many of the conglomerates are fine-grained, light or dark gray-green unbanded sedimentary fragments up to 5 cm, which were of original calcareous mudstone composition. These have often a lighter-coloured margin, probably a metamorphic reaction rim; in thin-section they are seen to be the most strongly metamorphosed components, often with prismatic amphibole clusters reaching 2 mm in size which sometimes cross the component margins. Their shape is normally angular, equidimensional or platy, but they have often been strongly deformed. They suggest moderate transport of the material.

Pure carbonate components are seen only locally and are possibly restricted to the higher unit of conglomerates. A large mass of coarsely crystalline marbles with an outcrop width of about 5 m is found northeast of Piz Avat on the path from Val Russein to Alp Avat (1825 m). The coarsest variety shows single crystals of dark calcite up to 1.5 cm, and the finer variety is a white saccharoidal marble. The outcrops are bounded by faults; banded metamorphic pelites are found nearby, and the limestones may form a relic of a more calcareous horizon in the succession.

The quartzites and igneous components are well rounded and preserve their original shape more than the fine-grained sediments. The igneous components reach 30 cm in size, and are the least affected by the metamorphism and deformation; in thin-section they show only cloudiness of the feldspars, recrystallization of the quartz and some marginal regrowth. Some of the igneous pebbles may be extracted from the conglomerates and show an almost undeformed, well-rounded shape. The amphibolite fragments are usually smaller in size (up to 1 cm) and strongly deformed.

The matrix of the conglomerates invariably shows strong development of metamorphic minerals, and is normally very rich in a fibrous or prismatic iron-rich actinolite (grammatite) to cummingtonite, which has often a core of darker common hornblende. EUGSTER (1951) thought that the hornblende was of sedimentary origin, but its growth across component boundaries and the general metamorphic fabric (see later) indicate a secondary growth for the greater part of all the amphiboles. Idocrase, titanite and some biotite and sericite are also present.

B. The Sandstone Member

In the northern area of Val Gliems a sandstone unit of 10—20 m has been mapped between the lower conglomerates and the pelites (it is included with the conglomerates immediately surrounding the main pelite area in the map of Fig. 7). Farther south only thin sandstone beds intervene between the conglomerates and the pelites. The sandstones are poorly bedded and locally contain small dark shale fragments; all are strongly recrystallized and some biotite can be seen on the cleavage surfaces. Many of these biotite psammites are rich in microcline and were originally arkosic in composition.

C. The Pelitic Member

The pelitic rocks are best exposed on the north and west flanks of Piz Gliems. They are generally seen as dark grey-green, banded hornfelses and slates, and less frequently as knotenschiefer with porphyroblasts reaching 3 cm in size. The dark colour of some of the pelitic beds appears to be caused by carbonaceous or graphitic material, but in the absence of further fossil evidence and the great dissimilarity with the Upper Carboniferous of Bifertengrätli, this cannot be considered an indication of Upper Carboniferous age for these beds.

The lithology and bedding features indicate deposition in relatively calm water, and in general the lithology is comparable with that of the metamorphic rocks which underlie the Upper Carboniferous of the NE Tödi (Bifertenfirn) area. The sedimentary banding is regular, of mm- to cm-thickness, with only local cross-bedding. Beds of sandstones or conglomerates are sometimes found within the pelites, but cannot be traced for long distances.

Thin limestone beds are seen in several outcrops on the south and west slopes of Piz Gliems. They rarely exceed 5 cm in thickness, but the lighter colour makes some of them conspicuous; these are dense, finely crystalline marbles. Less pure carbonates are grey in colour, but in these there is often a clear development of clusters of acicular amphibole porphyroblasts. The origin of the limestones is obscured by their metamorphism; traces of organisms are lacking and they were probably formed as thin inorganic limestones, possibly in a terrestrial environment.

The pelitic member is most important in the north of Val Gliems and probably showed a primary decrease in thickness towards the south.

D. The Upper Conglomerates

In the central part of Val Gliems the pelitic rocks are seen to pass upwards into conglomerates of comparable lithology to the Lower Conglomerates. The contact is folded concordantly with the major structures, and is parallel to the bedding of the pelites. The conglomerates south of Val Gliems on the north slopes of Piz Avat are believed to belong to this higher unit, bounded in the north by a fault contact against the Lower Conglomerates.

The components and the general appearance of the Upper Conglomerates is very similar to that of the Lower Conglomerates. The only difference is the presence, presumably as a stratigraphical horizon, of a 20—30 m wide outcrop of conglomerates and breccias with a much greater proportion of black siliceous components and a more siliceous and less hornblende-rich matrix. These were described by EUGSTER (1951) as psephites with a hornblende-bearing matrix, and marked as a separate unit on his map.

As in the Lower Conglomerates, fragments of fine-grained sedimentary rocks are locally the most abundant components, and are strongly affected by the metamorphism. Rounded leucocratic igneous components may reach 80 cm in size, and so do some marble boulders on Piz Gliems, indicating rapid deposition and short transport. The immaturity of the conglomerates is further indicated by the alternation of beds of angular crystalline breccias with conglomerates made up of well-rounded crystalline and sedimentary fragments.

E. Discussion of the Val Gliems metasediments and their age

Although EUGSTER (1951) advanced a number of arguments which suggested a correlation of the Val Gliems sediments with those of the Bifertengrätli Upper Carboniferous, the present comparative study suggests that they belong to an earlier metamorphic succession. The significance of the possible plant fragment described by EUGSTER is not known, as the specimen is no longer available.

The most plausible hypothesis is that the whole sedimentary succession of Val Gliems is pre-Westphalian-D and suffered a pre-Westphalian-D metamorphism and deformation. The style of the structures and the degree of metamorphism allow the sediments to be tentatively correlated with the metamorphic sediments of the Bifertenfirn area, which provided pebbles for the dated Upper Carboniferous conglomerates.

Apart from this correlation the age of the sediments cannot be determined; the carbonaceous beds in both Val Gliems and the Bifertenfirn metasediments indicate a possible Palaeozoic age, and a Lower Carboniferous age may be considered. With certainty it can be said that the deposition of the beds was preceded by strong relief building in crystalline massifs and the creation of basins in which the coarse conglomerates were laid down. The pelitic sediments and carbonates are in marked contrast to the conglomerates and must have been laid down in a more stable basin, possibly part of a landlocked basin that existed between periods of strong erosion of surrounding crystalline mountains. Thus uplift and erosion preceded the deposition of the Val Gliems and Bifertenfirn metasediments and further movements and metamorphism affected them before the deposition of the strongly volcanic Upper Carboniferous.

2. The metamorphism of the Val Gliems metasediments

The metamorphic assemblages seen in Val Gliems offer a number of interesting features. The variety of rock types and the relatively simple growth of porphyroblastic minerals which have suffered a slight retrograde metamorphism give an important illustration of what are considered to be the effects of the main "Hercynian" or mid- to late-Palaeozoic orogeny in the eastern Aar Massif. It is also important to emphasize the difference between these assemblages and the very low grade metamorphism of the Upper Carboniferous rocks of the nearby areas. EUGSTER (1951) gave details of the minerals present and their chemistry, but he overlooked the uniform nature of the metamorphic assemblages and regarded the metamorphism as a result of contact effects of minor cross-cutting dykes; this and the lack of details concerning the relations in the Bifertenfirn area made him suggest an Upper Carboniferous age.

The assemblages seen in Val Gliems correspond generally to the hornblende hornfels facies of contact metamorphism (TURNER and VERHOOGEN, 1960). The metamorphic rock varieties and the supposed original material are:

1. Deformed amphibole-bearing conglomerates: conglomerates with abundant calcareous mudstone components and a slightly calcareous matrix.
2. Deformed biotite-bearing conglomerates without amphiboles: siliceous conglomerates and breccias with siliceous and argillaceous matrix.
3. Marbles: pure limestones.
4. Diopside marbles: impure limestones.
5. Garnetiferous actinolite (cummingtonite) hornfels: slightly limy mudstone.
6. Biotite chiastolite hornfels: mudstone.
7. Biotite meta-psammite: impure sandstones.
8. Feldspathic biotite chlorite meta-psammite: arkoses.

The wide variety of sedimentary types resulted in the variety of metamorphic rocks, and the changes in intensity of the metamorphic reactions are largely an effect of local chemical variations and local changes in internal fabric of the original sediments. Local variations near the margins of the cross-cutting dykes as described by EUGSTER (1951) are difficult to verify, and equally well developed metamorphic mineral assemblages are found also far away from the contacts of the minor igneous intrusions.

The conglomerates show a clear development of biotite and amphibole in the matrix, although EUGSTER did not regard these rocks as showing comparable metamorphic reactions to the pelites. In his opinion most of the amphibole and biotite was detrital. The matrix growths of these minerals in the conglomerates, however, are clearly cross-cutting to the component boundaries; they are almost entirely of post-depositional origin, and are components of typical amphibole hornfels facies assemblages.

The amount of recrystallization and the large size of the new minerals in the conglomerates must have been caused by a combination of favourable conditions such as the chemical composition of the groundmass and the concentration of mineralising fluids in the large intergranular spaces during the metamorphism. The appearance of the recrystallized matrix and the recrystallization around the margins of the pebbles is seen in Figure 8. The amphibole found abundantly in the matrix constituting large areas or single euhedral grains is a slightly green, pleochroic actinolite, and is frequently associated with irregular areas of chlorite. The biotite, present as a minor associate of the amphibole or as the predominant metamorphic mineral, is a brown strongly pleochroic variety. Chlorite, sericite and epidote are present in smaller amounts, usually as restricted concentrations or flakes between the larger amphibole prisms, and magnetite may form prominent grains.

The crystalline components show signs of metamorphism only in the cloudiness of the feldspars, the fractured quartz and the abundance of sericite; the

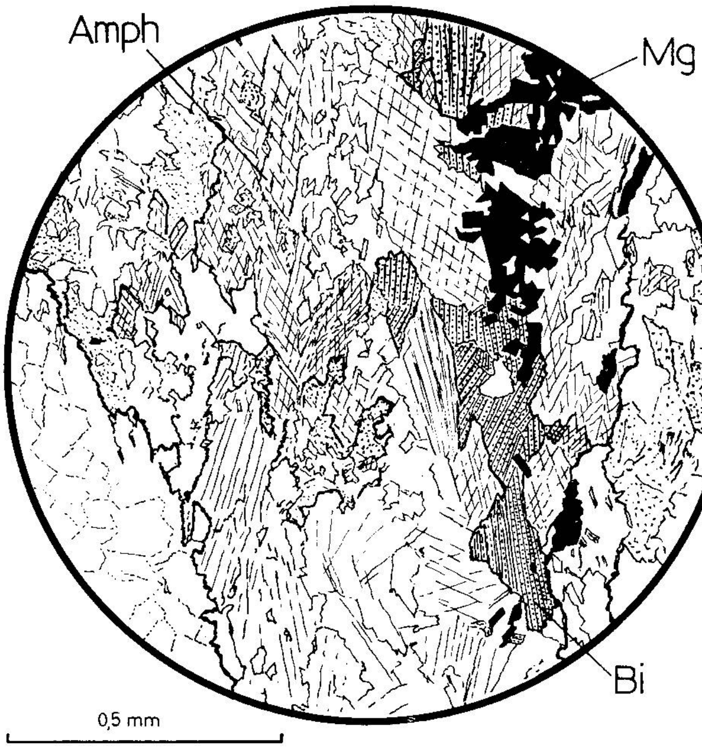

Fig. 8. Thin-section drawing of the recrystallized matrix of the conglomerates with abundant amphibole (actinolite), biotite and magnetite (Mg); quartzite component at left and granite at right.

sedimentary components, however, contain small amphiboles and some biotite, mainly near their margins, and sometimes garnet, epidote, chlorite and zircon.

Arkosic beds within the conglomerates frequently contain up to 35% feldspars, predominantly fresh recrystallized orthoclase and microperthite (Fig. 9b). Biotite, sericite, a greenish hornblende ($c \wedge Z = -25°$) together with some titanite, epidote, clinozoisite and apatite are present, especially in the impure arkoses and sandstones of the Sandstone Member at the top of the Lower Conglomerates. Some of the sandstone beds within the Pelite Member are very rich in plagioclase (An_{25-30}), and it is possible that sedimentary plagioclase and an abundant argillaceous matrix were originally present, giving the rocks a greywacke composition. The carbonate content of the sediments gave rise to abundant hornblende and titanite, although the plagioclase remained relatively low in calcium (Fig. 11b).

The pelitic rocks are true hornfelses, often showing slightly sericitic cleavage surfaces and in some localities large porphyroblasts. Large outlines of chiastolite, folded by late kink-zones, are seen in central Val Gliems (below the main waterfall) and on Alp Cavrein (Fig. 10); porphyroblasts of garnet (pseudomorphs) have been found near the same locality in Val Gliems with good dodecahedral forms up to 1 cm across. In thin-sections these large porphyroblasts are seen to be replaced by fine-grained sericite, chlorite, quartz and plagioclase; in some of the garnets the secondary minerals, together with a little epidote, are arranged radially in segments, marking dodecahedral twinning. The larger chlorites within the chiastolite pseudomorphs lie parallel

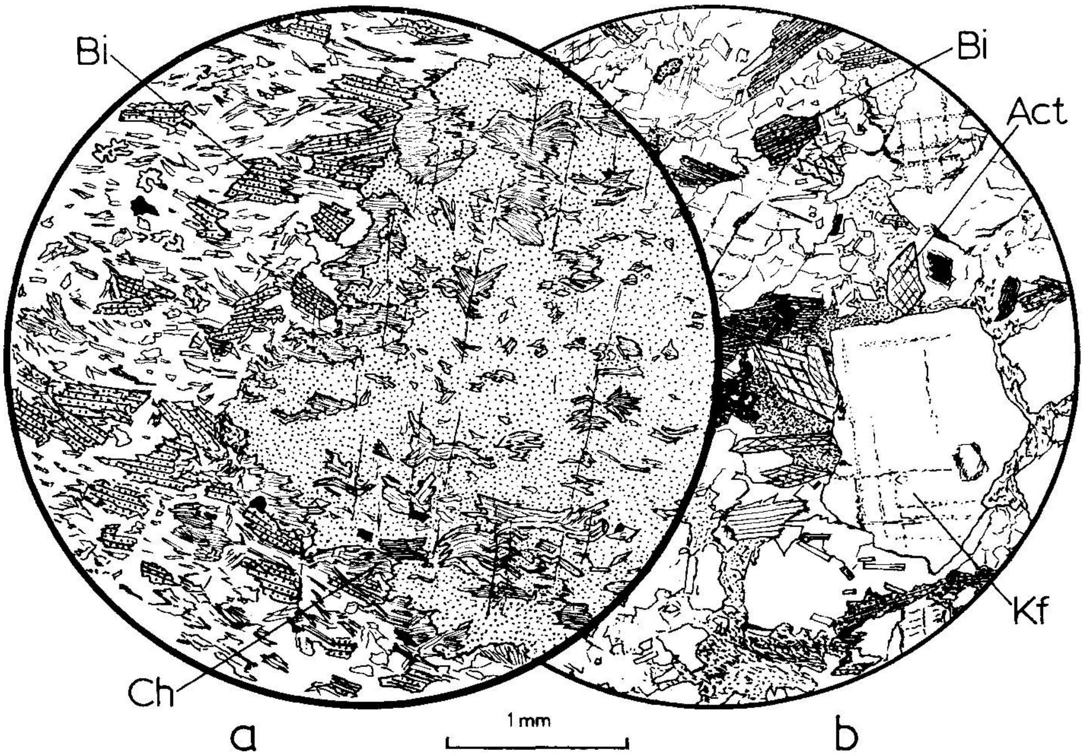

Fig. 9. a, Thin-section drawing of chiastolite hornfels with altered chiastolite porphyroblast, chlorite, biotite and a later cleavage. b, metamorphic arkose from the Sandstone Member with potash feldspar (Kf), actinolite, biotite, quartz and titanite.

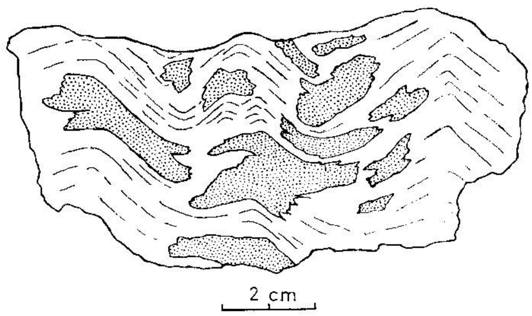

Fig. 10. Folded chiastolite pseudomorphs in hornfels, Pelitic Member, Val Gliems.

to a foliation marked in the groundmass by the growth of biotite and have been folded by later kink-zones (Fig. 9a).

The secondary alteration of the minerals typical for the hornblende-hornfels facies and the ubiquitous presence of epidote and chlorite in the psammites and conglomerates point to a retrograde metamorphism accompanied by stress. The later minerals, typical of greenschist facies assemblages; often mark a weak foliation in the rocks, and are assumed to have formed during a late stage of the pre-Alpine metamorphism. Alpine deformation produced no new minerals apart from some sericite and chlorite, but was probably the cause of the kink-zones in the pelites.

Further evidence of the two stages of the pre-Alpine metamorphism is seen

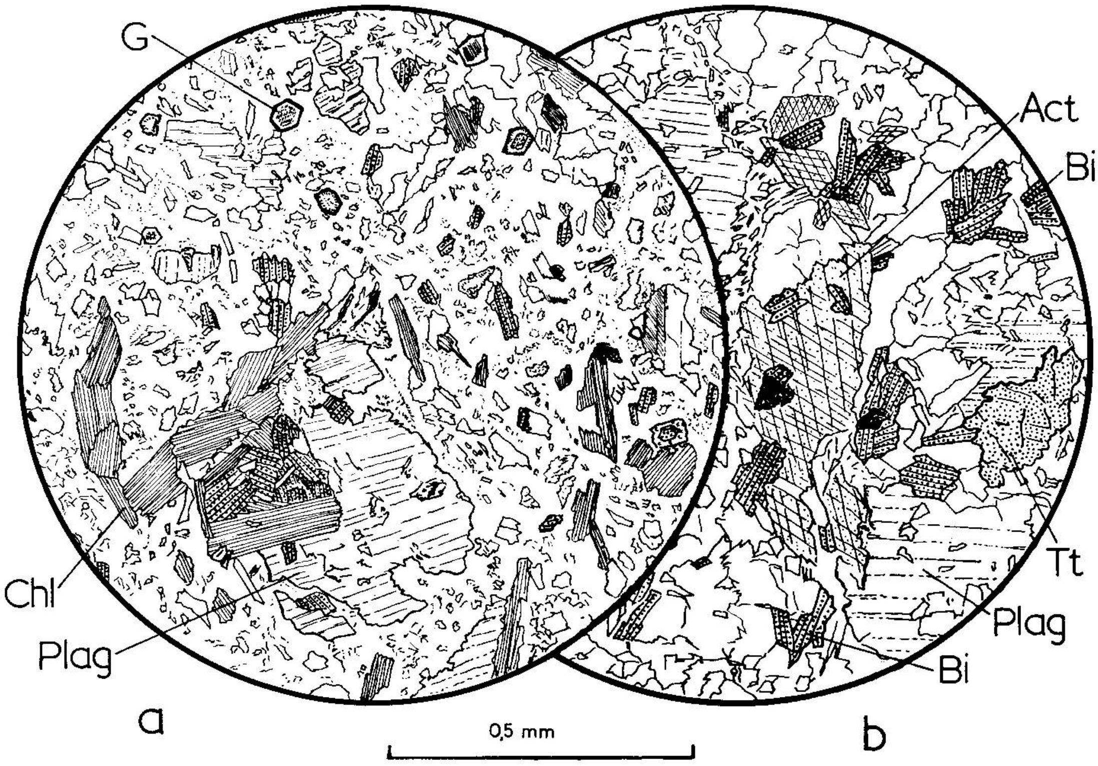

Fig. 11. a, Thin section drawing of garnetiferous hornfels with plagioclase (An_{25-30}) porphyroblast, biotite and later chlorite. Idiomorphic. b, meta-psammite from the Pelitic Member with plagioclase, actinolite, biotite and titanite (Tt).

in the mineral assemblages of the calcareous horizons within the pelites. The rapid alternation of argillaceous and calcareous layers allowed a number of assemblages to be formed, all of which show evidence of retrograde metamorphism. Figures 11 and 12 illustrate the metamorphic developments in rocks from a single outcrop on the southern slopes of Piz Gliems. The argillaceous bed, a garnetiferous hornfels (Fig. 11a), shows porphyroblastic plagioclase (An_{25-30}) surrounded and replaced by large chlorites. The biotite, apparently formed at the same time as the plagioclase, is replaced in parts by chlorite, and the idiomorphic garnets are sometimes surrounded by chlorite.

The gradation into the calcareous beds is marked by an increase in the amount of amphiboles, by larger garnets, the appearance of diopside, and a decrease in biotite content (Fig. 12a—c). Where no free calcite remains the diopside and amphibole have been replaced by chlorite, and in the marble bands the diopside is partly replaced by epidote. The garnets show a core of brown grossularite and an overgrowth of clear garnet which is seen to have developed after fracturing of the original porphyroblasts (Fig. 12a). The first stage of the metamorphism is thus characterized by amphibole, diopside, garnet, biotite and plagioclase and the later metamorphism—following and accompanying some

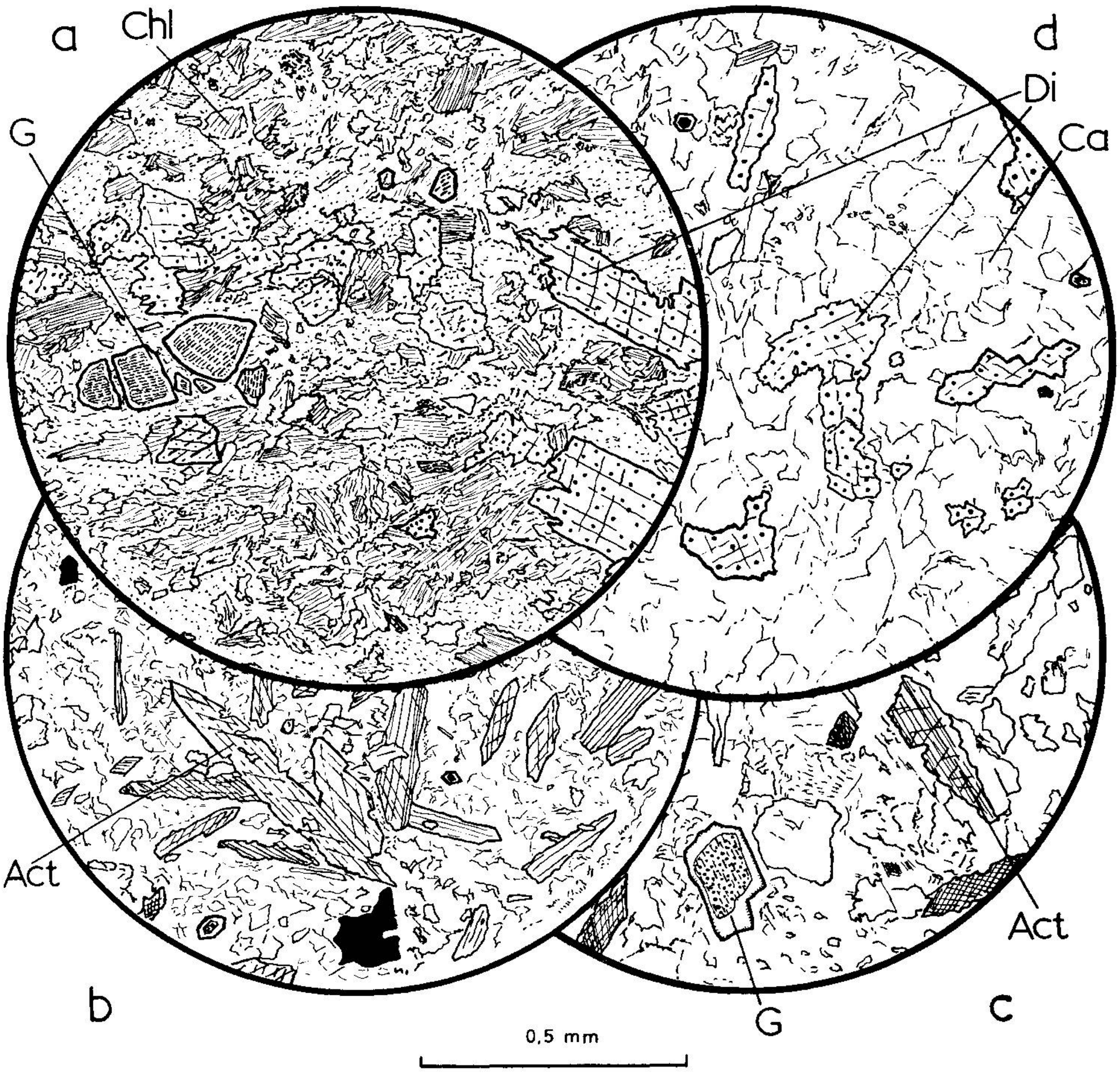

Fig. 12a–d. Gradation from garnetiferous diopside hornfels (a) through amphibole hornfels (b, c) into diopside marble (d). Act = actinolite, G = garnet, Di = diopside, Chl = chlorite.

tectonic stress—produced chlorite, epidote, muscovite and possibly the garnet overgrowths and some biotite.

The mineral assemblages produced during the two episodes can be seen most clearly in pelitic rocks such as those described above. The later phase of stress-accompanied metamorphism was probably at a similar temperature to that of the static phase, and consequently formed minerals more typical of the greenschist facies. The amphiboles of the conglomeratic and arkosic beds were apparently stable during this stage and became associated with epidote and muscovite. The deformation of the conglomerates and the foliation marked by biotite were caused by the stress effective during this later phase. The mineral assemblages combine aspects of the older hornfels facies with those of the greenschist facies, but the progression from one to the other was probably continuous, brought about by a building up of stresses during the later stages of the igneous intrusion.

The age of the metamorphism is taken as being pre-Westphalian-D on the evidence from the Bifertenfirn area, where both younger sediments and part of the older sedimentary sequence are present. The extent of the igneous body that caused the metamorphism is unknown; the Tödi granite—with a single Rb/Sr age determination (pegmatite) of 312 ± 12 m yrs (Wüthrich, 1963, 1965)—is the most likely body, but the shape of this granite mass cannot be satisfactorily outlined, and it is not certain with what igneous intrusions in the southern igneous complex it may be associated. There is some suggestion of a similarity with the Punteglias granite (see analyses in Hügi, 1956), and the intrusion of such a granitic body is assumed to be the cause of the metamorphism. Granodiorite dykes cut the sediments of Val Gliems and granitic lenses are seen in the more strongly tectonized western extent of the belt, but the dykes of the Val Gliems area at least are post-metamorphic.

3. The igneous intrusions in the Val Gliems metasediments

Two main groups of dykes are seen to cut the sediments of Val Gliems; the older, a suite of basic rocks described as kersantites by Eugster (1951, p. 113), forms thin dykes usually about 1 m thick which have been tectonically disturbed and appear to have been emplaced before the metamorphism. The second group are porphyritic granodiorites and are clearly later than the tectonic deformation and metamorphism of the sediments as they cut deformed pebbles of the conglomerates and show little secondary alteration (Fig. 13).

The first group of dykes are dark, holocrystalline, fine-grained rocks rich in amphibole. Thin-sections show the rocks to consist of about 60% of tabular interlocking hornblendes, green-brown in colour and often with a darker core. The plagioclase forms crystals up to 0.4 mm; they are strongly altered, preserve little twinning, and are intersected by hornblendes. Smaller grains of chlorite and epidote are abundant, and are associated with a little calcite and some quartz as alteration products around the plagioclase. The fabric of the rock and the minerals present indicate that they were formed by metamorphism rather than crystallization from a melt, and the assemblage corresponds to the hornblende-hornfels facies and the greenschist facies noted in the sedimentary rocks. Like many rocks of the lamprophyre group, this rock can be interpreted as a metamorphosed basic rock, originally of doleritic composition rather than an intrusive kersantite. The diorites described by Eugster (p. 95) with up to 60% amphibole are probably also metamorphic derivatives of the early basic igneous rocks, and he did in fact compare them with epidiorites of British authors, rocks generally regarded as metamorphic basic rocks.

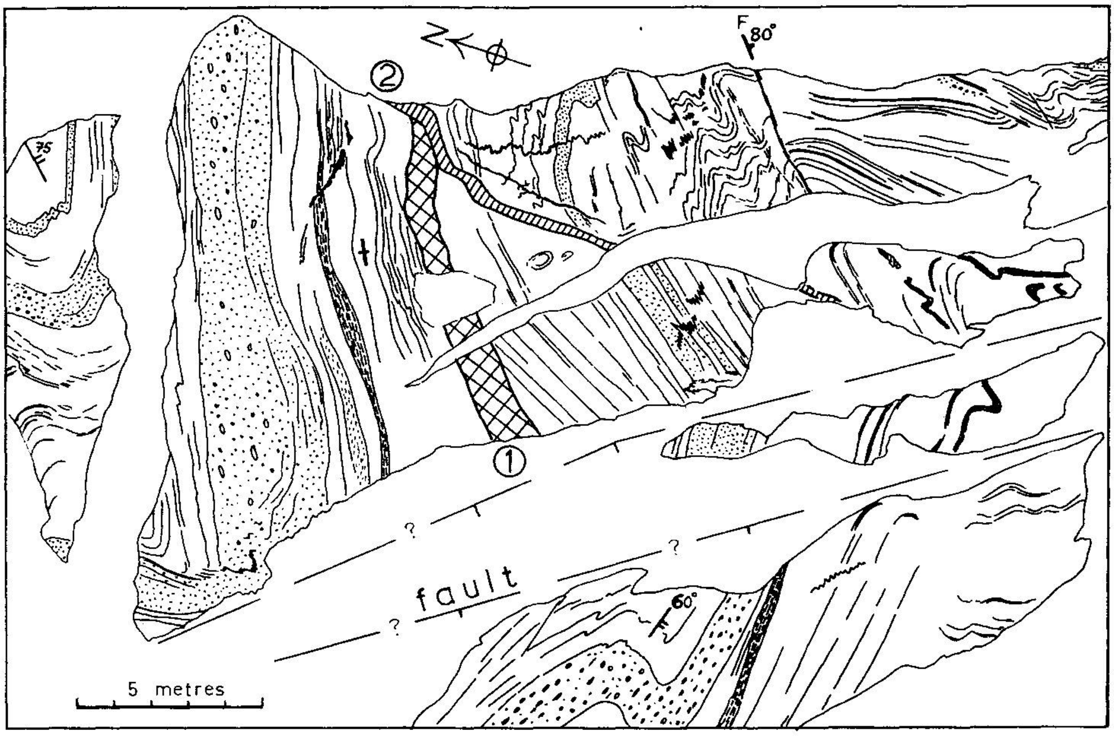

Fig. 13. Intrusive dykes and folds in the Val Gliems metasediments (Pelitic Member); 1. pre-metamorphic basic dyke; 2. post metamorphic porphyritic micro-granodiorite dyke.

The second group of dykes are massive, porphyritic, hemicrystalline rocks with sharp contacts against the country rocks. They consist of altered feldspars (50%), quartz (15%), sericite, chlorite and calcite with subsidiary ores and accessory epidote, zircon and apatite. In general the composition and appearance resemble those of the late quartz-diorite to granodiorite dykes of the Bifertenfirn area, to which they are probably genetically related. The large (up to 2 mm) plagioclase phenocrysts are relics of euhedral crystals; the smaller interstitial crystals are lath-shaped and show a microlitic texture. Quartz is restricted to the groundmass as interstitial grains up to 0.1 mm in most of the dykes. The calcite forms irregular areas up to 1 mm across, which replace the plagioclase, and the chlorite may form either single grains replacing ferromagnesian minerals (amphiboles?) or larger irregular replacement areas in the groundmass.

A prominent granodiorite dyke on the north slopes of Piz Gliems has a width of 3—4 m, and strikes NE-SW. It may belong to a later group of dykes related to the Central Aar granite such as those seen on the Klein Tödi (Franks, 1968) rather than to the pre-Westphalian-D dykes. Field relations in this area do not, however, give a more precise indication of its age. It is an altered granodiorite with potash feldspar phenocrysts up to 1 cm, rounded, resorbed quartz crystals up to 5 mm, and abundant small chlorite pseudomorphs after ferromagnesian minerals, probably biotite and hornblende.

V. THE TECTONIC PATTERN OF THE BIFERTENFIRN AND VAL GLIEMS METASEDIMENTS

The pre-Westphalian metasediments of the Aar Massif have been subjected to three principal phases of deformation, and their tectonic fabric is, as a result, rather complex. The first period of tectonic activity recorded by the Val Gliems and Bifertenfirn metasediments is here called the "main Hercynian deformation"; it took place before the deposition of the dated Upper Carboniferous sediments, possibly during the Middle to Upper Palaeozoic, but this age of folding can only be based on the tentative assumption of a Lower to Middle Palaeozoic age of the sediments affected. It is this first period of deformation which formed the major and minor folds in the Val Gliems sediments and which was accompanied by a metamorphism which did not affect the later Upper Carboniferous sediments.

The second period of deformation occured after the deposition of the Westphalian-D (Stephanian-A) sediments of the Bifertengrätli Formation; it is here termed the "late Hercynian deformation". It was less intense than the earlier deformation, forming the folds in the northern part of the Aar Massif, and probably also the major fault zones which bound the Val Gliems metasediments. Periodic and possibly rather local folding and faulting may have been the predominant style of deformation during the extended period at the end of the Palaeozoic, when volcanic and igneous activity seems to have been widespread.

The latest period of deformation took place during the Alpine orogeny; the Aar Massif rocks were cut by a number of major shear zones and given the southwards dipping schistosity common throughout the Massif. Various stages are recorded by the Alpine fabric (LABHART, 1966), but the effect on the older structures in the area under discussion is relatively slight.

The relationships between the various structures, and the interpretation of the folding of the early metasediments is shown schematically in Figure 2. The main structural trends in Val Gliems, the bedding, cleavage and elongation of the elements of the conglomerates are shown in Figure 7.

Measurements of the foliation surfaces, bedding and cleavages, and elongation are plotted in Fig. 14. The π-diagrams of the Bifertenfirn and the Val Gliems metasediments show an obvious similarity. A principal girdle with two maxima is seen in both figures, the maxima representing the statistical maxima of poles to the limbs of asymmetric, rather tight folds.

The fold axis (F) is constructed as the pole to the π-circle, the mean great-circle of the pronounced girdle of points. The constructed fold axes of both areas plunge steeply towards the east, with an axial plane (S') dipping steeply to the southeast and corresponding to the orientation of the cleavage (S_1) shown in Fig. 14c. The elongation directions of the pebbles lie in the plane of cleavage (Fig. 14e), with a maximum corresponding to the direction of the

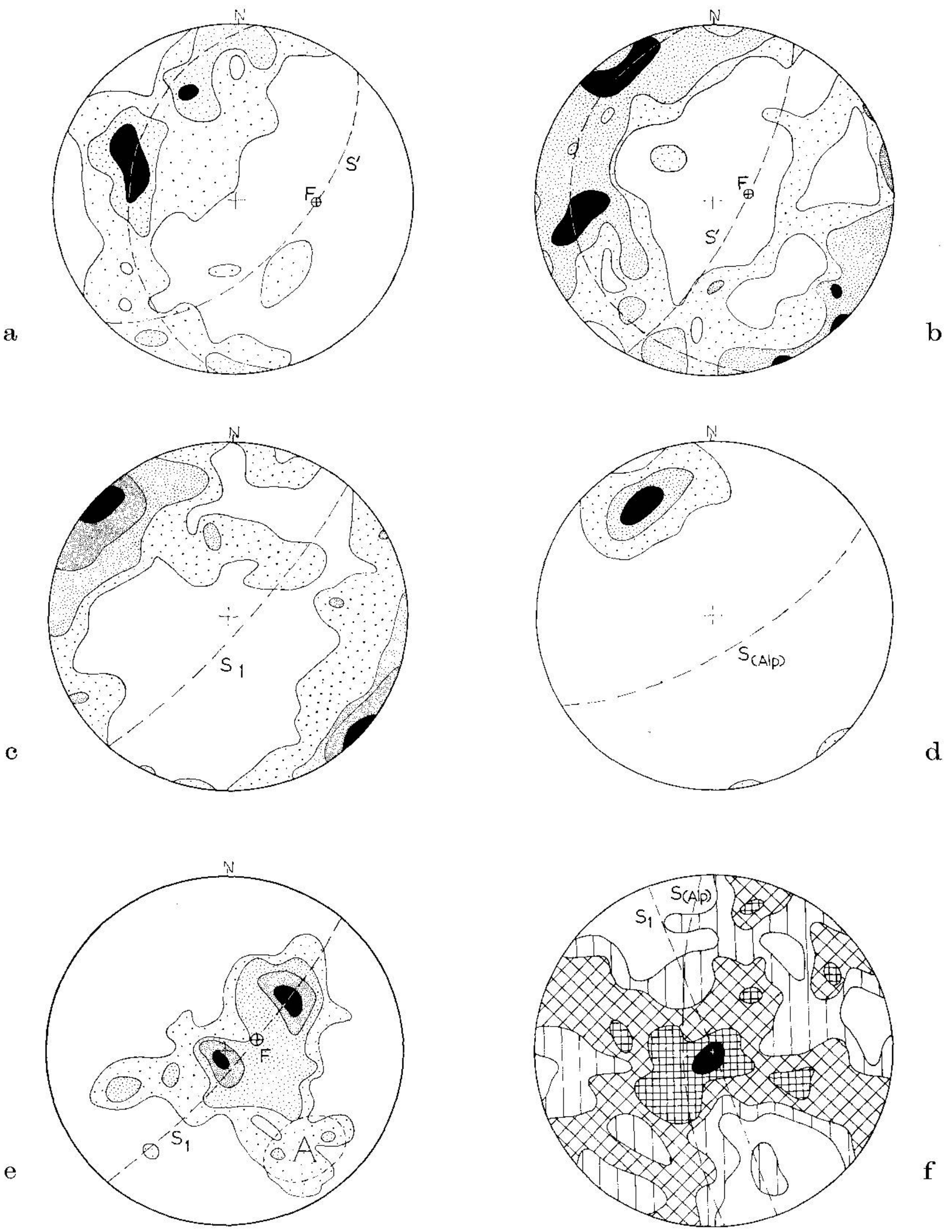

Fig. 14. Measurements of structural elements of the Bifertenfirn and Val Gliems metasediments: Lambert's projection, lower hemisphere. a, π-diagram (108 poles to bedding) of the Bifertenfirn metasediments. Contours 5%, 3%, 1% per 1% area. b, π-diagram of the pre-Triassic sediments of Val Gliems, 133 poles. Contours 5%, 2%, 1% per 1% area. F = constructed fold axis. c, Poles to pre-Alpine cleavage in the Val Gliems metasediments; 225 poles. Contours 20%, 10%, 5%, 1% per 1% area. S_1 = general cleavage plane. d, 70 poles to Alpine cleavage in Val Gliems; contours 15%, 7%, 1% per 1% area. e, Elongation directions in the Val Gliems metasediments, 74 point. Contours 10%, 7.5%, 3%, 1% per 1% area. S_1 = pre-Alpine cleavage plane; F = constructed fold axis from π-diagram; A = field of Alpine lineation. f, Orientation diagram for (0001) of quartz in quartzite pebble in conglomerates, Val Gliems, 362 grains. Contours 5%, 2%, 1.2%, 0.75% per 1% area.

constructed fold axis. Thus, although the elongation direction is everywhere rather steep, it would appear that it is a "B"-tectonic lineation. The stress responsible for this lineation can be regarded as succeeding the period of static contact metamorphism of the hornblende facies, and as being associated with greenschist facies metamorphism. The effect of this tectonic stress on the recrystallization of quartz in a quartzite component of the conglomerates is shown in Fig. 14f, where the central maximum is also the direction of elongation; the directions of the pre-Alpine and Alpine cleavages are marked as great-circles.

The diagrams from the Val Gliems area show a strong scatter because of later disturbance, but the scatter does not form very pronounced subsidiary patterns. The spread of the cleavage poles around a partial great-circle is the clearest indication of disturbance by Alpine movements, and the deviation from monoclinic symmetry in the π-diagrams is also due to these later effects; the lineation also shows a scatter which is related to the Alpine movements.

CONCLUSIONS

In spite of their small extent, the Bifertenfirn and Val Gliems metasediments do give valuable information about the pre-Alpine history of the eastern Aar Massif. The pioneer work of WEBER and the important study of EUGSTER cover many points of the petrography and metamorphism of the rocks, but there has been some confusion as to whether or not the Val Gliems rocks may be correlated with the dated Upper Carboniferous. It is now confirmed that the Val Gliems sediments do in fact mark an earlier period than the dated Upper Carboniferous.

The pre-Alpine history recorded by the sediments can be divided into three main stages:

1. Deposition of the sediments in local, possibly terrestrial basins on a surface of older gneisses and igneous rocks. Minor basic intrusions were emplaced before the next important tectonic phase.
2. Metamorphic and deformational events, and intrusion of the earlier Hercynian granite bodies. The course of events appears to have been first—a preliminary static metamorphism in the hornblende hornfels facies, and second—an episode of deformation and metamorphism at approximately the same temperature. These events have here been termed the main Hercynian phase.
3. Late Hercynian phase: volcanic activity and sedimentation in the northern part of the Massif, and erosion of the older metasediments. Late Hercynian intrusion (including the Central Aar granites) and disturbances, possibly in major fault zones.

Many major questions still remain unanswered, especially with regard to the earlier history of the Massif. Still little is known about the older gneisses, while the various intrusive bodies in the southern igneous complex offer interesting and important problems whose solution depends largely on field-work; absolute age determinations may constitute useful indications, as long as one takes into consideration successive metamorphic events. The southern igneous complex of the Massif differs from the northern areas, and the linking-up of igneous bodies across the important tectonic line that follows the Val Gliems metasediments may give further indications of the disturbances along this zone during the Hercynian movements.

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Manuscript received November 6th, 1967.