Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 61 (1968)

Heft: 1

Artikel: A study of upper paleozoic sediments and volcanics in the northern part of the eastern Aar massif

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DOI: https://doi.org/10.5169/seals-163585

Eclogae geol. Helv.	Vol. 61/1	Pages 49–140	36 figures and 1 table in the text	Basel, July 1968

A Study of Upper Paleozoic Sediments and Volcanics in the Northern Part of the Eastern Aar Massif[1])

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with 36 figures and 1 table in the ʻext

ABSTRACT

Westphalian-Stephanian volcanic and clastic sediments of E. Switzerland were deposited rapidly on an older complex of gneiss and Tödi granite. The Bifertengrätli Formation, the only fossil (plant) bearing formation of the eastern Aar Massif, consists of a Volcanic, Estuarine and Lacustrine Member. Farther west in the Maderanertal, only volcanic rocks are seen (Tscharren, Witenalp and Windgälle); these are predominantly silicic and sub-silicic tuffs and ignimbrites. The explosive volcanic activity was followed by the gentle uprise of the Central Aar Granite.

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[1]) Printed with financial assistance of the ETH Zentenar-Fonds.

FOREWORD

This study was commenced in 1961 during the tenure of a post-graduate exchange scholarship between the Imperial College of Science and Technology, London, and the E.T.H., Zürich. The primary aim was a study of the Upper Carboniferous sediments of the Biferten inlier, under the guidance of Professor Dr. R. Trümpy, Zürich. In 1962 the topic was accepted as a thesis study at the E.T.H., and further work during the summers of 1962–65 under the supervision of Professors Dr. R. Trümpy and Dr. A. Gansser extended the field work to the Maderanertal and Val Gliems areas.

The results were prepared in the Geological Institute of the E.T.H. and University, Zürich, where the detailed field maps and specimens are deposited.

My deepest thanks are due to Professors R. Trümpy and A. Gansser for the supervision of this work, their advice in the field and laboratory and their valuable criticism of the manuscript. The continued interest and encouragement of Professors J. Sutton and J. G. Ramsay of Imperial College are warmly appreciated.

During the preparation of the study much kindly assistance with various problems was given by Professors C. Burri and E. Dal Vesco and P.D. Dr. R. Hantke of Zürich. Profitable discussions and a field trip in the Biferten area in 1965 with Professor Th. Hügi of Bern are remembered for their cordiality. To all I wish to express my most sincere thanks.

Messrs. M. Zuber and E. Schärli are thanked for their help with the preparation of thin-sections and photographs.

The financial support of the exchange scholarship of the E.T.H. which made the greater part of this study possible is thankfully acknowledged.

Above all I wish to thank my wife, Sibylle Franks-Dollfus, for her help and understanding.

INTRODUCTION

Although pre-Triassic rocks cover an area roughly equal to that of the Mesozoic and Tertiary rocks in the Alps, their history is much less well known. They form relics of older orogenic belts which have been overwhelmed by the Upper Cretaceous-Miocene orogeny and involved with the later sediments in the complex Alpine deformation, partly overthrust, as in the Eastern Alps, the Pennine nappes and the Briançonnais Zone, locally remetamorphosed and intruded by younger igneous rocks. In the external massifs, from Argentera in the south-west to the Aar Massif in the north-east, the pre-Triassic rocks preserve their earlier structures and expose a fragmentary picture of the Hercynian and older basement complex and the small basins of Upper Palaeozoic sediments.

At the eastern extremity of the external massifs (Zentralmassive of most German-speaking authors), in the eastern Aar Massif, three small areas of pre-Triassic sediments are exposed within the crystalline rocks. These areas have in the past been studied separately by several geologists, and have given rise to a number of conflicting opinions on the origin and age relationship of the sediments. The present study has been undertaken to resolve some of the problems by detailed stratigraphical and structural investigations of these three isolated areas, and attempt to lay down some general correlations with the late Palaeozoic rocks of neighbouring areas. The results of previous geologists have been summarized for each area in order to illustrate the conflicting views and the evidence on which they are based. The regional significance of the results of the present study is discussed in the final chapter.

The Main Problems

One of the greatest controversies in the eastern Aar Massif concerns the age of the Tödi granite and its associated contact metamorphism, and the question of whether or not it is related to the Central Aar granites. Faul (1962) stated: '... the Tödi granite ... is thought to be stratigraphically younger than Westphalian D and probably older than Permian (Widmer 1949). It is the only stratigraphically recognized Hercynian rock in the central Alps, but it is badly altered and a measured age is not available.

The study of contacts between crystalline rocks and stratigraphically dated sediments is extremely difficult in areas as severely smashed as the Alps. It is not surprising that a contact may appear to be much more "eindeutig" in the literature than it actually is in the field. The question whether the Tödi granite really does intrude the Westphalian D would be answered quite differently by different field geologists who have studied the area.'

The two possibilities are that the Tödi granite and its related pegmatites do intrude the dated Upper Carboniferous sediments (Escher 1911, who considered that only the pegmatites intrude the dated sediments; WIDMER 1949) or that it is intrusive into an older succession and is overlain unconformably by the Upper Carboniferous (WEBER, in HEIM 1922; HÜGI 1941). The former explanation, implying post-Westphalian age for the granite or its pegmatites has been accepted in recent years and is incorporated in the most recent summaries (CADISCH 1953; HÜGI 1956).

The plant-bearing Westphalian D (?)-Stephanian sediments of the NE Tödi area are relatively easy to describe stratigraphically, for they are well bedded and contain distinct lithological types. The sediments further west, in the Maderanertal, are on the other hand rather problematical. They contain no fossils; they are predominantly volcanic and lack distinctive lithological types which may be used for correlation, and they are more metamorphic than the rocks NE of Tödi (with biotite and chlorite).

The earliest studies of these sediments described them as tufaceous rocks and flows (W. STAUB 1911; PFLUGSHAUPT 1927; BRÜCKNER 1943), whilst the latest study (SIGRIST 1947) denies the presence of surface volcanic rocks either as flows or as tuffs, and describes the rocks in question as intrusive sills with minor relics of Carboniferous slates (p. 76). The basic problem of the relative ages of the rocks north of the Central Aar granite had not been satisfactorily solved, despite its importance in dating the late Paleozoic magmatic history of the Aar Massif.

The Upper Carboniferous sediments in the north of the Aar Massif can be drawn as two more or less continuous belts, the northern one stretching from the Bifertengrätli area through the Klein Tödi into the Maderanertal and over Bristenstäfeli to Intschi in the Reuss valley, and the southern one passing from Tscharren to Rossbodenstock. A further belt of sediments is known from the southern part of the eastern Aar Massif in the Val Gliems and Val Russein area. These were described by WEBER (in HEIM 1922) as part of the older Carboniferous sedimentary succession. A later study by EUGSTER (1951) correlated these rocks with the Upper Carboniferous succession of the NE Tödi area as described by WIDMER and explained their higher metamorphic grade as a result of the post-Carboniferous granite intrusion. The uncertainties in the Carboniferous stratigraphy worked out by WIDMER hindered a comparison between the two area; it was not appreciated that the Upper Carboniferous lay unconformably above an older succession and that the volcanic Grünhorn Formation is in fact older than the plant-bearing Bifertengrätli Formation.

THE NE TÖDI AREA

INTRODUCTION AND SUMMARY OF PREVIOUS WORK

The Biferten inlier on the NE side of Tödi is the most significant area of the eastern Aar Massif for a discussion of the sedimentary rocks that form the younger part of the basement complex. Besides the dated Upper Carboniferous sediments, hornfelses, knotenschiefer, tufaceous sediments, granites, diorite and quartz porphyry have been considered as Upper Paleozoic. Hornblende gneisses are assumed to be the oldest rocks present as they contain structures which are not shared by any other rocks.

In 1809 CONRAD ESCHER VON DER LINTH described anthracitic schists from Bifertengrätli, but not until 1879 were determinable plant remains found by A. ROTH-

PLETZ (1880) and the unconformity between the Carboniferous and the overlying Triassic recognised. Illustrations and a brief description of the area were given by ALBERT HEIM (1878, Pl. IX, figs 10, 11, 12; Pl. XIII, fig. 2) and the folding of the Triassic unconformity was well documented. B. G. ESCHER (1911) studied the rocks in greater detail and gave some details of the fold structure of Bifertengrätli which he interpreted as a tight syncline overturned to the south and plunging with 11° to the east. He noted that the cleavage in the sediments was continuous with that in the older gneisses, and that plant remains were found where cleavage and bedding were parallel.

FR. WEBER's work in the eastern end of the Aar Massif was unfortunately never published in detail; it is summarized in ALBERT HEIM's "Geologie der Schweiz" (1922, II/2, p. 932), and his remarks for the Carboniferous sediments of Bifertengrätli cover also rocks considered as Carboniferous in neighbouring areas. A younger and an older group are distinguished; the older is composed of black shales, quartzites and conglomerates, and the younger is made up of black shales with inclusion sof granite, aplite etc., which pass upwards into arkoses occasionally containing anthracite. In the Biferten area the younger group is seen on Bifertengrätli and the lower group in Schneerunse. As the granite is seen to be intrusive into the older group, and the younger group to contain blocks of Tödi granite, it was assumed that the intrusion of the Tödi granite took place in a time interval between the deposition of the two groups, i.e. in Middle Carboniferous times.

HÜGI (1941) gave good petrological descriptions of many of the rocks of the area and classed most of the Carboniferous sediments under the title of "nachgranitische Bildungen". A summary of the geological history that he deduced is: sandy-silty sediments of possible Devonian to Lower/Middle Carboniferous age were intruded by the porphyritic microgranite (Granitporphyr) of the Tödi granite cycle (the porphyritic Tödi granite came earlier in the same cycle). Then followed erosion, sedimentation and the production of further magmatic rocks (quartz porphyry tuff and diabase), and the deposition of the plant-bearing sediments of Bifertengrätli. Plant material was dated as Westphalian D (–E) by JONGMANS, and the flora compared with that of the Stangalpe in the eastern Alps. The formation of graphite from the organic matter was thought to have taken place during the alpine dislocation.

WIDMER (1949) progressed further to the problem of the stratigraphy of the Carboniferous rocks and defined two formations: the Bifertengrätli Formation and the Grünhorn Formation[2]). The former he regarded as Upper Westphalian or possibly Lower Stephanian which was intruded by the Tödi granite, the latter as a younger formation of Stephanian of Lower Permian age. Because Widmer misinterpreted the structures of Bifertengrätli he came to false conclusions of the age relationships; the present study shows that the Grünhorn Formation is older than the Bifertengrätli Formation.

The Bifertengrätli Formation was described as a succession of coal-bearing psephites, psammites and pelites reaching a thickness of ca. 150 m. An illustration of convolute lamination indicated the possibility of mudflow action as suggested by BRÜCKNER (1943) for Carboniferous rocks of the Lötschental. WIDMER raised the

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[2]) WIDMER used «Serie», which in alpine German is equivalent to «formation».

question of the origin of the feldspars in this formation and pointed to a possible tuff or lava source. In the summary on the pre-Triassic rocks he mentioned coarse clastic deposits which pass laterally into volcanic rocks, but gave no further details or correlation with the Grünhorn Formation. The Grünhorn Formation comprises a 200 m thick series of mainly coarse terrestrial clastic and partly tuffogenous deposits, with conglomerates, breccias, sandstones, tuffs and shales.

The recent monograph of JONGMANS (1960) on the Carboniferous flora of Switzerland includes a summary of the important Carboniferous localities (RITTER 1960) and illustrated fossil localities of Bifertengrätli in a field sketch (loc. cit. fig. 9). The age of the flora from this locality was determined as Stephanian A, and the relationship to an Upper Westphalian flora looked upon as less definite than formerly (JONGMANS 1951). A reappraisal of the Westphalian/Stephanian boundary by REMY (1964a, b) supports this dating as lowermost Stephanian.

GEOLOGY OF THE BIFERTEN INLIER

The Position of the Upper Carboniferous Sediments

The Biferten inlier is a small area of crystalline and sedimentary rocks of the pre-Triassic basement[3]) which is separated from the main Aar Massif by a narrow strip

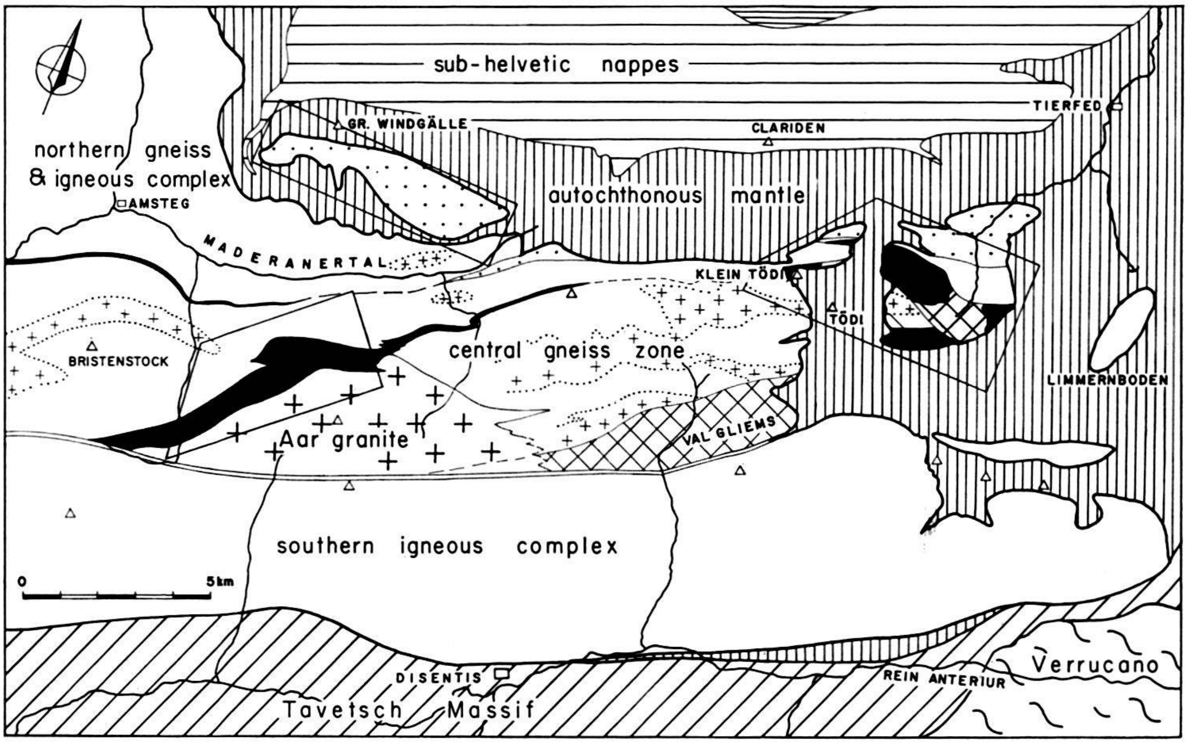


Fig. 1 Locality map of the pre-Triassic sediments of the eastern Aar Massif: black, areas of Upper Carboniferous sediments and volcanics; dots, Windgällen volcanics; cross-hatching, pre-Upper Carboniferous (Lower Palaeozoic?) sediments. Described areas outlined.

[3]) "Basement" is used here to designate all those rocks that lie below the pre-Triassic unconformity.

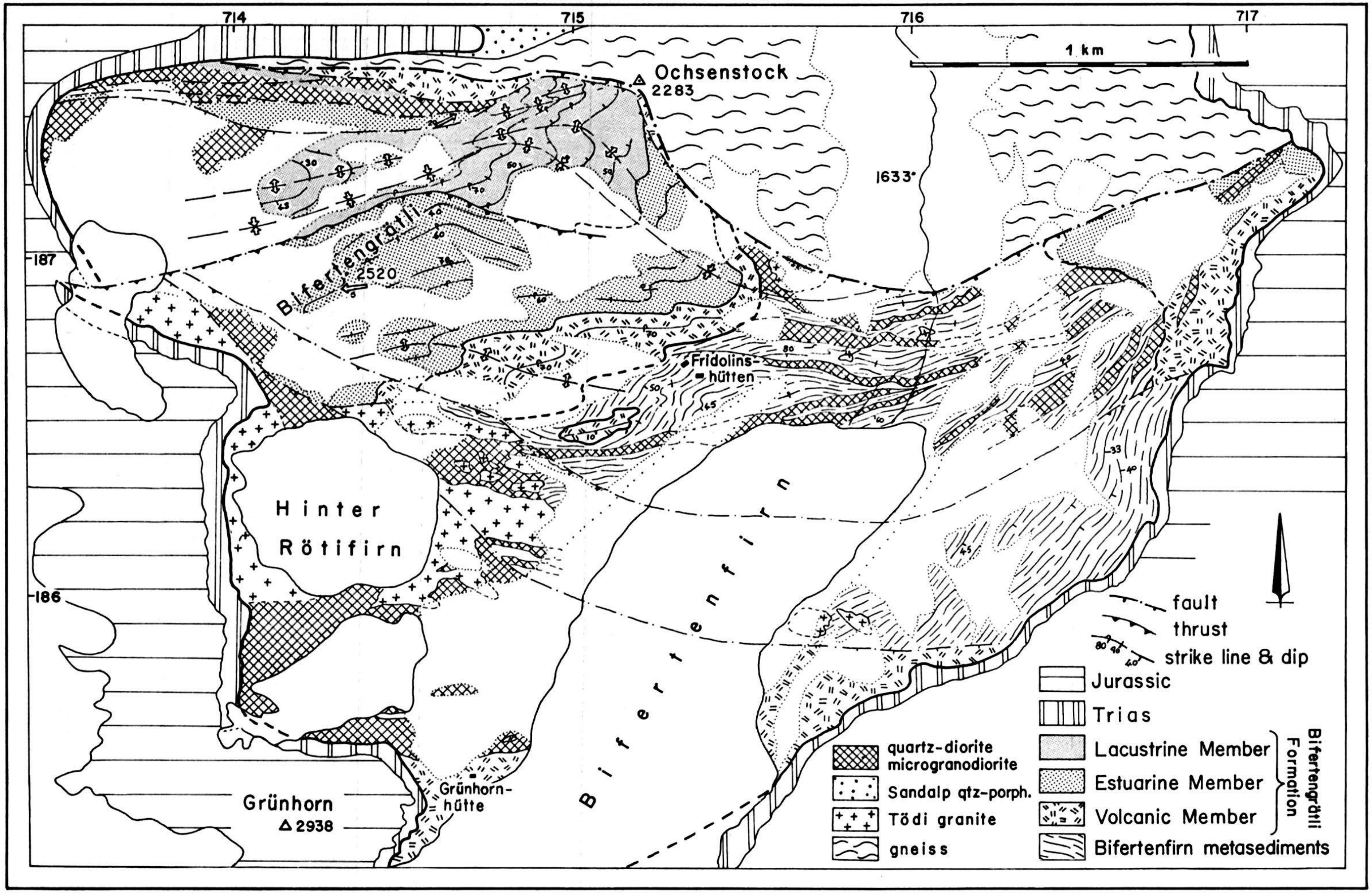


Fig. 2 Geological Map of the southern part of the Biferten inlier.

of Mesozoic rocks. The deep glacial valeys now occupied by the Sand and Biferten streams which flow northwards from the glaciers of Tödi (3620 m., 11,876 ft) have cut through the autochthonous carbonate succession of Triassic to Cretaceous rocks and provide good exposures of the basement. Further to the north the streams open out into the main Linth valley – the corridor of the Glarus Alps – which cuts through the basal thrust of the Helvetic nappes in the region between Linthal and Glarus.

The pre-Triassic sediments of the basement are exposed in the southern half of the Biferten inlier, and are separated from older gneisses and the Sandalp "quartz porphyries" in the north by a pronounced fault zone. Field mapping of this area established a succession of metamorphic rocks, the Bifertenfirn metasediments, unconformably overlain by three members of a dated Upper Carboniferous sequence. The latter were given the names of Volcanic, Estuarine and Lacustrine Members, in decreasing age, on the basis of easily observable field characteristics which specify the mode of origin (FRANKS 1966). The unconformity between the older sediments and the dated Westphalian D-Stephanian is shown by the abundance of metamorphic sediments in the basal conglomerates of the latter, and is also apparent in the structural pattern.

Both groups of sediments have been folded together by post-Stephanian pre-Triassic movements, and an angular unconformity is difficult to observe in the field. Pre-Upper Carboniferous structures are demonstrated by the existence of granite intrusions in the older sediments and the associated contact metamorphism, but no age can yet be given either to the metasediments or to the intrusive episode. The folds seen in the Upper Carboniferous are an overturned syncline and anticline (fig. 3). The movements which produced these folds were followed by strong faulting which brought the sedimentary rocks of the southern part of the Biferten inlier into contact with the gneisses in the north.

The Igneous and Metamorphic Rock of the Northern Biferten Inlier

The northern metamorphic and igneous rocks are not handled in detail by the present study, but a few general remarks are given. The oldest rocks are the hornblende gneisses and granitic and syenitic vein-material of the "Altkristallin". These are paragneisses and orthogneisses of amphibolite facies, with some local zones of migmatisation. The evidence from this area alone does not allow a satisfactory description of their metamorphic and deformational history, and they must be considered as part of the gneiss belt which extends along the whole of the northern part of the eastern Aar Massif. Petrographical descriptions of these rocks and their extension in Limmernboden are given by HÜGI (1941).

The Sandalp "quartz porphyries" are younger than the gneiss but their precise age is unknown. They are generally considered to be Permian volcanic or subvolcanic rocks (WIDMER 1949, p. 24), which succeeded the intrusion of the Central Aar granites, but the rocks are not amenable to a stratigraphical interpretation. The exposures are bounded by fault zones and the rocks are cut throughout by a strong cleavage. There is a strong similarity in the lithology of these rocks with those of the core of the Windgällen fold, and their position on the northern margin of the Aar Massif and the strike of their bounding faults is entirely comparable. The Windgällen rocks, however, are better exposed and offer more evidence of their origin; these are discussed later.

The Sandalp rocks vary in the field from phyllonites to sheared microgranites, everywhere cut by prominent sericite-coated cleavage surfaces which obscure the original texture of the matrix. Petrographical descriptions are given by HÜGI (1941, p. 50) and WIDMER (1949, p. 22). Both authors describe associated rare and poorly exposed clastic types which may be comparable with some of the pyroclastic rocks of the Windgällen area. A more basic rock type within the acid variety, exposed in the Rötibach between 1800 and 1900 m, has aroused some discussion (WEBER 1922 – diabase; HÜGI 1941 – melaphyr; WIDMER 1949, p. 23 – spilite). The two possibilities open for this rock are that it is a tectonic splinter of older rocks or a discontinuous dyke of later more basic material.

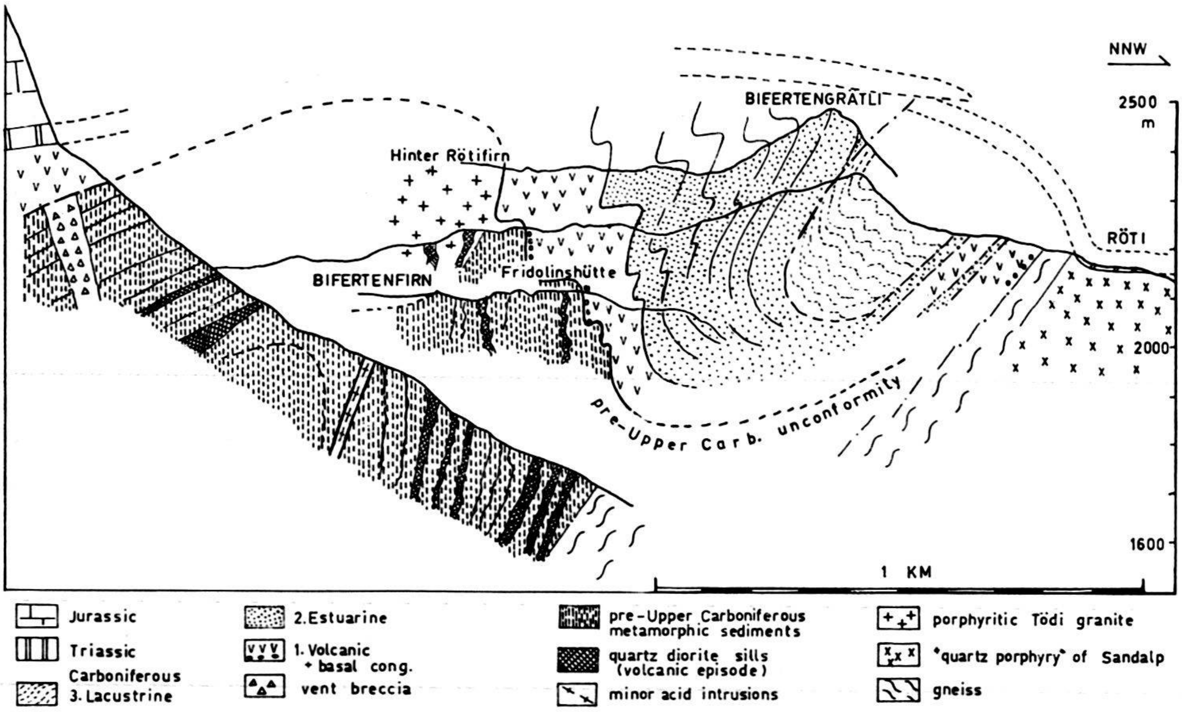


Fig. 3 Simplified section through the pre-Triassic sediments of the Biferten inlier.

The available evidence on the age of the Sandalp quartz porphyries is very inconclusive, but may suggest a pre-Stephanian age as originally advanced by ESCHER (1911). The following points are noted:

a) Rhyodacites (but rarely rhyolites) are present as fragments in the Volcanic Member of the dated Upper Carboniferous section.
b) Intermediate igneous rocks (altered andesites) are found in the conglomerates and may bear some affinity to the Rötibach rock.

c) Acid volcanic components are common in the Klein Tödi volcanic breccias.
d) The rocks have suffered a rather strong pre-Triassic deformation – strongly contorted quartz veins are cut by the unconformity.

The Bifertenfirn Metasediments

Below and north of the front of the Biferten glacier, the unvegetated cliffs offer good exposures of banded hornfelses and two main types of intrusive rocks. The hornfelses, here named the Bifertenfirn Metasediments, are definitely older than the Upper Carboniferous volcanics and lacustrine deposits, and are more fully described in conjunction with the metasediments of Val Gliems, with which they are probably roughly contemporaneous (FRANKS 1968). For the purpose of the present description of the Upper Carboniferous sediments it is important to note that these rocks furnished abundant components to the younger conglomerates.

Of the two main types of intrusive rocks, the Tödi granite is the older; the second intrusive rocks are found as sills between 2 and 10 m thick which intrude both the Tödi granite and the metasediments. Petrographically these later intrusive rocks are very similar to many of the blocks in the basal volcanic series of the Upper Carboniferous, and are thought to have been intruded during a subeffusive volcanic episode which closed just before the beginning of the Upper Carboniferous sedimentation and its accompanying explosive volcanic activity. A period of erosion separated the two volcanic episodes, and produced, in the NE Tödi area, a rather uniform surface on which the later sediments were laid down.

UPPER CARBONIFEROUS SEDIMENTS – THE BIFERTENGRÄTLI FORMATION

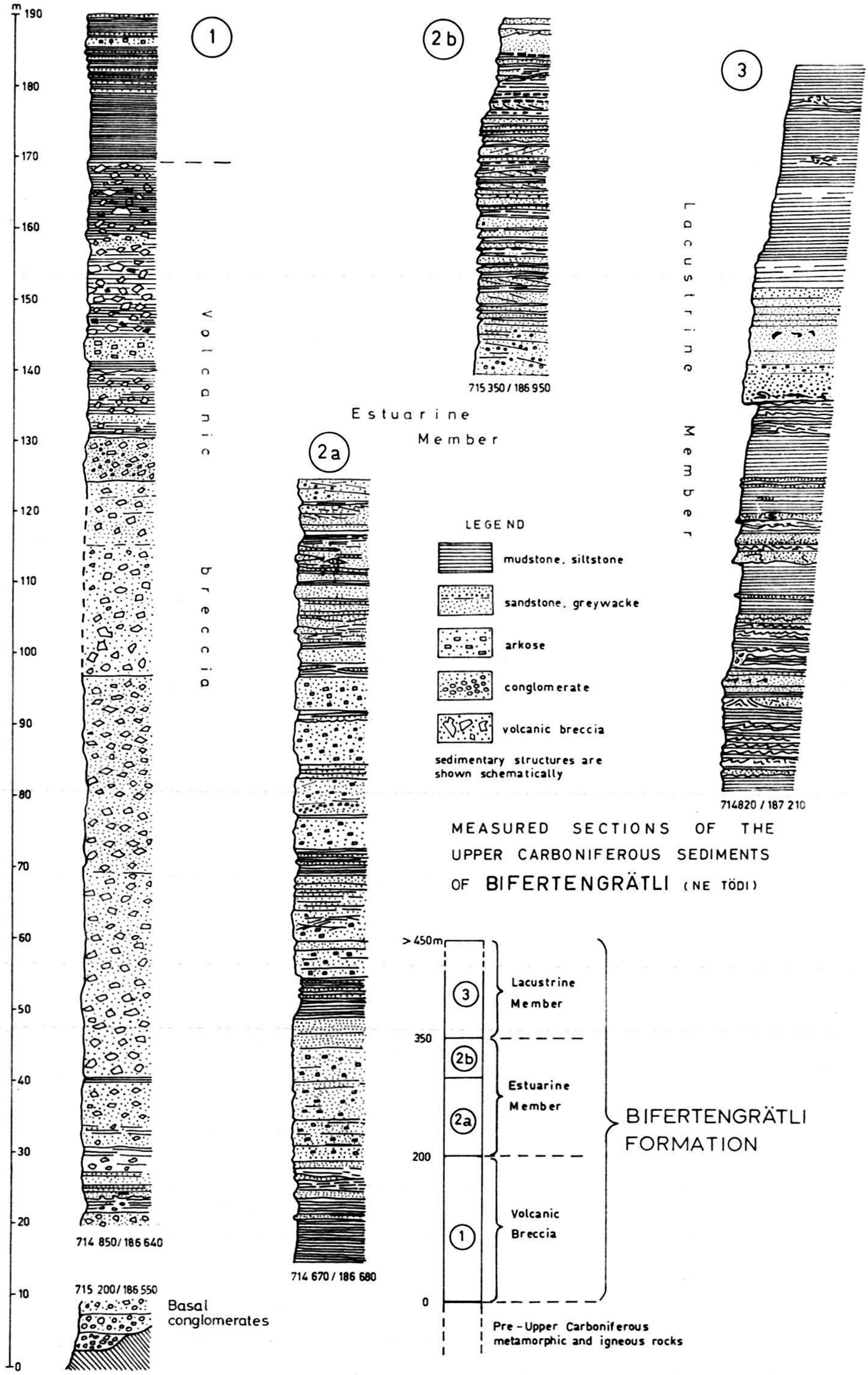
The Upper Carboniferous sediments of the Biferten inlier were divided by WIDMER (1949) into two formations: the Bifertengrätli and Grünhorn Formations. The former was supposed to be older, and as it was dated by plants as Westphalian or lowermost Stephanian; the Grünhorn Formation was considered to be Stephanian or Lower Permian. This age relationship, however, has not been corroborated; the Grünhorn Formation lies below the dated section, and in order to avoid confusion the name Grünhorn Formation is abandoned. The Bifertengrätli Formation as now defined consists of three members, the lowermost of which includes the sediments of WIDMER's Grünhorn Formation. Measured sections from the southern flanks of Bifertengrätli are shown in fig. 4; the extension and structures of the rocks are shown in figs 2 and 3. The type locality is easily accessible and the lithologies are clearly defined.

The succession on Bifertengrätli is:

4.	Lacustrine Member	to 200 m
3.	Estuarine Member	200–300 m
2.	Volcanic Member	+ 200 m
1.	Basal conglomerates	0–5 m

The progression of the facies shown in this section is described in FRANKS (1966).

The most important attribute of these beds is that they have delivered a rich, well-preserved fossil flora. The plants have received considerable attention (ROTHPLETZ


m
190
180
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90
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70
60
50
40
30
20
10
0
1
Volcanic breccia
714 850/186 640
715 200/186 550
Basal conglomerates
2b
715 350/186 950
Estuarine Member
2a
714 670/186 680
3
Lacustrine Member
714820/187 210
LEGEND
mudstone, siltstone
sandstone, greywacke
arkose
conglomerate
volcanic breccia
sedimentary structures are shown schematically
MEASURED SECTIONS OF THE UPPER CARBONIFEROUS SEDIMENTS OF BIFERTENGRÄTLI (NE TÖDI)
>450m
350
200
0
Lacustrine Member
Estuarine Member
Volcanic Breccia
BIFERTENGRÄTLI FORMATION
Pre-Upper Carboniferous metamorphic and igneous rocks

Fig. 4.

1880; CORSIN 1946; JONGMANS 1951, 1960), and the recent monograph of JONGMANS (1960) illustrates and names 32 species from this area. These date the formation as Westphalian D or lowermost Stephanian. The lithology of the beds has received little attention, and it is the aim of the present study to describe the lithology and stratigraphy as well as to discuss the depositional environment.

Conglomerates, breccias and coarse sandstones are the most abundant sediments, and many of these coarse clastic rocks contain a large amount of volcanic débris and are to be classified as volcanic conglomerates and agglomerates. Rocks of this type make up the bulk of the lowermost member. The Estuarine Member consists of cross-bedded arkoses and conglomerates with some anthracite layers. The upper member consists of mudstones, siltstones and sandstones with turbidities and aquatic slump structures.

Basal Conglomerates

The Basal Conglomerates South of Bifertengrätli

The basal conglomerates and breccias are well seen to the SW of the Fridolinshütten where they form irregular patches lying above the metamorphic rocks in the core of the Bifertengrätli anticline. The dip of the unconformity here changes from nearly horizontal to steeply north dipping; it is seen gently SE dipping just east of the footpath 200 m south of the Fridolinshütten, where there is some suggestion of slip along the contact. Although the area of these exposures is about 400 m^2 the thickness of the beds is never very great, and at the most reaches 5 m.

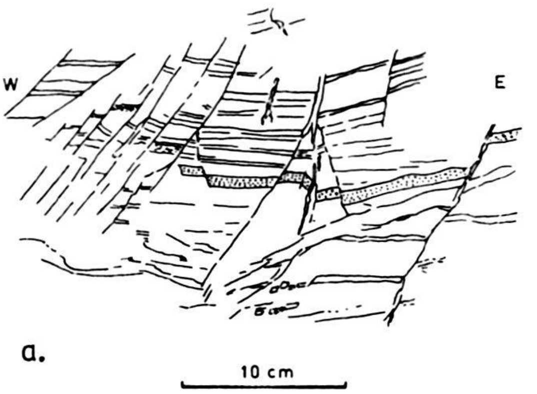
Field and macroscopic study allows the recognition of three lithological types:

a. monogenic breccias; locally derived from the metamorphic rocks;
b. polygenic conglomerates with no volcanic material: water-transported but badly sorted deposits;
c. conglomerates and breccias with a slight admixture of tufaceous material.

Monogenic Breccias

Monogenic breccias are found only locally and are restricted to the immediate neighbourhood of the unconformity. They are dark coloured rocks with angular blocks of banded hornfels up to 5 cm set in a well-cemented dark grey-green matrix. The proportion of matrix to blocks varies, and on weathered surfaces the angular blocks sometimes stand out in high relief. The components are directly comparable with the neighbouring hornfelses and knotenschiefer and appear to be locally derived. Acid igneous rocks and volcanic components are entirely absent. If the matrix is very scarce it is only under the microscope that one can recognize the disturbance of the metamorphic mineral banding, and in thin section displacements of only a few millimetres are seen which indicate the decomposition of the rock in situ.

Syngenetic disturbances are seen in the breccias (fig. 5) and similar small-scale syngenetic faults affect many of the overlying sediments. The displacements are similar to those of the post-metamorphic small-scale faults in the underlying rocks. Earth movements were therefore active during the Upper Carboniferous, and are most clearly displayed in beds immediately below volcanic deposits or in tuffaceous



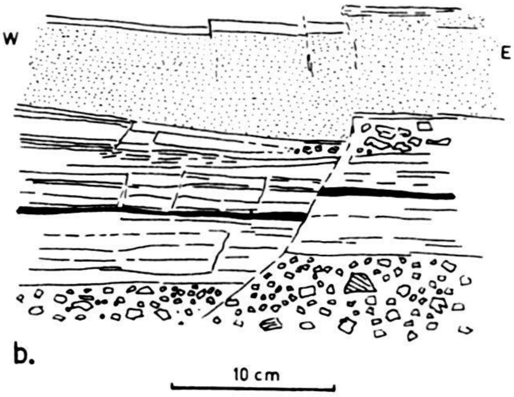
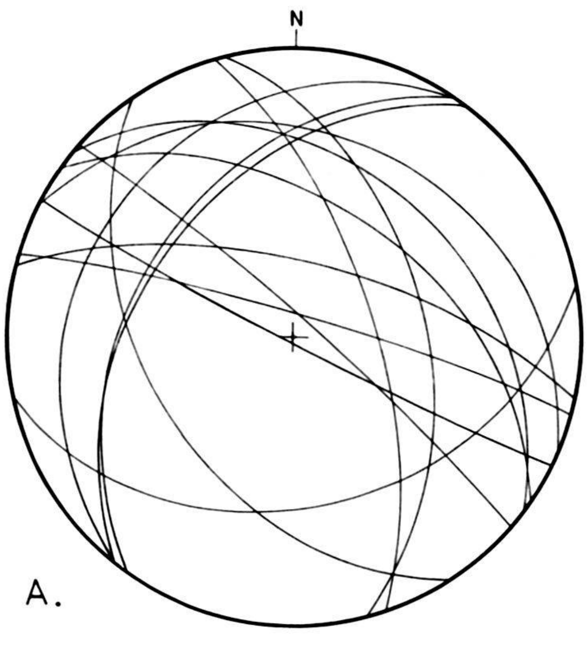


Fig. 5 *a.* Small-scale faults in the hornfelses SW of the Fridolinshütten. *b.* Small-scale syngenetic faults in the basal breccies of the Bifertengrätli Formation, SW of the Fridolinshütten.

sediments. Similar synsedimentary faults are also seen in lapilli tuffs on Klein Tödi and 15 km farther east in the Maderanertal.

A number of measured faults have been plotted and the beds unfolded to a horizontal position on the stereogram about a fold axis locally constructed from each locality from the intersection of the bedding with the cleavage (fig. 6). An error is introduced here, for the unfolding is constructed on the hypothesis of concentric folding without significant displacements on shear surfaces or cleavage. The error is about 15% if the beds have suffered a 30% compression by homogeneous pure shear (RAMSAY 1961). The results without a correction for internal strain show a general distribution of strike of the minor faults in a NNW–SSE direction, with some cross displacements at right angles to this NE–SW). The constructed fault planes and a schematic block diagram of the displacement planes are shown in figs 6.



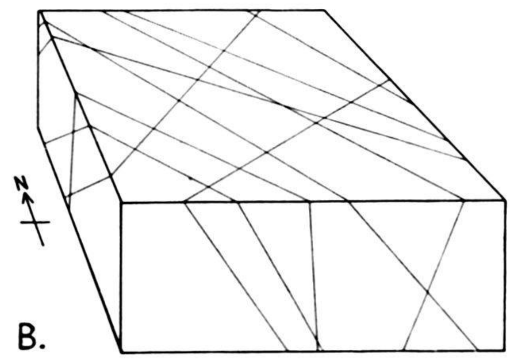


Fig. 6 *a.* Sterogram of unfolded minor faults (see text). *b.* Schematic block diagram of the fracture pattern during the volcanic episode of the NE Tödi area.

The monogenic breccias are not very abundant and attain a maximum thickness of 2–3 m. Their significance lies in the fact that they demonstrate the covering of an old land surface with locally derived material.

Polygenic Conglomerates

The polygenic conglomerates SW of the Fridolinshütte contain a mixture of rounded to subangular fragments up to 10 cm in size of quartzites, grey shales and hornfelses set in a grey sheared matrix which may make up 30–50% of the rock. They extend to the NE end of the Hintere Rötifirn and are accompanied by sandstone beds. The most distinguishing features are the abundance of quartz and metamorphic rock fragments and the rounding of the components. A count of 550 components in an area of 30 × 30 cm gave the size distribution shown in fig. 7. Small-scale faults of these beds are shown in fig. 5.

Thin sections show the metamorphic fragments to be similar to those of the nearby underlying succession; fine-grained quartzites with large muscovite flakes up to 0.5 mm are the coarsest type seen, and slates with different amounts of recrystallization are the common finer-grained rock types. Some shale fragments show the development of biotite, a mineral not commonly developed in the metamorphic rocks of this area. Quartz grains of sand size are angular and often cloudy. Some are strained and recrystallised grains of metamorphic derivation, but many are probably derived from an igneous source; rutile needles up to 0.5 mm in length are present as inclusions in some larger quartz components and indicate igneous origin. The fine-grained sericitic quartzose material is always abundant and is cut by an irregular cleavage on which some of the sericite is aligned.

The sandstones associated with the conglomerates are very badly sorted and immature; isolated angular quartz grains are set in a muddy matrix and lithic fragments are abundant. Metamorphic source rocks are demonstrated by the abundant

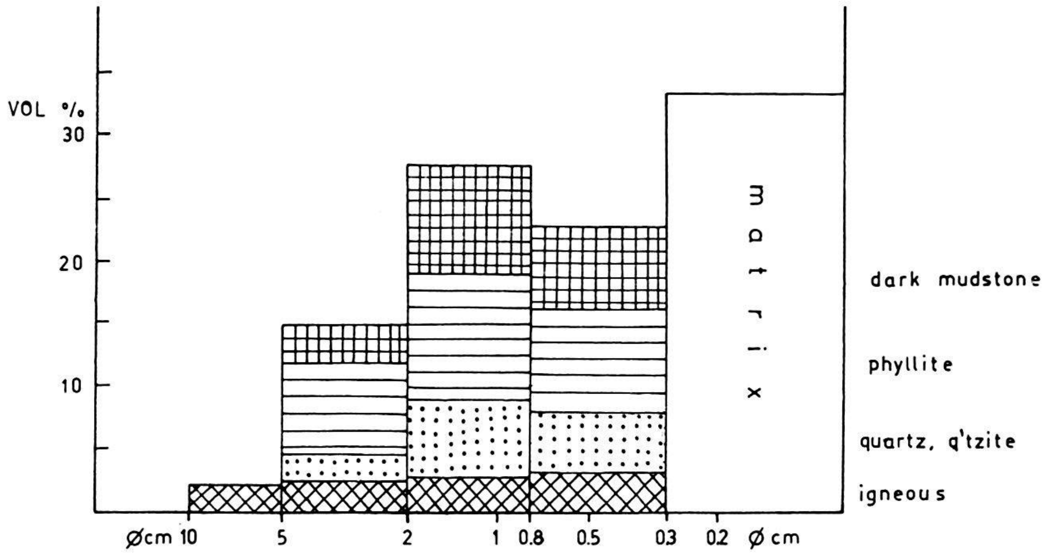


Fig. 7 Field analysis of conglomerate from Basal Conglomerates. (550 components counted on an area of 30×30 cm; matrix-here < 0,3 cm estimated at 1/3rd total area.)

micas, some of which are biotite and its alteration products; chlorite pseudomorphs, probably after pyroxene, and some small garnets and idocrase grains up to 1.5 mm. Apatite and magnetite are present, partly as isolated grains and partly as inclusions in quartz.

A sandstone of the basal conglomerates from immediately NE of the Hintere Rötifirn was studied quantitatively in thin section by measuring the long axes of 250 grains on an integration stage and using the correction factor of FRIEDMANN (1958) to construct the cumulative grain size distribution curve (fig. 13a, p. 34). The cumulative curve thus obtained contains errors because of the lack of sorting and the angular grain shape of the fragments. It may not be compared with data obtained from direct granulometric analysis, but it is of value when compared with data from other rocks of approximately equal grain size and sorting measured by the same technique. The curve shows quantitatively a distinction which is readily observed in thin section, and is interpreted as illustrating a uniform grain size distribution with a large amount of fine-grained material.

Mixed Conglomerates and Volcanics

Some of the conglomerates which belong lithologically to the basal conglomerate unit are seen in thin section to contain some volcanic material in addition to the metamorphic and igneous components. The volcanic material is present only in minor quantities, in contrast to the overlying beds of the Volcanic Member. The most common distinctive components which can be compared with rocks properly belonging to the volcanic episode are the resorbed quartz grains. These are sometimes single grains up to 2 mm, but they are more often contained in a fragment of a very fine-grained microcrystalline rock which is thought to be a recrystallized volcanic glass. Some of the quartz still shows crystal faces and uncorroded angles, and never exhibits the lobate form of quartz seen in many of the sills. Its presence in these basal conglomerates demonstrates the existence of volcanic rocks containing porphyritic quartz at the beginning of the Upper Carboniferous history of the eastern Aar Massif.

Basal Conglomerates North of Bifertengrätli

A small area of deformed basal conglomerates is exposed north of Bifertengrätli in the upper Rötibach, resting on sheared gneisses of the "Altkristallin". Their upper boundary is a thrust above which fine-grained rocks of the highest Carboniferous unit are exposed. The conglomerates are coarser than those farther south and have a much greater proportion of large angular igneous rock fragments, some of which reach 30 cm in size. The conglomerates are normally rusty brown on weathered surfaces and greenish when fresh, with visible components of granite, quartzite and small black shale fragments set in a consolidated sandy matrix of quartz, sericite and chlorite.

Thin sections show that the coarse-grained igneous rock fragments are altered leucocratic granodiorites comparable to those intrusive into the Bifertenfirn metasediments, together with altered granites which are comparable with the coarse porphyritic Tödi granite. Mica is very abundant in the matrix between the blocks, and some of it retains the brown colour and a slight pleochroism of biotite; small ore grains and sericite are the normal alteration products. The biotite enrichment is probably a result of sedimentary winnowing of the lighter minerals. Some fragments of a porphyritic plagioclase bearing rocks with resorbed quartz grains are also present in lesser amounts. The similarity of the suggested source area for these conglomerates with that of the conglomerates and breccias farther south is great, and it is probable that these deposits are lateral equivalents. The unconformity below the Upper Carboniferous therefore cuts across the Bifertenfirn metasediments, intrusive granites and an older gneiss complex.

Basal Conglomerates and Breccias of the Upper Sandalp

The sediments exposed on the upper Sandalp between "quartz porphyry" to the north and gneisses to the south appear to be comparable with the rocks described above as basal conglomerates. Both the northern and the southern contacts are faults. Along the nothern edge of the outcrops there are green porphyritic rocks with plagioclase phenocrysts (granodiorite/quartz-diorite association), and to the south there is a thin band of black shales along the fault zone. The exposures are small but, as WIDMER pointed out, they lie in the extension of the Upper Rötibach conglomerates and may be compared on structural grounds with these. The lithology is more akin to the Rötibach conglomerates than to those south of Bifertengrätli; the rocks are coarse conglomerates and breccias with fragments reaching 5 cm. Components are mainly of igneous origin (highly altered granite) together with fragments of dark shale and coarse sandstone. Bedding is seen in finer beds and is cut off sharply in places by coarser conglomeratic layers.

Here also the matrix carries a high proportion of mica; plates of 0.5 mm consist of sericitic alteration products after biotite. This, together with abundant microcline and small garnets, indicates an igneous and metamorphic source area as was assumed for the other sections of basal conglomerates. Rare fine-grained glassy rock fragments with quartz phenocrysts up to 0.4 mm and sericite laths after plagioclase resemble rocks of the volcanic suite, but their rarity demonstrates their minor relative importance and shows that a larger area of metamorphic and igneous rocks was exposed to erosion in the source area.

The Volcanic Member

Volcanic rocks have been mentioned by previous authors who have studied the Biferten inlier (HÜGI 1941; WIDMER 1949), but no further details of the nature of the volcanic activity or the significance of their occurrence have been given. The rocks regarded here as belonging to a single lithological unit are the equivalent of the Grünhorn Formation as defined by WIDMER, but contrary to his opinion they lie below and not above the dated Upper Carboniferous rocks.

The Volcanic Member covers an area of about 3 km^2, $1^1/_2$ of which are exposed, and lies mainly in the southern part of the inlier. Primary stratification is absent through most of the succession, and tectonic and genetic interpretation can be made only by a study of the composition of the clastic fragments. The dated part of the section lies between the Hintere Rötifirn and the Fridolinshütten, where the exposures coincide with a zone of strong deformation on the vertical limb of the fold of Bifertengrätli. The outcrops to the south, where the breccias are less deformed, are considered to belong to the same lithostratigraphic unit.

The unit is characterised everywhere by the abundance and sometimes exclusive presence of fragments of porphyritic, fine-grained, intermediate and acid igneous rocks and by the abundance of idiomorphic quartz and feldspar crystals of tuffaceous origin. Crystal tuffs and tufaceous sandstones are abundant as fragments in the breccias and indicate reworking of pyroclastic deposits. Many of the rocks, especially the coarsest breccias, appear to be the products of subaerial erosion, but some of the finer beds are regarded as ash deposits. The most abundant rock types are volcanic breccias, tuffaceous sandstones and sandy tuffs (PETTIJOHN 1957).

The wide distribution and uniform mixture of fine-grained and porphyritic acid (silicic) and intermediate (moderately silicic) igneous rocks is sufficient evidence to suggest a large nearby volcanic source for the material. The strong resemblance of many of the components of the breccias with the rocks of the sills in the Bifertenfirn metasediments suggests that the sills may have been associated with an early phase of subvolcanic intrusion and possibly volcanic extrusions. Strong erosion attacked these early volcanics and subvolcanics before the onset of deposition of the Carboniferous sediments. The volcanic activity that continued during the Upper Carboniferous was mainly explosive, and direct evidence of eruption within the Biferten inlier is given by exposures of a vent breccia (tuffschlot) on the east side of the Bifertenfirn.

Three basic premises have been established by the present study:

1. The rocks of the Volcanic Member were formed in a terrestrial environment under the influence of volcanic action.
2. All outcrops belong to the same lithostratigraphical unit.
3. The unit lies unconformably above the Bifertenfirn metasediments and is conformably overlain by the dated Upper Carboniferous sediments.

Regional Variation in Lithology of the Volcanic Member

The lithological variations which are observed in the Volcanic Member and its equivalent in the Klein Tödi area are shown in fig. 8. The lack of bedding prevents the correlation and the determination of the relative ages of these rocks, and the only fixed reference is that the type with coarse angular blocks (1) rests below the sandstones in which fossil plants are found.

The list of varieties given below refers to the numbers of fig. 8.

1. Coarse volcanic débris: predominantly one type of igneous rock in angular boulders up to 2 m. These rocks are notably lacking in quartz-bearing types and are mainly altered andesites and andesite tuffs.

2. More varied volcanic breccias in the south of the Biferten inlier. These deposits contain fragments of rhyodacite and dacite, smaller fragments of shales and tuffs and single euhedral quartz grains.

3. Coarse-grained strongly-cemented crystal and lithic tuffs.

4. Conglomerates with rounded boulders of Schiebenruns.

5. Volcanic vent.

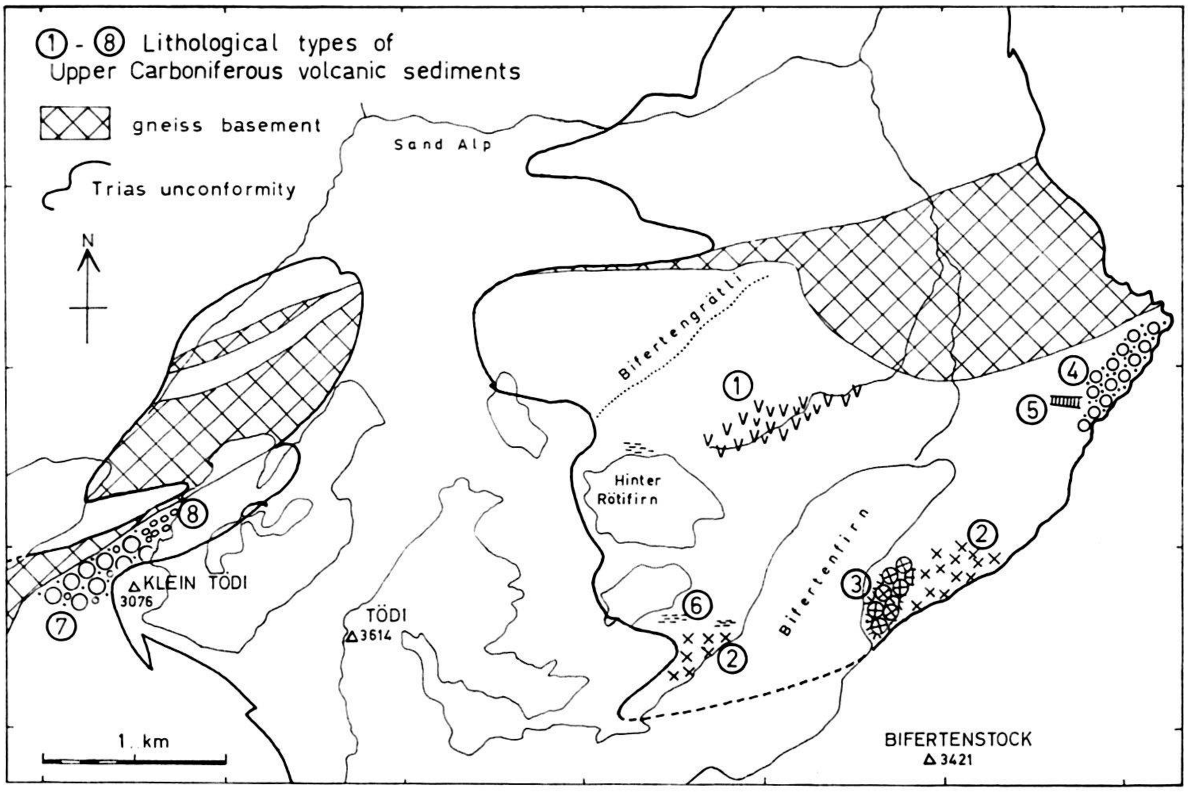


Fig. 8 Regional variations in the lithology of the Upper Carboniferous volcanics of the Biferten inlier and Klein Tödi areas (see text for descriptions of 1–8).

6. Other sedimentary tyes associated with the Volcanic Member.
7. and 8. are the volcanic breccias and lapilli tuffs of the Klein Tödi area respectively, and are discussed later.

Coarse Volcanic Débris (Type 1 of Fig. 8)

The coarse volcanic débris forms a succession of bedded volcanic breccias, agglomerates and tuffs that is seen south of Bifertengrätli as an outcrop 80–100 m wide on the southern inverted or vertical limb of the Bifertengrätli syncline. The measured section (fig. 4) is about 150 m thick, but deformation measurements show that there has been at least 40% shortening at right angles to the cleavage, which is here almost parallel to the bedding or dips 20–30° less steeply to the south. This implies a 30–40% thinning of the beds, and it is estimated that the original thickness was 200–250 m, on the assumption that the volume of the rocks remained roughly constant during the deformation.

Towards the core of the syncline in the north these beds become thinner, and the last northerly exposures of volcanic breccias on the west side of the valley are seen close to the core of the syncline.

The volcanic rocks lie directly above the basal conglomerates, and they are overlain by black shales and feldspathic sandstones of the Estuarine Member. Fine-grained beds with a pronounced green colour are seen in the lower part of the section immediately NE of the Hintere Rötifirn and are regarded as tuffs. The lower part of this section, which shows the greatest lithological variations, is described below.

Lower part of the volcanic succession, NE Hintere Rötifirn (base of section Ref. 714.850/186.640).

Base of section covered by scree

1. 2 m coarse greenish breccia or agglomerate containing angular grey-green crystalline or microcrystalline silicic and subsilicic igneous blocks up to 15 cm, in a predominant matrix of coarse sandy feldspathic material. Occasional black shale fragments up to 2 cm in size.
2. 2 m black and green shales and thin bands of fine to medium grained sand (tuffaceous) with irregular discontinuous bedding. The dark carbonaceous shales contain small fragments of feldspar, shales and larger fragments (up to 6 cm) of a lighter coloured fine-grained feldspathic tuff. Most of the fragments are subrounded, some are angular and all are of a lighter colour than the matrix.
3. 1.6 m light coloured feldspathic sandstone (tuffaceous), with discontinuous bands of dark sediment at the base. Some bomb-like fragments of crystalline rock with a 5 mm dark fine-grained rim are seen near the base. The lower boundary of the sandstone is irregular and shows erosion and load casting of the underlying mudstone. In a section slightly to the east, where large fragments are less abundant, thin (3 cm) graded beds are seen, the coarser lower part of the beds passing upwards into a fine-grained black band.
4. 1.4 m bedded greenish sediments and finer grained lighter coloured beds of 1–5 cm. The coarser material is feldspathic.
5. 4.5 m greenish feldspathic sandstone with occasional crystalline and lithic fragments up to 10 cm and more common smaller fragments of about 2 cm.
6. 10 m rather uniform fine breccias to sandstones with lighter coloured angular fragments up to 10 cm scattered in a greenish matrix. The fragments are of fine-grained porcellanous material or of fine-grained feldspathic rock.
7. + 40 m highly sheared breccias or agglomerates with little trace of bedding. Light-coloured fine-grained fragments, greenish crystalline blocks and some black shale fragments are set in a feldspathic sandstone matrix. The matrix becomes darker and more shaly in the higher parts of the section, and larger fragments (up to 80 cm) are observed.

In hand specimens the rocks are usually strongly cleaved and show irregular slightly sericitic surfaces and slightly elongated crystals of plagioclase and less abundant quartz. The matrix and fragments normally show an equal development of cleavage, but some finer-grained dense fragments are less affected. The fragments are fine-grained, hemicrystalline or holocrystalline; some are made up of smaller components. Their shape is angular to subangular, but they are flattened in the cleavage plane and elongated. The maximum size is about 1 m. Some smaller fragments up to 20 cm have a primary ovoid bomb shape.

In thin section all the rocks show strong alteration. The larger components of the breccias may be subdivided into single fragments of porphyritic andesite and composite andesite fragments with rare dacite components.

The individual fragments of andesite are composed of plagioclase or sericite pseudomorphs after plagioclase, sericite, chlorite, calcite; they contain epidote, apatite and abundant ore grains as subsidiary minerals and may exhibit a fluidal texture marked by the parallel orientation of the plagioclase phenocrysts.

The plagioclase (determined on the universal stage by the zone method of RITTMANN 1929) is albite in composition and occurs as euhedral tabular crystals up to 2 mm. Its degree of alteration is variable, and it may be replaced entirely by calcite, quartz and sericite, or more rarely be only slightly saussuritized and fractured. Chlorite forms irregular areas in the matrix or forms pseudomorphs after ferro-magnesian minerals, part of which, judging by the shape, may have been amphibole. The pseudomorphs often contain a core of calcite and a rim of chlorite and small ore minerals. The matrix, composing 50–70% of the rock, is a uniform mass of sericite and feldspars less than 0.03 mm in size. Quartz is present only in small amounts in the plagioclase pseudomorphs. Small epidote and apatite prisms are often associated with the alteration products.

The origin of the albite of these rocks is most probably secondary, and a more calcic original composition is suggested by the abundant replacement by calcite. The rocks are termed altered andesites; the name spilite is not applicable because of the secondary nature of the albite.

The composite andesite blocks are made up of fragments to about 1 cm of porphyritic andesite similar to that described above and small dark vitreous fragments set in a chlorite- and sericite-rich crystal tuff matrix of andesitic composition (fig. 9a). The plagioclase crystals of the matrix are often fractured and those of the andesite fragments broken at the margins. The matrix of many of the fragments consists of plagioclase microlites of 0.05 mm, or in others it is subvitreous and recrystallized. The shape of the fragments is rounded to subrounded or smaller angular shards, and they were probably derived by the ejection of consolidated or partly consolidated lavas with the crystal tuffs. Rare fragments of dacite and isolated quartz grains are present in bombs in the upper part of the section.

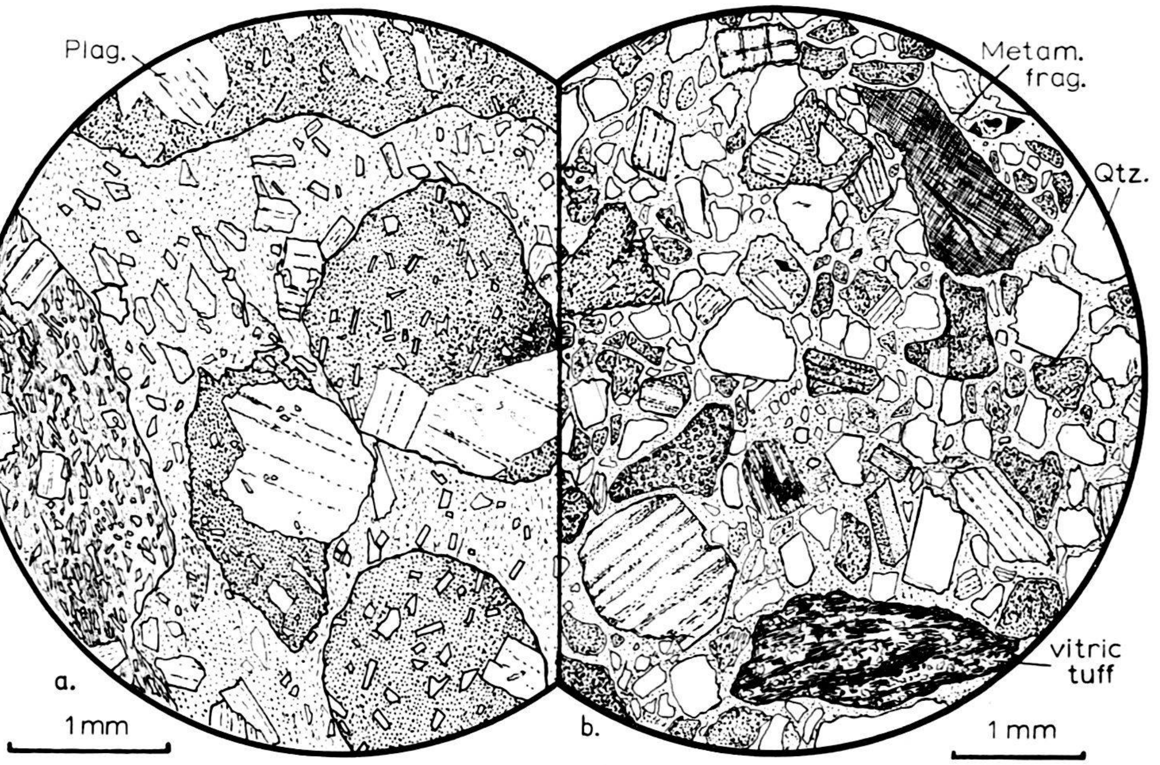


Fig. 9 *a.* Andesite breccia. Fragments of andesite and crystal tuff (left) in a tufaceous matrix. *b.* Tufaceous sandstone-breccia, with varied volcanic components.

Polygenic Breccias (2 of Fig. 8)

These are the most typical volcanic breccias of the area; they build the crag on which the Grünhornhütte stands and which WIDMER (1949) used as the type locality for this unit. This lithology attains its maximum development on the east side of the valley. The most characteristic feature in the field is the abundance of very fine-grained, green and light brown blocks up to about 5 cm in size. Occasional dark shale blocks are present and draw attention to the clastic origin of the deposits. The blocks are without exception angular, and they are embedded in a sandy grey brown matrix. Macroscopically visible feldspars are absent. No stratigraphical succession is determinable as bedding is absent; the rocks, together with type 3, appear to make up a large unstratified deposit of volcanic breccias and tuffs.

The components of these breccias are predominantly fine-grained and glassy igneous rocks; lesser amounts of shales and fine sandstones are present (fig. 9b). The amount and variety of the igneous rocks is great, and they are more varied than the type 1 breccias. They demonstrate a derivation from a number of different extrusive or shallow intrusive igneous bodies. The principal components are described below.

a) Granodiorite

The coarsest-grained igneous rock present is a holocrystalline, fine-grained granodiorite. Such components are not abundant; they are comparable with the coarser-grained sill north of the Bifertenfirn. In thin section (fig. 10b) subhedral plagioclase reaches 0.5 mm in size; quartz forms smaller interlocking anhedral grains. Ferro-magnesian minerals are represented by irregular chlorite areas, sericite and some partially bleached biotite.

b) Dacite-Phyodacite

The most abundant igneous rock fragments are porphyritic quartz-plagioclase bearing rocks of dacitic to rhyodacitic composition, which sometimes make up about 30% of the components. In thin section (fig. 10a) porphyrotic plagioclase (albite) reaches 2 mm in size and generally shows more or less strong alteration. Some potassic feldspars are present, but these are more highly altered. Quartz is present in most larger fragments as euhedral or slightly rounded crystals. As quartz phenocrysts occur only sporadically they are not seen in many of the smaller rock fragments and these are indistinguishable from porphyritic andesites. Ferro-magnesian minerals are completely replaced by sericite or chlorite, but the outlines of euhedral pseudomorphs suggest that amphibole and biotite were present. Flow banding is not seen in any of the fragments, and it is suggested that they were mainly deposited as volcanic ejecta (bombs); if they were derived entirely from shallow intrusions the breccias should contain a larger proportion of holocrystalline fragments and country rock. The rocks can be called sodic dacites and rhyolites, and the origin of their albite is thought to be secondary and metamorphic (autometamorphic ?) because of the large amount of alteration products present.

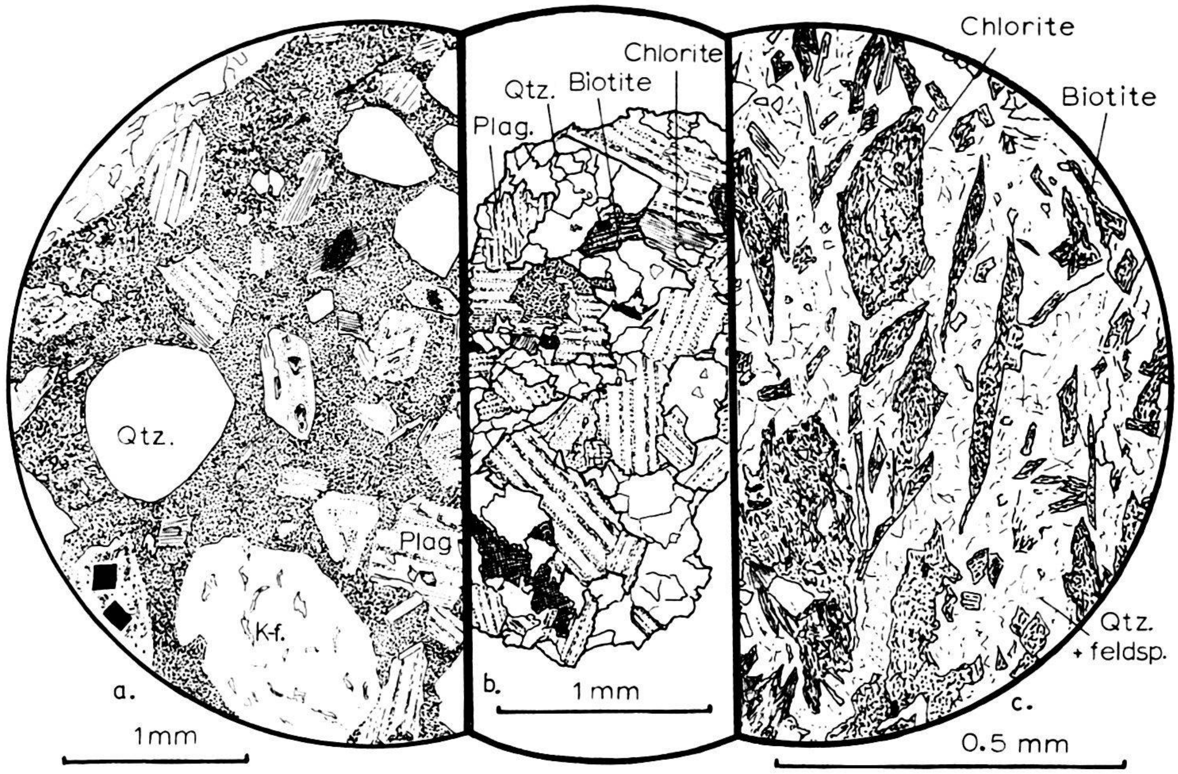


Fig. 10 Fragments in the volcanic breccias. *a.* porphyritic rhyodacite; *b.* granodiorite; *c.* altered amphibole-biotite hornfels of Val Gliems-type (chlorite pseudomorphs after accicular amphibole and biotite).

c) Microdiorite

Occasional fragments of microdiorite are seen; these consist of highly altered areas of equigranular anhedral plagioclase (ca. 0.1 mm) with rare larger euhedral plagioclase phenocrysts.

Porphyritic micrograndodiorites resemble the dacites in composition but contain a microcrystalline matrix of quartz, feldspar and sericite.

Reworked fragments of sandstones contain quartz and plagioclase as single grains, and lack reworked igneous fragments. Their grain size runs generally up to 1 mm, rarely up to 1.5 mm, and the grains are normally angular to subangular, with rare resorbed grains; microcline is also present as isolated grains. Such fragments are important in so far as they demonstrate the existence of older immature quartz sands with some volcanic material.

d) Tuffs

Finer-grained banded grey-greenish coloured fragments up to 4 cm in size, often forming the larger fragments in hand specimens, contain abundant plagioclase and quartz up to 0.05 mm, and much small sericite, chlorite and ores; they are probably fine-grained tuffs. Banding of the coarser-grained parts is sometimes graded; finer-grained parts are mainly sericitic.

e) Metasediments

Occasional hornfelses and knotenschiefer with large muscovite plates and sericitic cleavage surfaces are seen. Fragments with chlorite and sericite pseudomorphs of acicular and platy crystals, probably originally amphibole (temolite?) and biotite, in a recrystallized quartzo-feldspathic fine-grained matrix (fig. 10c) resemble in texture certain of the tremolite-biotite psammites of Val Gliems and were probably derived from similar, older metamorphic sediments.

Crystal and Lithic Tuffs (3 of Fig. 8)

These coarse-grained strongly-cemented rocks, which may appear rather granitoid in the field, are composed of visible quartz and feldspar crystals embedded in a uniform, light-coloured matrix; occasional small dark sedimentary fragments testify to the clastic or pyroclastic origin.

In thin section fragments up to 1 cm are seen, but as these are of the same composition as the matrix they are difficult to distinguish in sheared specimens. Most characteristic are small black fragments (up to 2 mm) composed of an opaque material containing some plagioclase and a little sericite. These are probably altered glass fragments. Coarse-grained granodiorite and porphyritic acid and intermediate igneous rock fragments are present. Many single grains of angular to subangular quartz, some of which are nearly perfectly idiomorphic, are seen in the matrix. Idiomorphic plagioclase crystals reach 0.5 mm in size. The quartz content and the predominantly acid character of this breccia separate it from type 1, and the higher degree of induration and lower content of reworked sandstones separates it from type 2. This very crystalline rock is interpreted as a reworked, well-indurated tuff with a high content of glass fragments. It contains only very little non-volcanic material (small hornfels fragments).

Finer grained rocks which are present in the same area appear to be rhyolites with a strong flow banding. In hand specimens these are dense, dull grey-green, banded, glassy rocks; in thin section the banding is seen to be of fine-grained crystalline quartz separated by darker bands richer in chlorite. Some altered feldspar crystals up to 1 mm are present; they are uniformly clouded and are surrounded by thin quartz rims and the banding flows around them. Small euhedral apatite and well-rounded zircons are present. Ore grains are widely distributed, and are sometimes arranged parallel to the banding. Later zones of alteration are seen in thin section to cut and disturb the banding, and small calcite veinlets occur as alteration products. Rock fragments which may also be rhyolites occur in some of the darker sediments associated with the Volcanic Member (see f below).

Conglomerates (4 of Fig. 8)

Conglomerates with rounded boulders south of Schiebenruns build large cliffs below the Triassic rocks. Unlike the well indurated volcanic breccias, the rounded boulders and pebbles of these conglomerates weather out of the less consolidated matrix. The lithology is contrasted with the other volcanic breccias, and the conglomerates may be somewhat younger, possibly even equivalent in age to the Estuarine

Member. They are tentatively placed in the Volcanic Member on account of their abundant volcanic components.

Large subangular fragments of about 30 cm are common, but the most abundant pebble size is 5–10 cm, and the shapes are frequently rounded, subrounded or subangular; the components are clearly water worn. Matrix material less than 2 cm makes up about one-third of the volume. The size range and the rounding of the fragments vary from place to place, but bedding is absent. The components are: sandstones, fine-grained igneous rocks, dark spotted sediments and slightly metamorphic mudstones.

a) Sandstone Components

The most abundant type of pebbles are light grey-green coloured sandstones of rather uniform composition and with an unstratified appearance. These contain occasional fragments, reaching 1 cm, of black graphitic shales and some lighter coloured greenish glassy material. They are petrographically greywackes (PETTIJOHN 1957), but in view of their high content of locally derived volcanic material it is preferable to calls them volcanic sandstones or sandy tuffs. The percentage composition of two of these rocks and the quantitative basis for their classification are shown in figs 12, 13b and c.

The sandstones contain at least two generations of lithic fragments, which indicate a repeated reworking. Quartz grains, up to 0.4 mm, show angular, broken shapes and only rare resorption or good development of crystal faces. Some of the plagioclase crystals are fresh and also show broken shapes. The larger grains are often interlocking, and interstitial material is at a minimum; this appears to be the result of intergranular crystallization resulting from filling of pore space or replacement of original matrix. Calcite is an abundant secondary replacement mineral and forms both isolated pseudomorphs after plagioclase and small rhombs which are especially common cutting the margins of plagioclase crystals, and which also cut and replace quartz grains. Some reversed pseudomorphs of quartz after calcite are present, the quartz forming small rhombs in larger grains of calcite. Chlorite is common between the grains, and is marginally intergrown with some of the quartz; it also forms aggregates of small radiating spherolitic crystals up to 2 mm in size which have an olive-green anomalous interference colour. Relatively fresh biotite occurs as flakes up to 0.3 mm; zircon, apatite and ores are present as accessories.

The coarse-grained sandstones (up to 0.4 mm in grain size) contain sporadic igneous rock fragments of granodiorite and porphyritic microdiorite, some of which have a matrix of plagioclase microlites up to 0.1 mm. The finer grained sandstones do not contain igneous rock fragments.

These volcanic sandstone pebbles are not of uniform composition, and originated from different sedimentation units. The variations are seen in the amount of matrix and in the difference of interstitial growth. In all of them the volcanic source rock is evident, and they probably represent reworked tuffs (tuffites). The presence of reworked grains and carbonaceous matter suggest water-laid deposits, with only short transport and little exposure to weathering. In most of these sandstones the relatively good sorting within individual fragments and the relatively low matrix content are features which distinguish them from the sandstones of the Estuarine Member. The most probable correlation is with the sandstones of the basal conglomerate and volcanic beds of the succession established on Bifertengrätli. This would imply that the Schiebenruns conglomerates were younger than the basal beds of the Upper Carboniferous succession and that they were formed during or after the deposition of type 1 volcanic breccia or during the deposition of the plant-bearing beds of Bifertengrätli.

b) Igneous Components

Fine-grained igneous rock fragments in the conglomerate include both holocrystalline fine-grained granodiorites and porphyritic hemicrystalline plagioclase bearing types. These are comparable to the rocks described as components of the type 2 breccias and to the sills which intrude the Bifertenfirn metasediments.

c) Metamorphic Components

Dark metamorphic hornfelses are common components; they occur as angular to subrounded slightly deformed fragments attaining 5 cm. Most are comparable with types found nearby in the Biferten inlier; they are characterised by the development of darker pigmented spots, the growth of muscovite plates and the recrystallisation of the grain boundaries. Some appear to be somewhat more metamorphic than local rocks and are more comparable with meta-mudstones found farther south in Val Gliems. These components demonstrate that the foundation of older rocks was exposed at the time of deposition, but the abundance of volcanic material shows that the volcanics were also exposed to denudation and river transport.

d) Matrix

The matrix of the conglomerates is mainly a sand sized aggregate of quartz and plagioclase crystals mixed with smaller volcanic and tuffaceous fragments. It is badly sorted and shows little breakdown of the minerals.

Volcanic Vent (5 of Fig. 8)

The volcanic vent breccia (tuffschlot) seen on the east side of the valley (Ref. 716.710/186.910) is situated within dark banded rocks of the metamorphic group below and to the south of the Schiebenruns conglomerates. The marginal relations, which furnish the evidence of vent character, are shown in fig. 11. About 2 m of the margin of the vent are exposed in the ravine bed 250 m S of Schiebenruns (alt. 2050 m; often covered with avalanche snow). The contact to the dark banded hornfelses in the north is irregular but sharp; the bands of the hornfelses have been fractured at the contact, and smaller zones of faulting and brecciation are abundant in the hornfels near the contact. The outermost margin of the vent filling is composed of medium to coarse-grained crystalline tuffaceous material in which some large hornfels blocks are embedded. This marginal zone is variable in width and is followed in the south by a band of fine-grained to glassy green rock with faint traces of bedding marked by darker layering. This banding is cut off to the south along a rather smooth

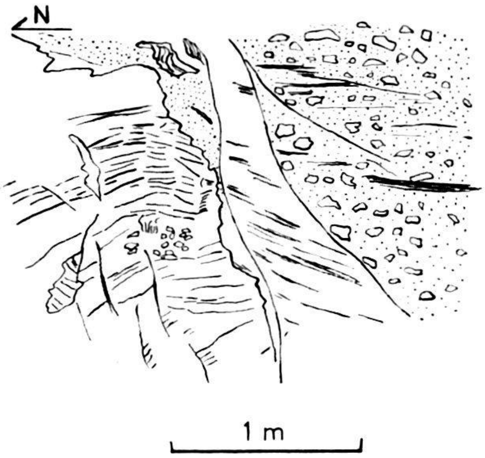


Fig. 11 Margin of vent breccias cutting banded hornfels, E. Bifertenfirn.

contact by the main vent breccia which extends to the south for at least 3 m. The breccia is composed of fragments up to 20 cm, with pronouncedly angular shapes, of green coloured porphyritic granodiorite to dacite. The fragments are of uniform composition; they are embedded in a finer grained tuffaceous matrix with abundant small pyrite cubes. Faint bedding of darker bands within the breccia is roughly perpendicular to the vent margin and demonstrates that the vent was filled by pyroclastic material falling back into the opening through which it had been ejected.

Mixed Sediments (6 of Fig. 8)

Other sediments associated with the Volcanic Member: in the exposures between the Hintere Rötifirn and the Grünhornhütte several small areas of dark coloured shales and sandstones are found amongst greenish fine-grained porphyritic igneous rocks which belong to intrusions of the volcanic episode. No banding can be traced and the connection with other sediments is unknown.

In thin section the rocks prove to be fragmentary tuffaceous rocks made up of angular broken quartz up to 1.5 mm, plagioclase up to 0.6 mm, and fine-grained porphyritic fragments up to 2 mm set in an abundant matrix. They are similar in composition to the sandstones found in the conglomerates, but they are darker in hand specimens and contain more matrix (30–40%).

One such area of sediments is seen in the lower cliffs NE of the Grünhornhütte, and appears to be a xenolith in the fine-grained porphyritic igneous rock. The contacts of the igneous rock at this locality do not suggest that they were flows, and it is unlikely that the uniform igneous rocks with a rather high mafic content were formed as ignimbrites. The most probable explanation is that they are slabs of sediment that were caught up in a near-surface intrusion; if this is correct, it is strong evidence of intrusion after the beginning of the Upper Carboniferous sedimentation.

Similar dark sediments are found locally north of the Hintere Rötifirn; again these consist of tuffaceous fragments set in a very fine-grained matrix, and small rounded fragments of recrystallised banded rhyolite and other porphyritic volcanics are present. Rounded zircon and ore minerals are present as accessories in the matrix.

Discussion of the Biferten Inlier Volcanic Member

Two phases of volcanic or subvolcanic activity are seen in the Biferten inlier. The first was largely subvolcanic, and resulted in the shallow intrusions which form the sills in the Bifertenfirn metasediments. These rocks were rhyodacites, dacites, andesites and coarser grained equivalents where cooling was slower. Erosion removed any surface manifestation of these from the Biferten inlier before the subsidence which initiated the Upper Carboniferous sedimentation. The lowest conglomerates were mainly locally derived from the hornfelses and granite of the area. The second volcanic phase commenced shortly after the onset of subsidence; this gave rise to volcanic explosions which rapidly increased in intensity. Volcanic vents encroached locally into the area of the Biferten inlier. The most abundant material of this activity was made up of rhyodacites and rhyolites together with the related crystal tuffs. Crystal tuffs continued to be ejected from a nearby volcano during the greater part of Upper Carboniferous sedimentation, sometimes burying areas of tropical swampy forests or falling into the shallow lakes which formed during the continued subsidence of the area.

The general character of the volcanics shows strong affinities with typical post-orogenic andesitic volcanism, the "subsequent" volcanic activity, which in this region may be assumed to have followed the "main" Hercynian orogeny.

The Estuarine Member

The conglomerates, sandstones and mudstones of the Estuarine Member form the typical plant-bearing beds of Bifertengrätli. They are well exposed over an area of $1^3/_4$ km^2 and on the southern slopes of Bifertengrätli they form a section of about 200 m of well-bedded sediments which trace out the fold structure very clearly.

The boundary with the underlying volcanic breccias is seen in the section NE of the Hintere Rötifirn as a gradual passage from the coarse breccias. The onset of new conditions is marked by the increase in the amount of dark mudstones and feldspathic sandstones and the gradual disappearance of the coarser volcanic components. The upper 25 m of the breccias contain black shale fragments, some areas of dark matrix and isolated silicified wood fragments. The lowest dark coloured mudstones contain isolated blocks of light coloured volcanic material up to 20 cm and many feldspar grains, and they thus indicate a continuity of the volcanic source area between the deposition of the coarse volcanic breccias and the deposition of the finer grained beds.

The lowest 15 m of the Estuarine Member are thinly bedded black mudstones with occasional sandstone and siltstone beds. Small-scale synsedimentary faults are seen, with both normal displacements lowering the eastern side and reverse displacements lifting the western side. Coarser feldspathic sandstones form at first isolated beds up to 1 m thick and then higher in the section form the bulk of the rock, normally in beds of 1–4 m in thickness. Cross-bedding is common but irregular in direction. Irregular channel fillings and cutouts are frequent.

Alternating plant-bearing mudstones and coarser sandstones are typical of the upper part of the Estuarine Member, and often form rhythmic units of coarse feldspathic sandstone (50–100 cm), siltstone (10–30 cm) and mudstones with isolated plant fragments (1–5 cm) or thin fractured anthracite beds 0.5–5 cm thick. On the upper part of Bifertengrätli, on the inverted limb of the fold, the rhythmic units are thickest and contain the coarsest material, whereas further north, in the core of the syncline, the units are thinner and the material finer grained.

Most of the fossil plants have been found in the exposures of upper Bifertengrätli. Small plant fragments are often aligned on bedding surfaces of the mudstones, and on weathered cross sections these are seen as small white layers. Mudstone bands rich in small plant fragments are much more common than accumulations of plant material into thin anthracite layers, which reach a maximum thickness of only 10–20 cm on the upper part of N Bifertengrätli, NW of point 2520.

Large *Calamites* (*C. suckowi* and *C. gigas*) are often found in the sandstone beds in an upright position. The largest stem seen reaches 3.2 m in length (upper Bifertengrätli, 100 m SSW of the summit), and two adjacent stems of 60 and 80 cm are preserved in growth position at 70° to the bedding (Franks 1966). The filling of these stems is of coarse sandstone, and is normally much coarser than the host rock. This is ascribed to burial of the plants by finer grained material and a later filling of the stems with coarse sand when the organism had decomposed. The stems are thus probably preserved in their original site of growth (Schrock 1948), although no seat earths are to be found.

Conditions of Deposition

The evidence points to a fluviatile or estuarine site of deposition of these beds, in an area undergoing rapid subsidence, with occasional overflooding by deeper water to give the interbedded mudstones rich in plant material. The lack of thick accumulations of plant material to give thicker anthracite beds suggests that sedimentation was rapid and continuous. The plant stems preserved in growth position indicate very shallow water, and possibly partially terrestrial conditions.

Granulometry and Classification

A wide range of petrographic types is present in the rocks of the Estuarine Member, and their main common feature is rather their mode of deposition, as indicated by the bedding and sedimentation features. A number of field types have been distinguished and their components studied in thin section. Several thin sections were counted quantitatively using the method of chord intercepts (Muenzner & Schneiderhöhn 1953); these data were plotted on QFR and MLQ diagrams together with data from sandstones of similar grain size from other stratigraphical units (fig. 12). The QFR and MLQ diagrams allow a comparison of the rock types and permit a more precise naming of the rocks. Nomenclature of impure sandstones is, however, rather confused, and four different classifications proposed by various authors are indicated on the two diagrams (Pettijohn 1957; Folk 1954; Packham 1954; Crook 1960). The nomenclature based on the QFR diagram uses the composition of the sand-sized fraction only, and does not take the amount of matrix into consideration. The classifications of Packham and Crook employ genetic features of the rocks, if observed, to separate an arkose-quartzose sandstone suite from a greywacke suite.

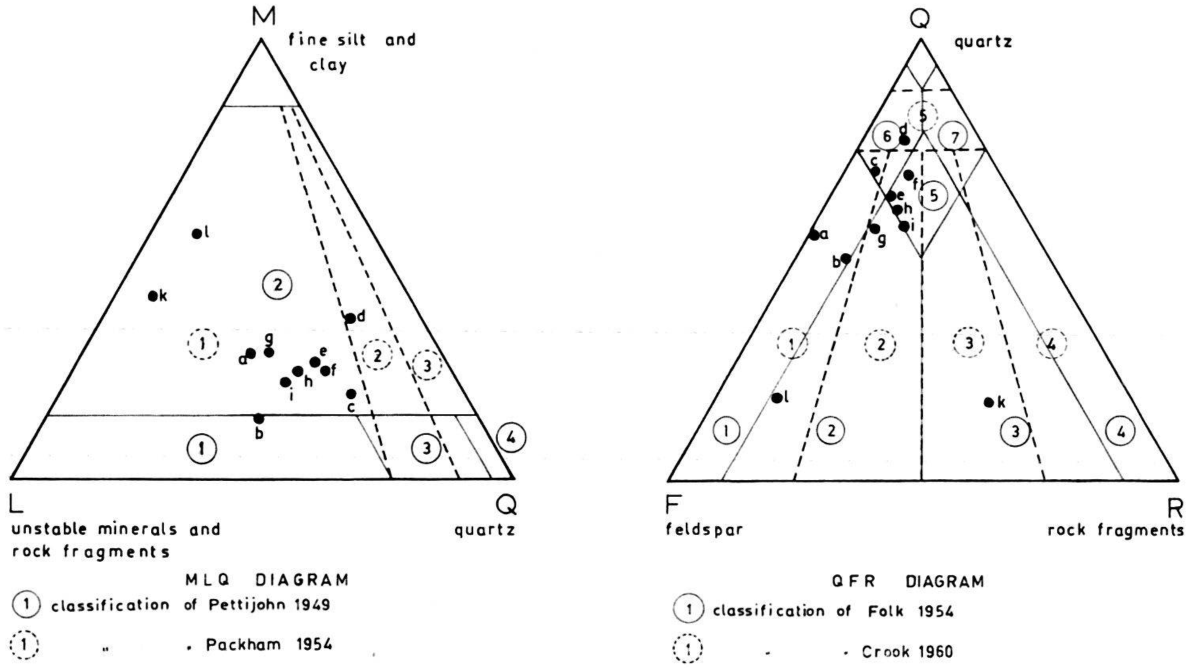


Fig. 12 Composition of the sandstones of the Bifertengrätli Formation: MLQ and QFR diagrams and a comparison of various proposed classifications.

Legend:

MLQ Diagram

PETTIJOHN (1949)

1 arkose and subgreywacke
2 greywacke
3 protoquartzite and subarkose
4 orthoquartzite

PACKHAM (1954)
Arkose-Quartzose sandstone suite
1 arkose and labile sandstone
2 feldspathic sandstone and sublabile sandstone
3 quartzose sandstone

QFR Diagram

FOLK (1954)
1 arkose
2 impure arkose
3 feldspathic greywacke
4 greywacke
5 feldspathic subgreywacke
6 subarkose
7 subgreywacke

CROOK (1960) generalized arenite diagram
1 feldspathic arenite
2 litho-feldspathic arenite
3 feldspatho-lithic arenite
4 lithic arenite
5 sublabile arenite (feldspathic and lithic)

a. Sandstone in the basal conglomerates; *b–g.* Sandstones of the Estuarine Member; *h., i.* Sandstone components in the Schiebenruns conglomerates; *k., l.* Sandstones in the Lacustrine Member.

The rocks of the Estuarine Member fall into an arkose-quartzose sandstone association, and from the generalized arenite QFR diagram of CROOK (1960) they fall into a broad compositional group of feldspathic arenites. This is synonymous with the group of arkoses, labile sandstones, feldspathic sandstones and sublabile sandstones of the MLQ diagram of PACKHAM (1954).

The alteration of these rocks does not permit an exact reconstruction of the grain size distribution, as many of the feldspars have been altered and approach the groundmass in appearance, and the groundmass grains smaller than 0.05 mm have been

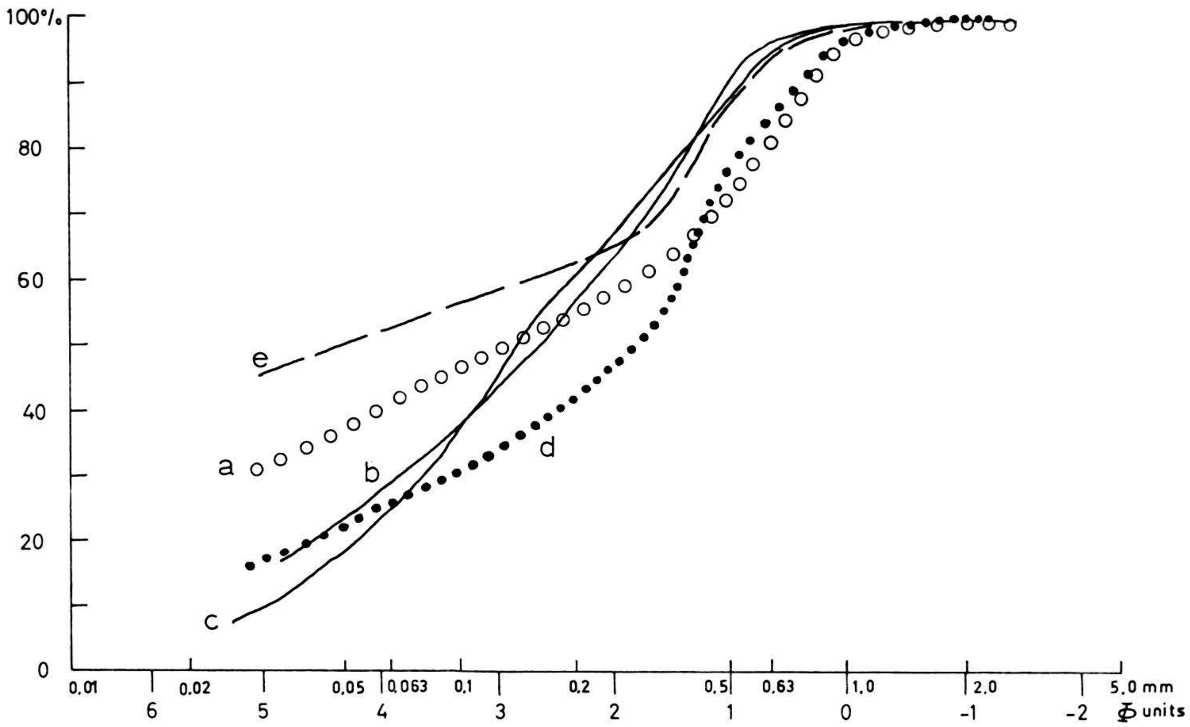


Fig. 13 Grain size distributions of sandstones of the Bifertengrätli Formation from thin section measurements. *a.* Sandstone in basal conglomerates: *b.* sandstone fragment in Schiebenruns conglomerates; *c.* sandstone fragment in Schiebenruns conglomerates; *d.* sandstone of Estuarine Member; *e.* feldspathic sandstone in Lacustrine Member.

recrystallised. The grain size distribution of one typical arkose of the Estuarine Member was constructed by measuring 250 long axes of grains on an integration stage using the technique and correction factor of Friedmann (1958) (fig. 13). The same microscope data were also corrected to give a granulometric analysis using the statistical calculations of Greenman (1951), which are less satisfactory and more time consuming. Considering the errors inherent in this technique, resulting from the lack of sorting of the rocks, the subangular to subrounded grain shapes and the amount of alteration, the given grain size distribution curve is not comparable with normal granulometric analyses from unconsolidated rocks. It is most useful to compare with other curves derived from similar material by the same techniques, provided that the differences lie outside the limits of error.

Lithological Types

Conglomerates

Conglomerates and pebbly sandstones are seen throughout the succession as isolated beds and as lenses within coarse sandstones. The pebbles are generally of less than 2 cm in size, but isolated blocks of granite up to 25 cm are found. With decreasing grain size these beds pass into arkoses, but differ from these in composition by their higher content of lithic fragments. Conglomerates are most frequent in the lower part of the succession and are well seen on the southern slopes of Bifertengrätli. The components are usually rounded to subrounded, but angular fragments of hornfels are sometimes present. The components consist of acid igneous rocks, tourmaline aplite, intermediate to acid fine-grained porphyritic igneous rocks, metamorphic sediments and fine-grained sediments.

Fragments of *acid igneous rocks* that resemble the Tödi granite are common amongst the larger pebbles. These contain subhedral plagioclase, strongly altered anhedral potash feldspar and abundant fractured quartz together with much sericitic alteration products. Some fragments, richer in plagioclase, are leucocratic coarse-grained granodiorites.

In the *tourmaline aplites* the tourmaline (up to 1 mm) is set in a granular mosaic of microcline and fractured quartz.

Volcanic Fragments; The intermediate to acid fine-grained porphyritic rock fragments are types that are abundant in the underlying volcanic breccias of the Volcanic Member. (1) Fragments of porphyritic dacite are relatively common; they contain euhedral plagioclase crystals set in a quartz-rich recrystallised matrix. (2) Rhyodacites with resorbed quartz grains and strongly altered potash feldspar are occasionally found. (3) Small rare fragments of a microcrystalline to devitrified matrix rich in ores, chlorite and sericite contain small grains of pigeonite (up to 0.1 mm). This is unusual, as normally the pyroxenes are strongly altered to chlorite.

The metasediment fragments are noteworthy for their freshness. Psammitic types resemble the fine-grained micaceous sandstones of the Bifertenfirn area, and some types rich in biotite resemble the sandstones of Val Gliems. Pelitic types include fine-grained andalusite hornfels with obvious pseudomorphs of fine-grained sericite after twinned andalusite reaching 2.5 mm in size.

Some fine-grained *sedimentary fragments* resemble the lower grade equivalents of the Bifertenfirn metasediments.

The matrix of the conglomerates consists of angular quartz grains mixed with recrystallised mud and silt fraction of sericite and chlorite.

Muddy conglomerates and pebbly mudstones with a black carbonaceous mud matrix are found mainly in the middle and upper part of the Estuarine Member and form many of the beds between the thin anthracite layers. Large boulders (max. 25 cm) of granite correspond to the Tödi granite, and are believed to be water-carried boulders left stranded in the mud as a result of changes in current velocity.

Arkoses

Arkoses make up much of the lower part of the Estuarine Member. They occur as uniform beds of 1 to 4 m, which sometimes show weak bedding and cross-bedding of finer grained layers, separated by thinner mudstone beds. They are very light-coloured rocks in hand specimen, with prominent and abundant feldspars reaching 6 mm in size. In thin section the quartz and feldspar occur as subangular gravel- and sand-sized grains surrounded by a sericitic matrix. Quartz varies in shape from subrounded to angular; some is strained and fractured, and some occurs as composite grains with sericite inclusions. The feldspars are all strongly altered. Many of the larger grains appear to have been orthoclase and are now largely sericitised. Many are large chessboard albites (up to 6 mm) which contain smaller inclusions of well twinned albite and quartz. Some indicate a zonal structure in the alteration products. Staining of these specimens for potassium gave no positive result, and the potassic feldspar seems to have been completely altered or replaced by albite. Composite grains of coarse-grained quartz and plagioclase illustrate the granodioritic origin of much of the material. Other lithic components, up to about 10% of the rock, are of finer grained banded quartz sandstone. The muddy matrix, which varies in amount from 10 to 20%, consists of sericite and chlorite, and contains occasional heavy minerals such as zircon, tourmaline and ores.

The muddy arkoses are darker coloured rocks, similar in composition to the arkoses, but with up to 35% matrix, and normally with a less prominent content of large feldspars. They are found mainly in the upper part of the member.

Calcareous Sandstones

In some sandstones calcite forms an important part of the goundmass. It has been checked by staining, and may constitute 15% of some of the rocks. It is present mainly in finer grained beds which contain small angular plagioclase and quartz grains, and which are probably reworked volcanic rocks. The calcite is developed as individual areas up to 0.2 mm or os scattered throughout pseudomorphs after plagioclase. It is especially concentrated around plagioclase grains, and is seen to replace both plagioclase and quartz. Larger calcareous concretions to 20 cm in diameter are found locally and are seen in thin section to contain small relics of quartz and plagioclase set in a fine-grained matrix, and to be associated with fragments of volcanic rocks. The association of calcite with volcanic components is thought to be a result of diagenetic alteration of a calcic plagioclase, and transport and enrichment of the calcite by ground waters, possibly assisted by fumarole activity near the site of an extinct or waning volcano.

Alteration of the Sandstones

The post-depositional alteration which the sandstones have undergone is a recrystallisation of the groundmass and feldspars and a tectonic deformation. In all the specimens studied a weak cleavage cuts the rocks, and in thin section is seen as discrete lines of clay minerals and aligned sericite at intervals of 0.5–1 mm. These surfaces are irregular and follow the matric around larger grains. Small displacements are seen locally on the cleavage surfaces; they are generally about half the distance between two adjacent surfaces. The recrystallisation has affected the matrix of all the sandstones and resulted in a fine-grained aggregate of irregularly oriented quartz and sericite, with some chlorite, epidote and clinozoisite. It is very low grade metamorphism indicating no great rise of temperature, and probably took place during the folding of pre-Triassic age and was accentuated during the Alpine movements.

The Lacustrine Member

The Lacustrine Member is a complex of mudstones, siltstones and sandstones of at least 150 m (probably 200 m) thickness which is exposed on the NE part of Bifertengrätli. The type locality is found near the footpath leading down from the Ochsenstock towards the Fridolinshütten, about 250 m from the highest point of the path (Ref. 715.030/183.300; 2220 m). The lower boundary of the Member is not clearly exposed, but on the overturned limb of the fold the sandstones of the Estuarine Member lie above a sheared zone of these fine-grained rocks in an inverted position.

The mudstones of the Member are all dark in colour, and they are banded in layers of mm–cm thickness with silt and sand layers of lighter colour. Black coaly bands to a maximum thickness of 1 cm are occasionally interbedded with dark mudstones in the upper part of the section. Numerous small-scale sedimentary structures are present, and are shown very clearly by the favourable contrasts of lithology. Various types of slump structures and an explanation of their origin in the limnic environment which must be assumed for these beds, is given in FRANKS (1966).

Many of the sandstones show a strong proportion of volcanic fragments and crystal tuff, much of which was probably laid down directly in the water. The volcanic explosions to which these sandstones testify is the last volcanic activity recorded in the Biferten inlier.

Lithology and Classification

Mudstones

Mudstones and siltstones give little problem of nomenclature. They are generally thinly banded by alternating layers associated with less abundant sandstone beds. In thin section the grading of the some siltstone beds is seen. The base of the thinly laminated graded beds is usually a fine sandstone and may show micro-channelling into the underlying mudstone; these may be cross sections of grooves or drag marks. Matrix usually makes up about 50%, fine-grained quartz 15% and small feldspars up to 35%. Brown pleochroic detrital biotite is relatively common, but other heavy minerals are rare. Alteration products seen in thin section are sericite and chlorite; a thinly spaced cleavage ((0.1–0.05 mm intervals) cuts the rocks.

Sandstones

The sandstones offer more difficulties in petrography and genetic interpretation. They often show graded units of 5 cm or more and are variable in composition. Petrographically they are felspathic or lithic labile arenites of a greywacke suite (CROOK 1960) or labile greywackes (PACKHAM 1954). The plots of the composition of two measured specimens (Sp. k, l) on the MLQ and QFR diagrams (fig. 12) fall significantly outside the compositional group of the Estuarine Member, and are marked by their high content of matrix and labile components.

Most of these sandstones show a direct admixture of tuffaceous material into a muddy matrix, and should be classified as muddy volcanic crystal- and lithic-tuffs. Reworking and mixing with other arenite material resulted in tuffites. The admixture of tuffaceous material is seen in the cumulative curve (fig. 13e) as a sharp break in the graph at 0.3 mm; the finer fraction is the normal detrital sediment and the coarse fraction is interpreted as rather well-sorted tuffaceous ejecta. The coarser material is composed of 70% angular plagioclase, 20% of smaller angular quartz grains, and 10% of lithic material – mainly volcanic glass. One specimen (Sp. Bg 35) showed porphyritic fragments with abundant glass shards in the matrix and indicates the reworking of ignimbrite deposits. The euhedral plagioclase, determined on a universal stage, is albite (An_{0-10}), and reaches 2 mm in length; it is normally rather fresh, but contains as alteration products sericite and clinozoisite. Some contain myrmekitic intergrowths of quartz. Much of the larger albite shows chessboard twinning.

Conglomerates

The coarsest beds are the conglomerates at the base of the 10 m sandstone unit of NE Bifertengrätli. These contain subrounded to angular pebbles of fine-grained porphyritic volcanic rocks measuring up to 4 cm; some glass fragments without porphyritic crystals; coarse granodiorite; some metamorphic mudstones and occasional hornfels fragments. Single grains are rather fresh albite, quartz with frequent idiomorphic outlines or as angular grains, and biotite as somewhat pleochroic grains up to 1.5 mm. Calcite, sericite, chlorite and some epidote and clinozoisite form alteration products of the darkish coloured mud matrix. These components indicate a derivation from a nearby volcanic area of acid to intermediate lavas, tuffs and some coarser grained igneous rocks and metamorphic country rocks. They were probably laid down originally in a shallow-water or deltaic environment by rivers flowing from a varied hinterland, and reached their present position in the mudstones by mass slumping.

Discussion of the Detrital Rocks of the Bifertengrätli Formation

The detrital rocks, the Estuarine and Lacustrine Members of the Bifertengrätli Formation, were laid down after a period of violent volcanic activity, and were repeatedly influenced by the waning activity. This lends the sediments several peculiarities, of which the following are mentioned:

- Abundance of idiomorphic plagioclase, largely derived from the erosion of the volcanics. Some were deposited directly as tuffs.
- Calcareous concretions and calcareous cement; warm circulating groundwaters, expected under the warm, humid climate which must be assumed for the area, removed the carbonate from the volcanic rocks and concentrated it in favourable positions.
- Pyritic nodules in the uppermost Volcanic Member and lowest Estuarine Member are possibly a result of fumarole activity.

The climate of the area must have been warm and very humid to support the rich vegetation and cause the heavy rainfalls responsible for the rapid erosion. Coal beds were formed very locally during the period of estuarine conditions. During the lacustrine conditions plant material was continuously carried into the lake and sank to give uniformly distributed small fragments throughout the muds, and became somewhat enriched in layers formed during slower sedimentation.

A very significant feature of the sediments is that they contain very few fragments that may have been derived from the basement gneisses. The bulk of the material can be traced to volcanic rocks, which must have formed an extensive blanket in the source area of the sediments. The foundations of this volcanic blanket, based on components of the conglomerates, were hornfelses of the Bifertenfirn metasediment type, metasediments of the Val Gliems type, and granite or granodiorites of the Tödi granite type. The older sediments are presumably Paleozoic, and their intrusives very probably of "main Hercynian" age. The area seems to represent a "main Hercynian" (Sudetic?) synclinorium with a superposed Upper Carboniferous (Saalic?) synclinorium. This is quite different from the situation in the west of Switzerland, where the Carboniferous of Salvan and its extension further south in the Aiguilles Rouges Massif contain conglomerates compoased mainly of protogene components (the Vallorcine conglomerates) (OULIANOFF 1924).

The lithology and petrography of these beds may be matched rather closely with geologically younger, and therefore more clearly understood, formations produced by the erosion of andesitic volcanic rocks under tropical conditions. A good example of comparable volcanic and tufaceous sediments is given by EDWARDS (1950) in formations of Miocene age in Papua.

STRUCTURES AND DEFORMATION

The Mesozoic rocks of the area overlie stratigraphically a variety of rock types; this classic unconformity between basement and cover demonstrates the existence of pre-Triassic structures. The folding of the Carboniferous rocks and the bringing of the Carboniferous sediments and the quartz porphyry against the hornblende gneisses are thus pre-Triassic structures, the folds in the Carboniferous have been tightened by the later Alpine movements but cannot have been formed entirely by disharmonic movements of Alpine age below the Triassic unconformity.

The presence of at least two pre-Triassic deformations, fully confirmed by the present study, was implied by both ESCHER (1911) and HÜGI (1941), but received little attention. A similar situation has been extensively described in the Aiguilles Rouges Massif (LUGEON 1911, 1930; OULIANOFF 1924), where LUGEON named the pre-Stephanian movements "segalunian" and the post-Stephanian/pre-Triassic movements "allobrogian".

Deformation of the Unconformity

The folding of an unconformity between younger sedimentary rocks and their basement of older crystalline rocks is a complex process which may take place in a number of ways, commonly with a zone of strong shearing near the contact (HUDSON 1955; BRACE 1958). HEIM (1921, p. 157–60) noted many features of the contact region between the Aar Massif and its cover, especially the varieties of cleavage phenomena.

The folds traced out by the basement-cover contact in the NE Tödi area are broad monoclines with some minor overthrusting in various positions around the folds (fig. 14). The folds change in intensity and character along the strike, and over a distance of $2^1/_2$ km between the sides of the valley the minor overthrusts change their position slightly in relation to the folds. South of the studied area two important wedges of Mesozoic rocks (with a maximum depth of about 400 m) sink into the basement; these are seen on S Tödi and the Punteglias Pass, the latter forming an

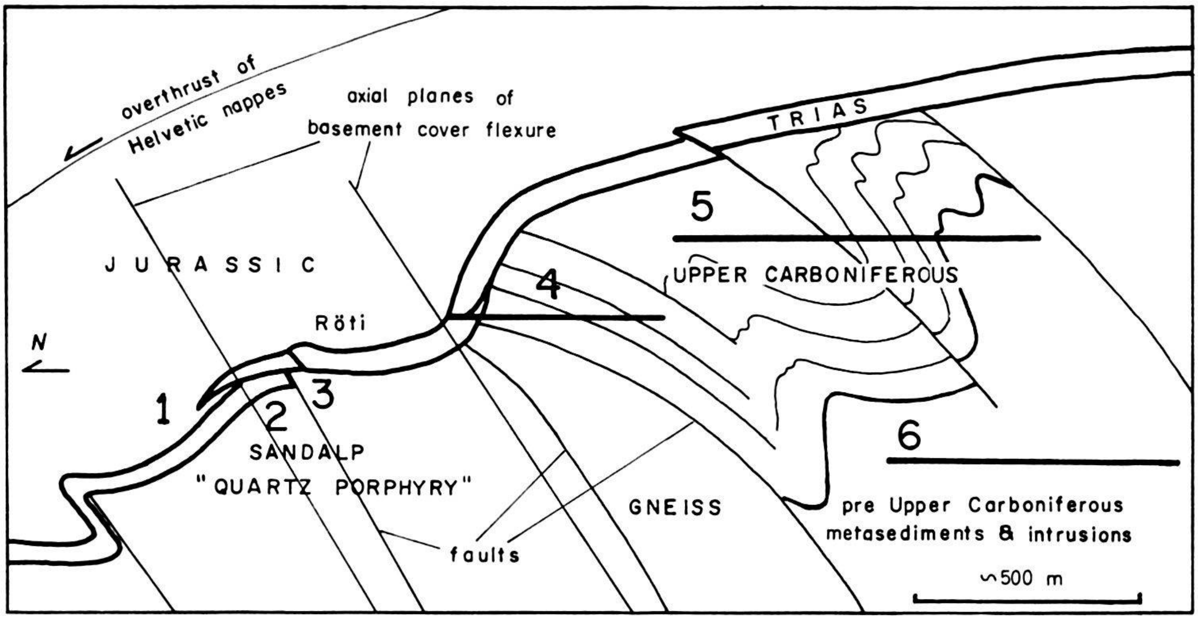


Fig. 14 Sketch section of the types of geological structures of the NE Tödi area. The numbers 1–6 refer to sections described in the text.

important line of separation in the Aar Massif and extending into the area of the Brigelser Hörner, where KAECH (in preparation) describes its effect on the Mesozoic rocks and the overlying nappes.

During the Alpine deformation the basement rocks split into a number of ENE–WSW blocks separated by strong zones of deformation in a style comparable to that described by BAER (1959, p. 78) at the western end of the Aar Massif. The differential uplift of the individual blocks was largely responsible for the monoclines of the NE Tödi area. The separation of the basement into blocks resulted in a superposed anisotropy of the rocks, which as pointed out by WEGMANN (1947, p. 231), does not always follow the lines of pre-existing weakness.

The overthrusts which are seen in the Triassic are thought to have developed in two stages. The first preceded the main vertical displacements of the basement and was largely disharmonic with respect to the basement – the amount of displacement increases away from the basement. The basement was mainly passive, but did develop a flat lying cleavage near the unconformity. The second stage in the growth of the overthrusts took place during the uplift of the blocks; i.e. the basement was now actively participating in the deformation. These movements locally caused the cleavage of the basement to bend over to the north and come closer to the dip of the unconformity.

The very strong inhomogeneity of the Alpine deformation of the basement is typical of the whole Aar Massif, and accounts for many of the structures in the Mesozoic rocks, especially the detachment of slabs of Triassic dolomites (well illustrated by ROHR 1926) and the local zones of interaction between basement and cover. The style of deformation seen here may possibly be regarded as illustrating an embryonal stage in the development of larger overthrust masses such as the East Alpine or Penine nappes.

Structures of the Mesozoic Rocks

The deformation of the Mesozoic rocks is not handled in detail here, but the following points are important and are mentioned in passing.

(a) A disharmonic set of structures with respect to the basement top surface is present from the Röti dolomite upwards. It is marked as a cleavage within the Mesozoic rocks, often almost parallel to the bedding, which is frequently the most prominent structure, especially in the shaly beds. It forms the axial surfaces of some minor recumbent folds in the banded shaly limestones of the Lower Malm (ca. Oxfordian), and frequently contains a strong N–S lineation.

(b) No equivalent structures to those of the Mesozoic rocks have been observed in the basement rocks. This may be explained in two ways: (1) movements were restricted to the Mesozoic rocks, either (gravity sliding of the sedimentary cover off the basement or the result of the drag of overriding nappes, or (2) movements compressed cover and basement equally, but because of differences in lithology left the marks of different structures on each.

(c) The Triassic dolomites formed competent slabs which broke loose from their basement and became involved in the deformation of the less competent Jurassic rocks.

(d) The near-bedding schistocity in the Mesozoic rocks is locally deformed by a steeper cleavage.

(e) The deformation style of the Mesozoic rocks depends strongly on the lithology. In the Middle Jurassic, quartzite beds show concentric folding and associated shales show cleavage folding.

(f) The oolitic bed at the top of the Middle Jurassic sequence could be used to estimate deformation quantitatively. The ooids do not appear to have been perfectly spherical originally, and their deformation varies rapidly in the field from a negligibly small to an unmeasurably large amount. This presents a problem outside the sope of the present study.

Basement Structures

The discussion of the basement structures is divided into descriptions of subareas 2 to 6 in Fig. 14.

Subareas 2 and 3

In the Sandalp quartz porphyries below the steeply dipping Triassic unconformity south of Obersand (section 2) two sets of cleavage may be seen. These probably correspond to the two sets observed in the Jurassic rocks, but they cannot be traced into the massive Röti dolomites, and are less strongly seen in the basal Triassic sandstones which are much poorer in mica than the basement rocks. The coarsely spaced, steeply dipping cleavage of the strain-slip type is developed only locally within the quartz porphyry outcrops and is concentrated below the steeply dipping parts of the unconformity.

The small reverse fault below the roots of the overthrust of the dolomites on N Röti (section 3) cuts the Triassic dolomites at a rather steep angle (60–75°). The plane of detachment of the overlying slab lies in less competent shaly beds at the base of the dolomites. In the basement the small reverse fault that forms the root of the overthrust continues as a steeply dipping zone of quartz segregation 3–5 m wide. This zone can be traced onto the east side of the valley and probably marks a belt of strong plastic deformation of the basement. Some of the compression attested by the displacement of the dolomite may have been dissipated in the basement by the development of the older near-bedding schistocity which is locally strong in the basement rocks near the unconformity.

Subarea 4

The basement rocks lying south of the Mesozoic outcrops of Röti illustrate the late-Hercynian structures and demonstrate also how these, along localised zones, become obliterated by Alpine structures. The rocks immediately south of the vertical Triassic rocks lie in such a zone and show a high degree of deformation; strong cleavage is shared by crystalline gneisses, granitic rocks, "quartz porphyry", intermediate igneous rocks of the volcanic association, and Carboniferous sediments. Few undisturbed contacts are recognisable, and the repetition of thin dark slatey bands between strips of crystalline rock suggest a dislocation movement along fault zones. This zone is described by WIDMER (1949, p. 13–14), who favoured the explanation of a normal stratigraphical succession, and by HÜGI (1941) as an area of quartz porphyry tuffs comparable with those farther east on Tscharren.

This is the only area of the Aar Massif that exposes massive microquartzdiorites in direct contact with the dated Carboniferous sediments, but deformation of the contacts make it impossible to say whether they are intrusive, extruxive or thrust contacts. A disturbed intrusive contact seems most probable, and would support the intrusive stock character of the diabase described by HÜGI (1941) from the western end of the zone. Contact metamorphism has not been observed, but shallow intrusions comparable to those of the Briançonnais (FEYS 1963) seem most probable, for although the associated sandstones are tuffaceous, no evidence of lavas has been seen. Many of the outcrops in the western area of this zone were covered by large rock falls in August 1964 and January 1965.

The relatively flat cleavage is the most prominent displacement surface, and cuts foliation in the gneisses and bedding in the sandstones. In the frequently intervening shaly layers of the thrust zone, strain slip cleavage and some minor folds are developed. Rotation indicated by the strain slip cleavage depends on the orientation of the earlier structures, and the fact that this may show rotation opposite to the general rotation of the area indicates inhomogeneous simple shear as a result of compression, whilst the larger belts below the upturned Triassic dolomites was, as a whole, one of homogeneous simple shear.

In most of the lithological types found in this zone of deformation the Alpine movements have employed the pre-existing cleavage and brought this to a shallower dip near the contact of the upturned unconformity. This is a requirement of the deformation, because unrestricted slip on the unconformity, which would be necessary if the older cleavage were to keep its original dip, is not possible. An earlier cleavage, cut by the strain slip cleavage is seen only in thin slatey beds. Farther away from the unconformity the steeper pre-Triassic cleavage retains its orientation, and the Alpine deformation was mainly accommodated by movements on the same planes.

The small-scale deformation structures in this area cannot be separated into Alpine and Hercynian by measuring a difference in strike direction between them, as OULIANOFF (1937, 1944) suggests is possible for the more western external massifs. In the Tödi area the two directions are more nearly parallel, and later movements used the older planes when the lithology was suitable. The only structure which shows a certain obliquity in a style similar to those in the Aiguilles Rouges-Mont Blanc Massifs (CORBIN & OULIANOFF 1925; OULIANOFF 1937, 1944) is the fault contact and mylonite zone that separates the Carboniferous from the older gneisses (fig. 2). Over a distance of about 3½ km this shows a divergence of 18° with the Alpine direction, although the folds in the Upper Carboniferous trend more closely to the latter.

Subarea 5

On Bifertengrätli the pre-Alpine structures are less disturbed by Alpine movements. The northern contact of the Carboniferous sediments with the gneisses coincides here with the zone of strong Alpine deformation (section 4), but an undisturbed contact is seen farther east in the stream bed north of the Bifertenfirn and on the east valley side. This is a major zone of displacement with a strongly developed, compact mylonite 1 m wide with crystalline lenses. It separates the hornfelses, granite and Upper Carboniferous sediments from the older gneisses in the north. No sense of movement can be determined, and the maximum elongation of the crystalline lenses in a roughly horizontal direction is suggestive, but not conclusive evidence of major horizontal displacements. A large downthrow of the south side is certain, and took place after the folding of the Stephanian rocks, for the major structures of these are seen to run slightly oblique, more nearly parallel to the ENE–WSW Alpine direction. The presence of a major post-Stephanian fault in an E–W direction is not easily compatible with the NE–SW graben of the Permian Verrucano postulated by STAUB (1954). Two further fault zones parallel to the first have been mapped

Fig. 15 Measurements of bedding, cleavage and lineations in the pre-Triassic sediments of the Biferten inlier.

a) Combined π-diagram of Bifertenfirn metasediments and Bifertengrätli Formation, 320 poles, contoured at 5, 2, 1, ½%.

b) π-diagram of Bifertenfirn metasediments, 108 poles, 5, 3, 1%. Constructed axial plane (great circle) and constructed fold axis (FM).

c) π-diagram of non-inverted beds of Bifertengrätli Formation, 166 poles, 8, 4, 2, 1%.

d) π-diagram of inverted beds of Bg Formtn, 46 poles, 15, 10, 5, 2%. Constructed fold axis (Fč).

e) Poles to cleavage in the pre-Triassic sediments, 157 poles, 20, 10, 4, 2%. Cleavage plane great circle; fold axis of Bg Formtn (Fc).

f) Lineations; o = cleavage/bedding intersection in Bg Formtn, • = cleavage/bedding intersection in Bifertenfirn metaseds., + = elongation direction of fragments in volcanic breccia, C = principal cleavage pole, and its great circle.

800 m and 1200 m to the south. The northerly one brought the granites of the Hintere Rötifirn to a higher level, lifting the southern side (accentuated by Alpine movements), and the southerly one probably lowered the southern side, bringing the volcanic rocks of the Grünhorn hut area to a lower level.

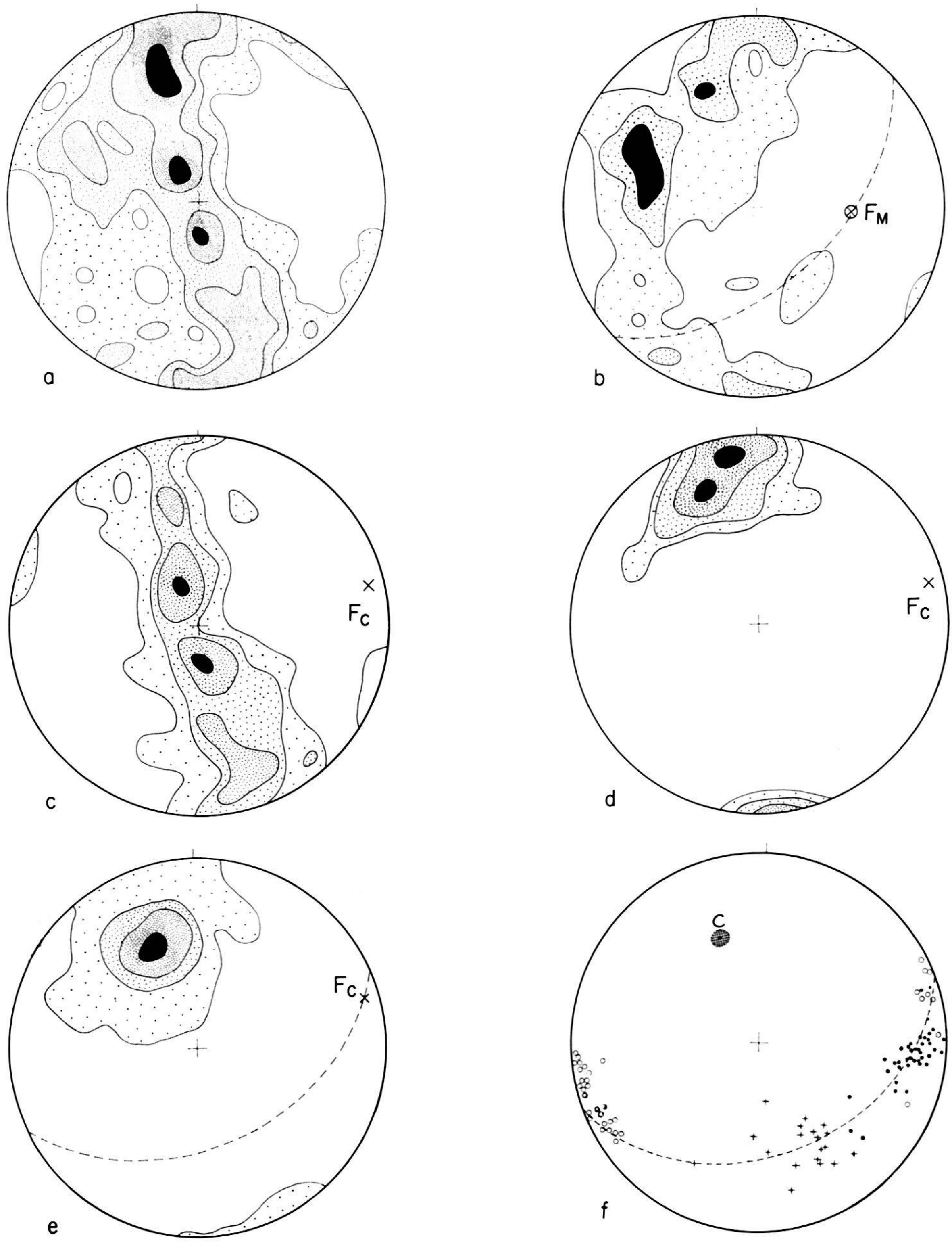


Fig. 15

Bifertengrätli

At the NE end of Bifertengrätli one of the most southerly dislocations of section 4 is followed by the path from Röti to Ochsenstock. South of this line fine-grained dark sediments show folds which are presumably late-Hercynian in age; they are small folds with 1–3 m amplitude and run N 65° E, their axes horizontal and their axial planes dipping south at ca. 50°. The folded fine-grained sediments of the NE end of Bifertengrätli dip generally northwards, and sedimentary structures shown them to lie the right way up. Farther SW (714.600/187.150) a sheared zone, followed by inverted beds of coarse feldspathic sandstones marks the sheared out inverted section of the fine-grained rocks. The coarse sandstones cannot be followed around the synclinal closure, but they are seen lower in the succession of the normal limb some 200 m below, on the southern slopes of Ochsenstock (Oelplanggen).

The continuation of the ridge to the summit of Bifertengrätli (2520 m) crosses the inverted sandstone beds; just south-west of the highest point a recumbent fold can be seen bringing the beds back to the horizontal and turning the beds the right way up. This is probably near the core of the postulated larger anticline of the area. The inverted limb of the fold can be followed across the southern slopes of Bifertengrätli in the well-bedded but strongly cleaved sandstones and mudstones. Three smaller folds with an open S-shape, with shorter limbs of about 20 m and longer limbs of about 100 m, can be traced out in the lower boundary of the sandstone bearing member of the succession. A more complex fold, probably forming the core of the major anticline, is seen 400 m NE of Hintere Rötifirn. The cleavage here is seen to lie in the axial plane direction of the folds, but it shows some refraction as it passes through beds of different lithology.

The constructed axial surface of the folds in the Carboniferous – folds which are assumed to be late Hercynian and not Alpine – have roughly the same orientation as the constructed axial planes of the broad Alpine folds of the basement-cover contact. The folding of the Carboniferous is, however, more intense than that of the unconformity.

The cleavage in the Carboniferous varies in intensity, judged from the field appearance, in different lithologies and in different localities. It is generally present as a coarse fracture cleavage as defined by Lieth (1905), i.e. it breaks the rocks into cm- or mm-thick slabs and there is very little recrystallisation on the cleavage surfaces. Locally on the overturned limb of the fold the cleavage is more intense, and a true schistocity is developed by the growth of mica. Measurements of deformed fragments from this zone indicate more intense deformation.

The intersection of the cleavage with the bedding forms a lineation which is theoretically parallel to the fold axes; field measurements of this lineation are shown in fig. 15f. For the dated Carboniferous rocks its orientation strikes ENE–WSW and is horizontal or plunges with a 5–10° angle. A further lineation is sometimes present on the cleavage surface dipping south-east at about 50°; this is marked as a stretching direction of small quartz and feldspar grains and as the long axes of deformed lithic fragments in the lowest member of the Carboniferous (elongation directions in fig. 15f).

Deformation of the Breccias

The amount of deformation which has taken place in the overturned limb of the Carboniferous rocks can be quantitatively estimated from the stretching of fragments of the lowermost agglomeratic member of the succession. A large number of fragments was measured on the cleavage surface and on a surface at right angles to this, and the measurements (designated $2a > 2b > 2c$) plotted as ratios in fig. 16. The methods employed for the calculations of the strain are those of CLOOS (1947), OFTEDAHL (1948) and FLINN (1956, 1962) which are based on the deformation of spherical objects. The fragments measured are angular, but assuming an originally

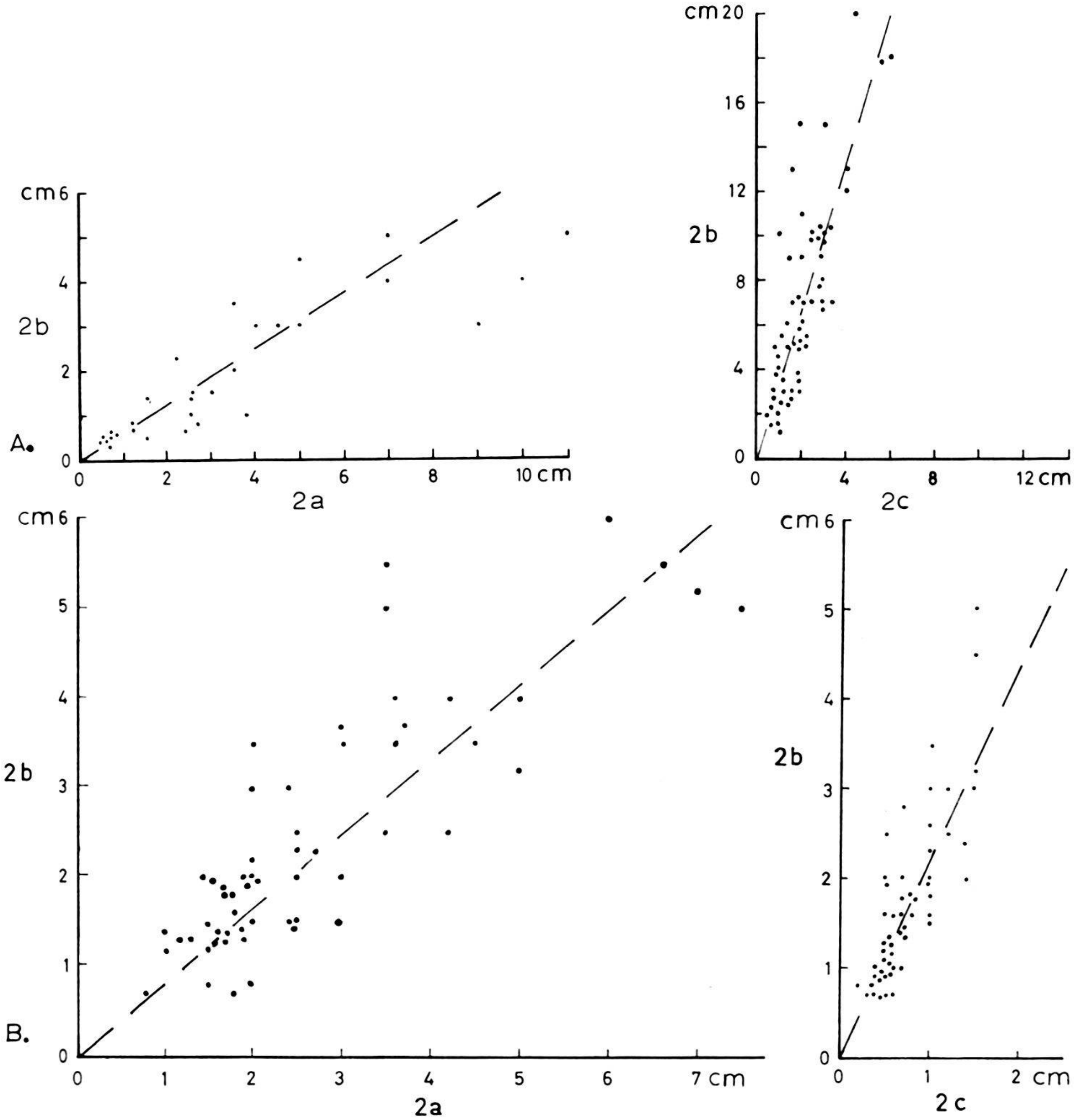


Fig. 16 Mesurements of deformed fragments of the volcanic breccias: 2a, 2b, 2c are major axes of fragments on wheathered surfaces perpendicular to the axes.
A. South Bifertengrätli, locality 1. B. Bifertengrätli, locality 2.

equidimensional unoriented fabric, the mean of a large number of measurements gives an approximation to the ratios that would be given by the axes of a deformed sphere. The radius of such an original sphere is given by:

$$r = \sqrt[3]{a \cdot b \cdot c}$$

and the strains in X, Y and Z by:

strain in $X = (a - r)/r \times 100\%$ extension; strain in $Y = (b - r)/r \times 100\%$ extension, or

strain in $Y = (r - b)/r \times 100\%$ compression; strain in $Z = (r - c)/r \times 100\%$ compression. The results are plotted on a deformation plot (FLINN 1962) in fig. 17.

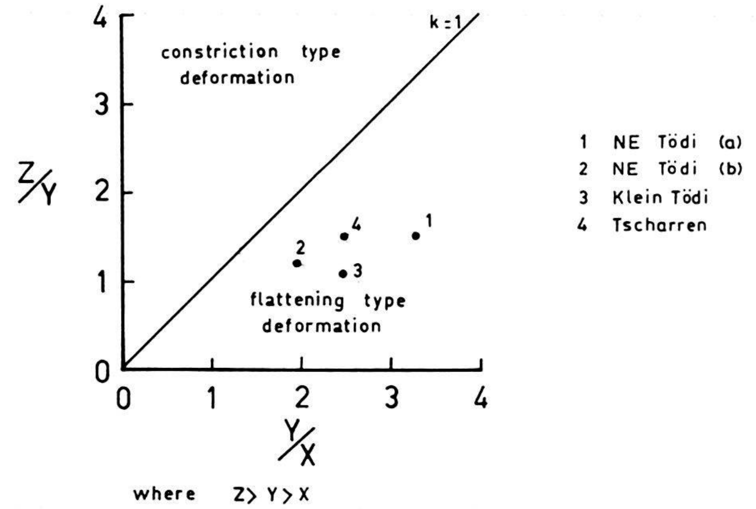


Fig. 17 Deformation plot of deformed fragments from the Upper Palaeozoic rocks of the eastern Aar Massif.

Table 1 Deformation measurements of pre-Triassic sediments of the Eastern Aar Massif (see Fig. 17).

	Ratios of strain ellipse				Strain (%) // to		
	a	b	c	r	X	Y	Z
Bifertengrätli:							
1 Volcanic breccia (715220/186760)	15	10	3	7.65	+95%	+30%	−61%
2 Volcanic breccia (714850/186740)	12	10	5	8.42	+43%	+19%	−41%
Klein Tödi (711720/186270)	11	10	4	7.60	+45%	+32%	−47%
Tscharren	15	10	4	8.40	+78%	+19%	−52%

Deformation of the Plants

A comparable estimate of deformation for two dimensions using different material in the same structural position is offered by the plant remains. Small leaf impressions are most commonly found where cleavage and bedding are parallel – as on the upper

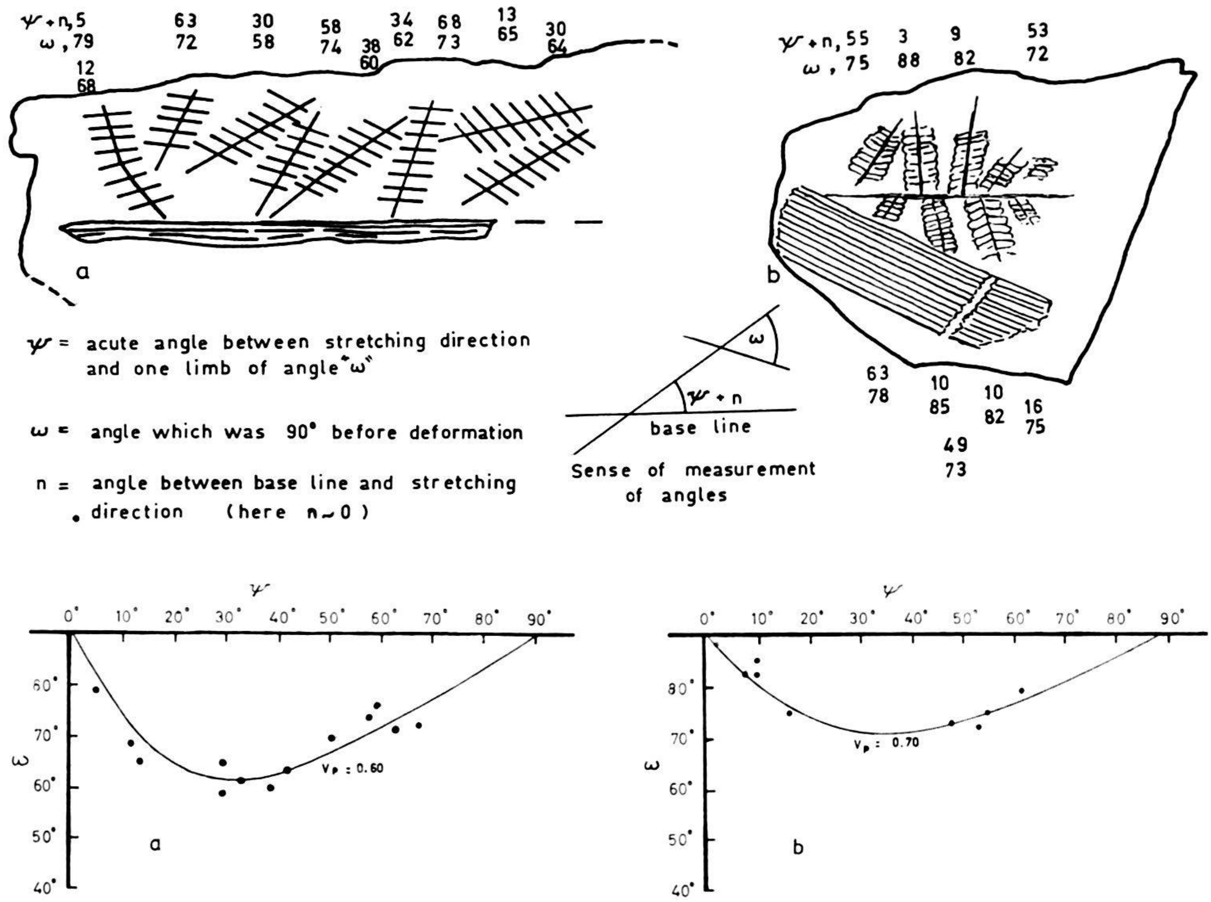


Fig. 18 Deformation of plant fragments in the Bifertengrätli Formation, showing the amount of change of an angle that was originally approximately 90% (ω), depending on its orientation to the stretching direction. The ratio of the axes of the deformation ellipse on the surface measured (Vp) are derived from the formula $Vp = \sqrt{\tan\psi \cdot \tan(\omega - \psi)}$, which is plotted graphically.

parts of the southern slopes of Bifertengrätli – and their shapes are often seen to be disturbed. Using an adaption of BREDDIN's (1956) methods for angular deformation on a plane, specimens gave results of $Z{:}Y = 1.4$–1.7 (where $Z > Y$), as shown in figs 18a, b. Similar figures are obtained using the construction of Mohr's circles (BRACE 1961). As the bedding on which these plant fragments lie is parallel to the cleavage only the ratio of the largest to the intermediate axes of the strain ellipsoid can be determined. The amount of compression at right angles to this, which would also include the amount of sedimentary compaction, cannot be determined from these figures. The ratio $Z{:}Y$ is, however, in agreement with that determined from other measurements, as is seen in the deformation plot fig. 17.

Interpretation of the Deformation Figures

The deformation of the Upper Carboniferous sediments has been selectively concentrated in the overturned limb of the fold, where it is obvious that the original thickness of the sediments has been reduced. The bedding has been brought into a position near to that of the cleavage in this area, so that the thinning of the beds is only slightly less than the maximum compression (strain in Z). Under conditions of no volume change an average of 50% decrease in thickness took place on the strongly deformed parts of the overturned limb, and a corresponding extension in a direction roughly perpendicular to the fold axis in the cleavage surface.

This mechanism cannot be extrapolated over the whole fold, and it is possible that elsewhere the local strain axes were differently oriented with relation to the fold axis. The inhomogeneity of deformation in this area is marked by strong zones of compression separated by less deformed blocks, and is well seen in the deformation caused by the folding of the Upper Carboniferous sediments.

Subarea 6

This section covers the pre-Stephanian metasediments in the area north of the Bifertenfirn. The contact of these to the dated Upper Carboniferous sediments is not well exposed, and can be traced over a distance of only 1 km. The hornfelses below the unconformity show more generally steeper dips than the Upper Carboniferous and a more variable strike, which reflects the pre-Stephanian structures. Field measurements of the bedding are shown in fig. 15b.

Small-scale structures are rare. One minor fold with its axial plane vertical and parallel to the general sedimentary banding is seen on the glaciated surfaces north of the Bifertenfirn, and appears to plunge steeply to the east in a direction similar to that of the constructed fold axis. This is a pre-metamorphic fold, as no axial plane fractures are seen and the hornfels texture is not disturbed. The fold is cut by later minor faults striking NNE–SSW. Boudinage, also probably a pre-metamorphic structure, is seen in a lighter coloured layer embedded in a dark pyritic hornfels (stream bed 100 m N of Bifertenfirn).

These rocks were compact hornfelses at the time of folding of the Stephanian sediments, and accommodated the later movements principally by fracturing, the development of a coarse cleavage, and probably by larger displacements on narrow fault zones parallel to the cleavage in the overlying sediments. In thin section the later cleavage is seen to cut the metamorphic minerals and to form two sets of discrete fractures with opposing displacements and a slight growth of new sericite; the pattern produced is that of synthetic and antithetic fractures (Voll 1960), of which the synthetic set is the more strongly developed.

The latest set of structures recorded in the Bifertenfirn metasediments is a zone of fracture on steeply N-dipping surfaces. This is seen as local knick folding north of the Bifertenfirn, and as sets of quartz-filled tension gashes on the east valley side. These structures lie in the strike of similarly moved larger faults in the basement-cover contact below Tödi and are probably genetically related to these; both structures may be ascribed to the late uplift of the Aar Massif.

THE KLEIN TÖDI AREA

INTRODUCTION AND SUMMARY OF PREVIOUS WORK

Pre-Triassic sediments exposed on the north face of Klein Tödi (fig. 19) give the best evidence of pre-Triassic volcanic activity within the eastern Aar Massif. The age of the sediments has not been conclusively proved, but the lithological similarity with the volcanics of the Biferten inlier strongly suggests that both are more or less synchronous, and thus of Upper Carboniferous age. Direct evidence of Permian age is lacking, and the similarity with Verrucano rocks is much less evident than that with the nearby Carboniferous.

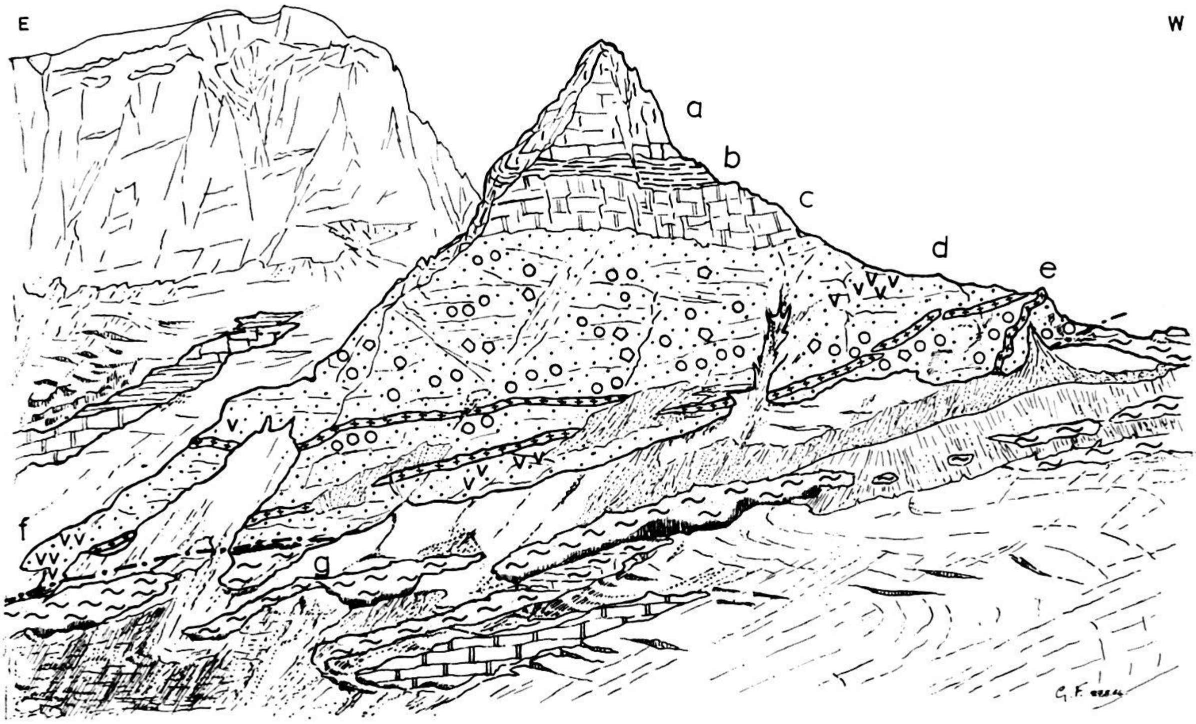


Fig. 19 View of Klein Tödi from the north (footpath at 2640 m) with Tödi (3620 m) in background. Legend: a = Malm, b = Dogger, c = Trias, d = coarse volcanic breccias with areas of lapilli tuffs (v), e = cross-cutting microgranite dykes, f = good exposures of lapilli tuffs, g = gneiss.

The bulk of the sediments are coarse breccias with a black mud matrix, but some finer-grained lighter-coloured well-bedded sediments are present. The presence of lapilli (fig. 20) indicates that some of these at least are of direct tuffaceous origin. Porphyritic microdiorites are found on the southern margin of the outcrops, where they are exposed, and the clearer northern border is a reverse fault contact with older hornblende and granitic gneisses. Two fine-grained porphyritic acid dykes cut across the sediments in an E–W direction from the west ridge of Klein Tödi to the eastern margin of the exposures.

Summary of Previous Work

ALBERT HEIM was the first to describe the rocks on the north face of Klein Tödi as being comparable with the anthracite-bearing rocks of the Bifertengrätli area, and illustrated the exposures in a field drawing – but marking some of the sediments as gneiss (1878, Vol. I, p. 46 and Atlas Pl. XII). The extent of the pre-Triassic sediments was drawn correctly in the map of WEBER (1924), where they were named as conglomerates and breccias of Upper Carboniferous age. WIDMER (1949) described these sediments as graphitic schists, and considered them to be most probably the equivalent of the beds of Bifertengrätli because they lie in the same strike. EUGSTER (1951) doubted the existence of Carboniferous sediments on the grounds that gneisses are exposed on the Sandpass itself, and that the dislocation metamorphism makes recognition of petrographic types difficult. None of these authors mention the lithology and the volcanic nature of the sediments.

LITHOLOGY OF THE PRE-TRIASSIC SEDIMENTS

The coarse conglomerates and breccias which make up the cliffs of the north face of Klein Tödi are best observed in fallen blocks. No primary bedding has been recognised in the western cliffs, and no further subdivision is possible, although the composition of the breccias varies markedly from place to place. Finer-grained well-bedded lapilli tuffs are easily accessible in the lower exposures at the eastern end of the north face (Ref. 711.725/186.250; 2600 m) and prove the volcanic nature of much of the sediment. For the lithological descriptions the north face of Klein Tödi is divided into a western, a central and an eastern area.

The Western Area

The cliffs north of Klein Tödi that lie nearest to the Sandpass, on the western side of the face, are predominantly of grey coloured volcanic breccias with some lapilli, angular blocks, and a quartz-feldspar matrix with calcareous concretions and much iron staining. The presence of lapilli amongst these unbedded breccias shows a pyroclastic origin for part of the material at least. Many of the blocks reach 30 cm in size, but most of the breccias are made up of smaller components up to 10 cm.

The most abundant fragments are intermediate to acid igneous rocks with porphyritic plagioclase and some quartz in the fine-grained groundmass. In some of the fine-grained blocks the plagioclase forms slightly altered crystals with simple outlines, while the larger plagioclase of the coarser varieties often show a zonal alteration. These rocks are porphyritic dacites of similar composition to those in the Bifertengrätli Volcanic Member. Some glassy fragments are seen with plagioclase and chlorite up to 0.05 mm, and in some varieties long plagioclase laths form a massive microlithic texture. Some banded rhyolite fragments are present. Fragments of granite and granodiorite of coarser grain represent material derived from older igneous rocks; in these the plagioclase (up to 4 mm) is often xenomorphic against the larger orthoclase, and the quartz is frequently strained or recrystallised. Single grains in the matrix of the breccias range in size from 0.05 to 0.5 mm and consist of angular, idiomorphic or corroded quartz grains; sericitised plagioclase which shows fresh parts, and sericite, calcite and clinozoisite as alteration products. Much of the matrix and some of the blocks are probably of pyroclastic origin, but the large size and the variety of the blocks speak for their normal clastic derivation.

The Central Area

Farther east, beyond the lower of the two acid dykes, the lighter coloured breccias of the western area give way to coarser breccias with a dark matrix. In hand specimen these are the most polygenic breccias found, and contain large fragments (up to 50 cm) of black shale and quartzite, lighter-coloured acid igneous blocks up to 20 cm, grey sandstones, hornfelses, gneisses and small carbonaceous fragments. Some irregular areas of sandy or tuffaceous sediments are present. The lithology is similar throughout the greater part of the cliffs, as far as may be judged from the accessible parts.

Much of the material is of a volcanic origin comparable with that of the other breccias of this area and of the Volcanic Member in the Biferten inlier. The important characteristics are the large size of the components and the abundance of metamorphic sediments and igneous rock fragments. The metamorphic rock fragments are fine-grained slates, hornfelses and metamorphic sandstones similar to those found in Val Gliems. Some coarse hornblende gneisses are present as angular blocks and are probably derived from the older metamorphic basement. Most of the metamorphic minerals of the fragments are strongly altered and are replaced by sericite and chlorite. A black and dark grey matrix of sand and mud is abundant.

The Eastern Area

The exposures at the eastern side of the north face of Klein Tödi are mainly of lighter-coloured finer-grained breccias and bedded tuffs which appear to lie normally dipping to the SE. Good exposures of lapilli tuffs are seen in the lowest easternmost exposures (grid reference above). The lapilli are sparsely distributed throughout a light-coloured quartz-feldspar rock or may form beds up to 5 cm thick. They are most abundant in the lower part of a crag 5 m high of well-bedded fine-grained tuffs and breccias with a rather light grey colour, and are often associated with fine-grained white glassy fragments of up to 2 cm. Higher in the cliffs the lapilli tuffs give way to coarser breccias in which bedding is only rarely seen.

Small-scale faulting is found in the fine-grained tuffs and lapilli tuffs (fig. 21). These structures correspond in shape and style to those of the Biferten inlier basal conglomerates and volcanics; displacements are usually in the order of 1–5 cm, spaced at regular intervals along one bed. They often die out upwards in coarser beds and were probably formed during the deposition of the coarser volcanic explosive rocks. Displacements with a reverse fault movement uplifting the eastern side have been observed near normal faults lowering the eastern side. The movements do not appear to have given uniform displacements, but are more in the nature of joints. They seem to have a similar N–S strike to the majority of the corresponding faults of the Biferten area.

In thin section the lapilli tuffs are composed of about 10 to 30% of crystalline quartz and plagioclase up to 0.5 mm in size set in a finer grained matrix of comminuted crystals and recrystallised volcanic dust. Idiomorphic shapes are rare and most of the

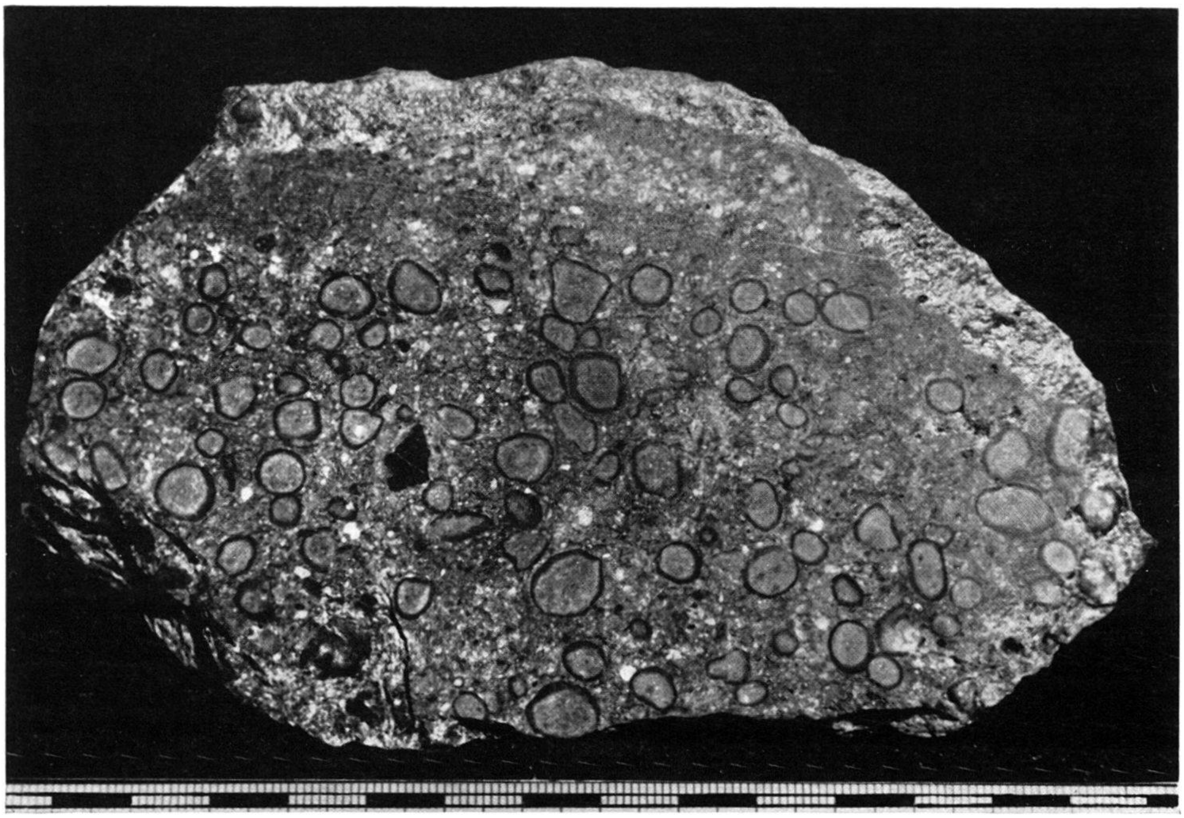


Fig. 20 Lapilli from the north face of Klein Tödi. Scale in cms and mm.

crystals are broken or subangular, and the feldspars strongly altered or replaced entirely by calcite. The lapilli are composed of similar material to the bulk of the rock, but they are of finer grain size and surrounded by a darker rim of devitrified glass 0.2 to 0.5 mm thick (fig. 20). Occasional irregularly shaped or angular darker glassy fragments up to 2 mm are seen. Chlorite and calcite as alteration products

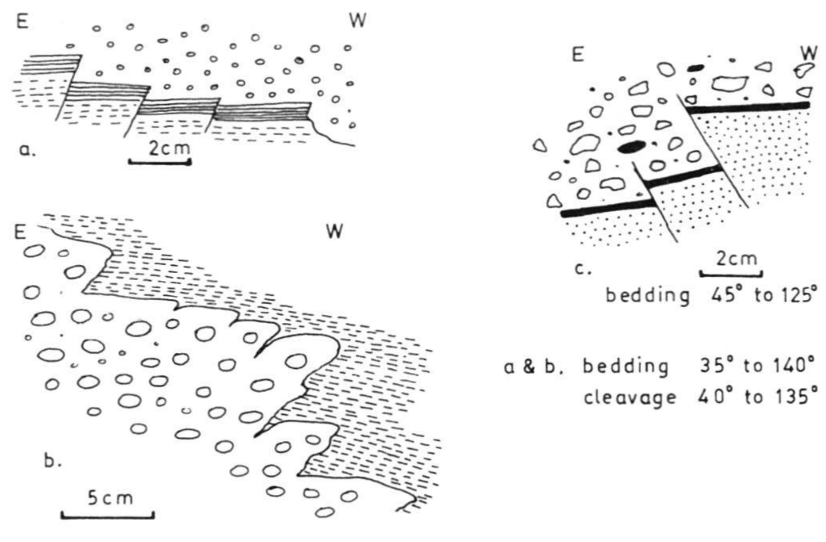


Fig. 21 Small-scale synsedimentary faults in lapilli tuffs.

form large areas up to 1 mm, and sericite is restricted to very fine plates in the groundmass.

Amongst the light-coloured igneous rock fragments of the coarser breccias associated with the lapilli tuffs, the most remarkable are rhyolitic to microgranitic fragments which show textures of welded tuffs of ignimbrites in thin section (fig. 22). These ignimbrites have been determined mainly in specimens from the eastern cliffs, but blocks of similar rock are found elsewhere in the Klein Tödi breccias. In thin section they are seen to contain quartz as idiomorphic or slightly corroded grains which reach 2 mm in size; alkali feldspars and some plagioclase are also present in grains up to 1 mm. The feldspars are mainly altered. Glass shards and quartz splinters reach 1 mm in size, and parts of the fine-grained matrix are recrystallised and welded to give microcrystalline quartz-feldspathic bands which cut the rock irregularly.

INTRUSIVE DYKES OF MICROGRANITE TO RHYOLITE

Three dykes cut the sediments and are shown in fig. 19. In hand specimen they are very light-coloured fine-grained dense hemicrystalline rocks with visible phenocrysts of feldspar and quartz. The thickness of the dykes is 4–5 m, and little visible contact metamorphism is seen in the field, although a thin section of a sediment from the contact showed recrystallisation of the groundmass and new growths of plagioclase.

In thin sections the rock is seen to contain feldspars of up to 1.5 mm and less abundant quartz of up to 0.5 mm scattered in the very fine-grained (0.05 mm) groundmass. The small quartz grains are usually resorbed; some quartz occurs as composite grains made up of fine aggregates of 0.1 mm and may represent recrystallised glass fragments. Orthoclase in large crystals with simple twinning is more abundant than the smaller plagioclase, which is frequently seen in crystal groups. Alteration of the feldspars to sericite and a carbonate is rather strong, and sericite is uniformly dispersed through the groundmass or enriched on cleavage surfaces. No flow structure is evident, although the plagioclase crystals are roughly aligned. Phenocrysts make up only about 10 to 20% of the rock, but from these the composition of the rock is judged to be granitic; i.e. the dykes are of rhyolite to microgranite.

THE GNEISSES AND GRANITE-GNEISS TO THE NORTH OF KLEIN TÖDI

The rocks to the north of the cliffs are gneisses of the "Altkristallin" which have been deformed, but which retain much of their original structure – as seen on the Sandpass. The boundary of the gneisses to the sediments in the south is brecciated and accompanied by quartz veins and quartz segregations. The northernmost sediments are a band 3 m wide of black slates followed to the south by coarse breccias (3 m) and another fault zone marked by 4 m of green schists.

Coarse, deformed granitic gneisses are seen mainly at the base of the eastern cliffs. In hand specimen this rock is coarse-grained holocrystalline with sericitic surfaces and a noticeable chloritic colouration. In thin section it is a holocrystalline rock which was originally coarse-grained, with quartz, orthoclase and plagioclase. The quartz occurs as irregularly outlined grains forming a cataclastic network which

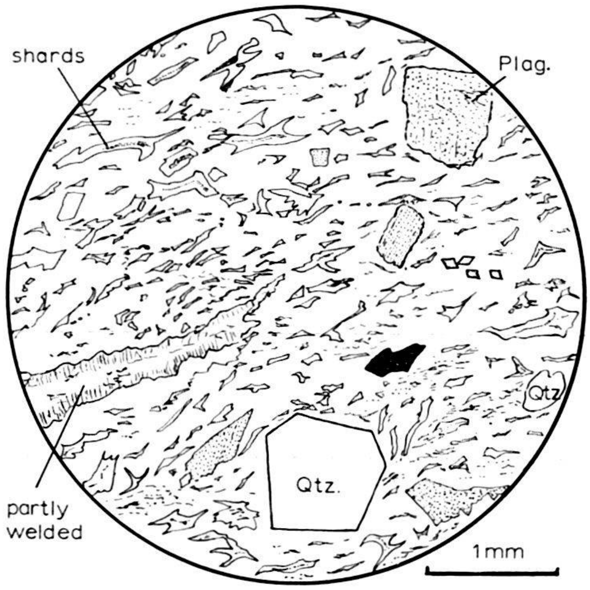


Fig. 22 Thin section drawing of a welded tuff from the volcanic breccias of Klein Tödi: glass shards and local zones of complete welding.

surrounds the other minerals. Microcline is present as altered areas full of sericite and cut by mica plates. It is equal in size to the quartz and contains inclusions of smaller plagioclase crystals. The granite gneiss belongs to an older granitic complex than that of the intrusive dykes. It is believed to be part of the crystalline basement on which the volcanic rocks were deposited, and may be equivalent in age to the Tödi granite.

STRUCTURES

The pre-Triassic unconformity has been strongly deformed by folding and thrusting in the Klein Tödi area, and the pre-Triassic sediments have presumably suffered a similar amount of deformation, although their structures are less clear than those of the overlying rocks. Pre-Triassic structures cannot be distinguished from Alpine structures in this area. The dykes in the basement are seen to be displaced by fractures, and the lapilli are deformed, but the lack of bedding within the coarse clastic sediments prevents further description of the geometry of the basement structures.

In relation to the Alpine structures the Klein Tödi rocks occupy a position comparable to the northern Bifertengrätli/southern Röti area, where the pre-Triassic unconformity has been deformed into an upright position. The displacements lie above shear zones in the basement, and increase in magnitude towards the west; on Klein Tödi the vertical limb of Triassic dolomites is 400 m in extent. In the upper part of Klein Tödi there is considerable overthrusting of the Triassic.

An estimate of the amount of deformation of the pre-Triassic sediments may be obtained from the deformed shape of the lapilli on the assumption that these were originally spherical. The lapilli are flattened on the cleavage, but show only a slight elongation. Measurements of the lapilli are shown in fig. 23, where $2a$, $2b$ and $2c$ are the lengths of the principal axes in hand specimens. The strain indicated by these measurements is shown in the table (fig. 17), where $Z > Y > X$ are the principal axes of the strain ellipsoid. The ratios $Z:Y$ and $Y:X$ are shown on a deformation plot (FLINN 1962) in fig. 17. The plot from this area falls together with plots from other pre-Triassic sediments in a broad group of flattening type deformation.

The elongation direction seen in the volcanic sediments plunges to the SE (145°) on a cleavage dipping to the SSE (50° to 155°); this is approximately the same orientation as that in the Biferten inlier, but it is also a direction of the Alpine structures. The measured deformation is therefore probably a combination of Alpine and pre-Alpine components which cannot be separated.

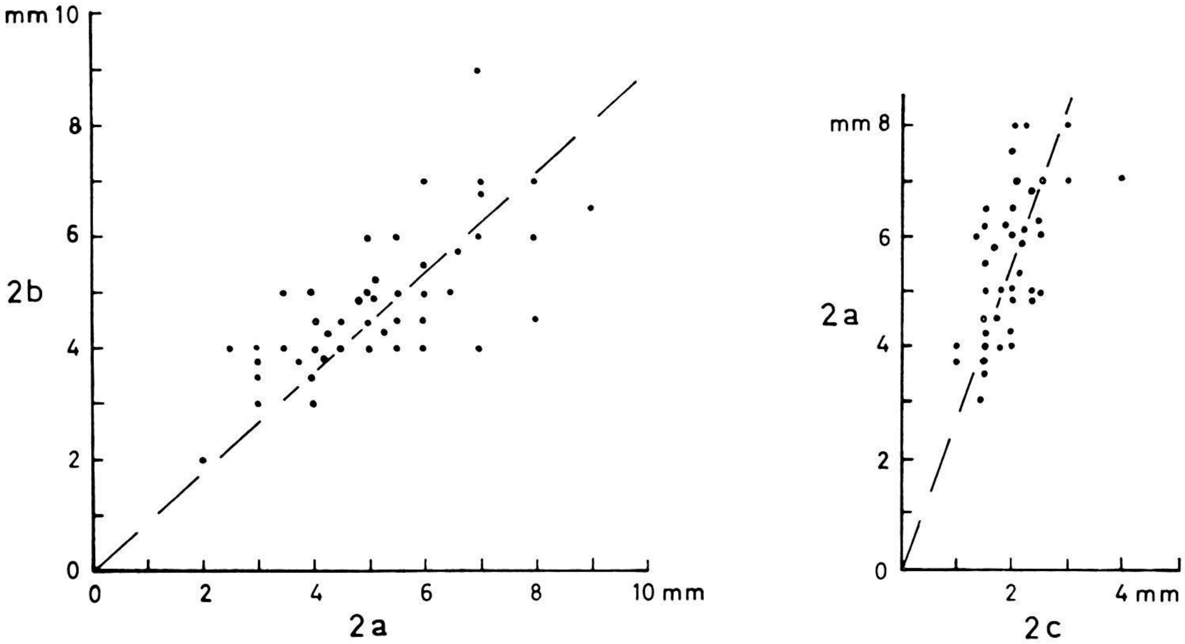


Fig. 23 Measurements of deformed lapilli from Klein Tödi, plotted as in Fig. 16: strain calculation and deformation plot shown in Fig. 17.

DISCUSSION OF THE KLEIN TÖDI VOLCANICS

The Klein Tödi rocks are believed to be equivalent to the Volcanic Member of the Biferten inlier, and add greatly to the reconstruction of the volcanic activity. Three further important facts about the activity emerge:

(1) Lapilli tuffs are absolutely indicative of pyroclastic deposits from a nearby volcanic centre. The ejection of these tuffs was accompanied by small-scale syngenetic faulting.

(2) Ignimbrites or welded tuffs are present as components and are therefore older than the breccias themselves. They may be of similar age to the Sandalp quartz porphyries, and they possess strong similarities with the acid pyroclastic rocks of Windgällen and Tscharren farther to the west.

(3) The breccias are cut by acid dykes which are probably related to a larger granite intrusion, possibly the Central Aar granite. The acid pyroclastic rocks of the breccias are clearly separated from these intrusions by the period of erosion and deposition of the Klein Tödi volcanics. These intrusions may support the late, post-volcanic age of the main Central Aar granite intrusions.

In reference to the Biferten area the Klein Tödi rocks correspond to the late explosive activity. The greater abundance of acid types and the presence of gneiss boulders from the basement are in contrast with the Biferten inlier rocks. This may indicate a slight age difference, the Klein Tödi rocks being somewhat younger, but it is more likely to be a result of deposition on ground which remained under rigorous terrestrial conditions and did not subside into a more protected basin farther removed from the source rocks.

THE MADERANERTAL

INTRODUCTION AND SUMMARY OF PREVIOUS WORK

The Maderanertal cuts into gneisses, granites and schists of the northern border of the Aar Massif. To the north and south of the main valley there are small areas of pre-Triassic slightly metamorphic formations, which are mainly of volcanic origin. Those to the north form much of the core of the Windgällen recumbent anticline, and those to the south form a belt of 14 km by 4 km on the northern border of the main Central Aar granite. It is important that these two outcrop areas be discussed in close conjunction, for although their direct connection has been destroyed by the erosion of the valley they both provide evidence of volcanic activity of probable Upper Carboniferous age. The petrography of most of the rocks has been previously described, and the present study has been aimed at providing an explanation of the origin and history of the rocks which have been qualified as quartz porphyries, quartz porphyry tuffs and as Carboniferous sediments.

Summary of Previous Work

The earliest observations of anthracite-bearing rocks of assumed Carboniferous age in the Maderanertal and of the porphyritic rocks of the Windgällen appear to have been made by ARNOLD ESCHER in 1841, but publication of his notes was held back. His successor, ALBERT HEIM, studied a large area of the eastern Aar Massif, the Windgällen in particular, in the years from 1870 to 1890. The earliest studies grouped together the pre-Triassic low-grade metamorphic sediments as so-called Lower Veruccano or Casanna schists, possibly of Lower Paleozoic age (1878). The crystalline rocks were described petrographically by SCHMIDT (1886); the intimate relation of the porphyritic acid igneous rocks of the Windgällen with Carboniferous sediments, and a comparable relationship on the south of the valley suggested a correlation with other Carboniferous rocks of the Massif. Schmidt discussed the possibilities that the porphyritic acid rocks were a pre- or Lower Carboniferous intrusive stock, or that they were connected as a marginal facies to the Aar granite. He gave petrographical descriptions of 5 types of porphyritic rocks from the Windgällen, some microgranitic and others granophyric or felsitic. The descriptions of Heim and Schmidt were extended over a larger area of the Massif in 1891 and the crystalline rocks were divided into zones similar to those established farther east by BALTZAR (1880) and FELLENBERG (1893).

A map and short text of KOENIGSBERGER (1910) contain the first published account of the porphyries north of the Central Aar granite of Oberalpstock and on the ridge of Tscharren. These were given more attention by W. STAUB (1911), who thought that the acid porphyritic rocks were viscous flows or dyke intrusions of a marginal facies of the Central Aar granite.

Two petrographical doctoral theses cover parts of the area (PFLUGSHAUPT 1927; SIGRIST 1947) and provide the most detailed descriptions available. The conclusions of these two works are not entirely compatible, although the petrographical descriptions of rock types are accurate. PFLUGSHAUPT studied the area of Bristenstock and Tscharren and derived the following late Paleozoic history:

(1) Mid-Upper Carboniferous deposition of anthracitic sediments.

(2) Folding by the second Hercynian movements.

(3) Upper Carboniferous: intrusion of the Aar granite and possible derivation of pebbles from this to give conglomerates.

(4) End of Carboniferous/beginning of Permian: intrusion and extrusion of quartz porphyries into and onto these sediments and slight contact metamorphism. This was partly an explosive eruption of a gas-rich residual magma of the granite which ejected blocks of granite, porphyry, mudstones and ash. These deposits alternate with normal extrusive quartz porphyries and the very leucocratic rocks of Tscharren represent final residual flows.

SIGRIST (1947) regarded all the quartz porphyries as intrusive, and found no evidence of tuffaceous sediments or surface flows on Tscharren. The history he deduced is:

(1) Deposition of Carboniferous sediments: dark mudstones and some thin calcareous lenses of originally iron-rich sandy limestone composition (0.5 cm to first size).

(2) Folding during the Upper Carboniferous.

(3) Intrusion of the granite during or immediately after the folding.

(4) Uppermost Carboniferous/lowermost Permian: intrusion of quartz porphyry along weak zones and the transport of granitic schollen during violent intrusion: the schollen sank into the magma and produced schollen-rich area. The light quartz porphyry preceded the dark variety.

BRÜCKNER (1943) in more general remarks, mentioned the abundance of mudflow deposition in the Upper Carboniferous sediments of the Aar Massif, and suggested a volcanic origin, either as direct volcanic mudflows or as reworked lavas for some of the beds. The rocks of Tscharren, associated with layers of true "quartz porphyry tuff", are included in this type.

GEOLOGY OF THE PRE-TRIASSIC FORMATIONS OF THE MADERANERTAL

The localities and distribution of the rocks of the studied area are shown in fig. 24. A magnificent recumbent anticline on the northern margin of the Aar Massif (s. str.) carries the crystalline rocks of the Windgällen area in its core; this has been well illustrated by HEIM (1878, 1922 vol. 2, pl. 7) and W. STAUB (1911).

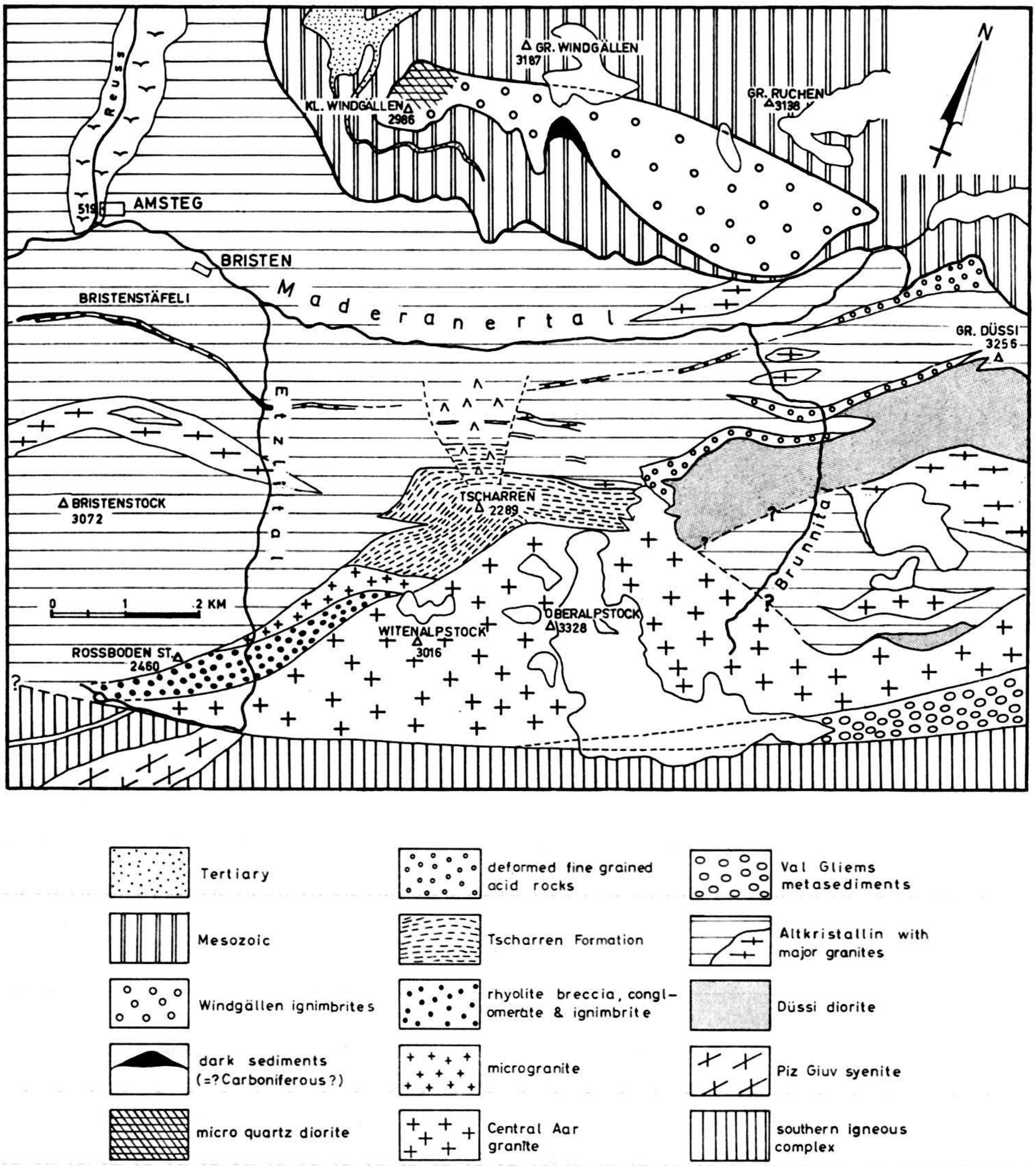


Fig. 24 Geological sketch map of the Maderanertal area.

The aim of the present study is to describe (a) lithological types and stratigraphy of the Upper Paleozoic rocks, and (b) late pre-Alpine basement structures of the Aar Massif and their relation to Alpine structures.

THE UPPER PALEOZOIC SEDIMENTS OF TSCHARREN (THE TSCHARREN FORMATION)

The sedimentary and volcanic rocks here described include many of the porphyritic micrograniic rocks of SIGRIST's (1947) post-granitic igneous intrusions. The difficulty of interpretation stems from the association of acid volcanic rocks and fine-grained acid intrusive rocks in the proximity of the Central Aar granite, and from the metamorphism and new mineral development (biotite, chlorite, epidote) in all the rocks.

The section seen on the southern slopes of Tscharren is looked upon as inverted on the evidence of cross-bedding, small-scale load casts and graded bedding. The structural interpretation of the area is shown in fig. 25. The fold hinge is seen on the saddle at the east of the Tscharren ridge, and the rocks above this, which form the lowermost part of the measured section, lie the right way up. The measured section is shown in fig. 26.

The stratigraphical succession observed may be subdivided into

(1) Light-coloured acid tuffs and ignimbrites, the Ignimbritic Member.
(2) Conglomerates.
(3) Dark-coloured vitric and lithic tuffs, the Tuffaceous Member.

These three units form a continuous section which has been named the Tscharren Formation. The type locality is the southern slopes of the upper part of the ridge of Tscharren (2488 m) on the south side of the Maderanertal.

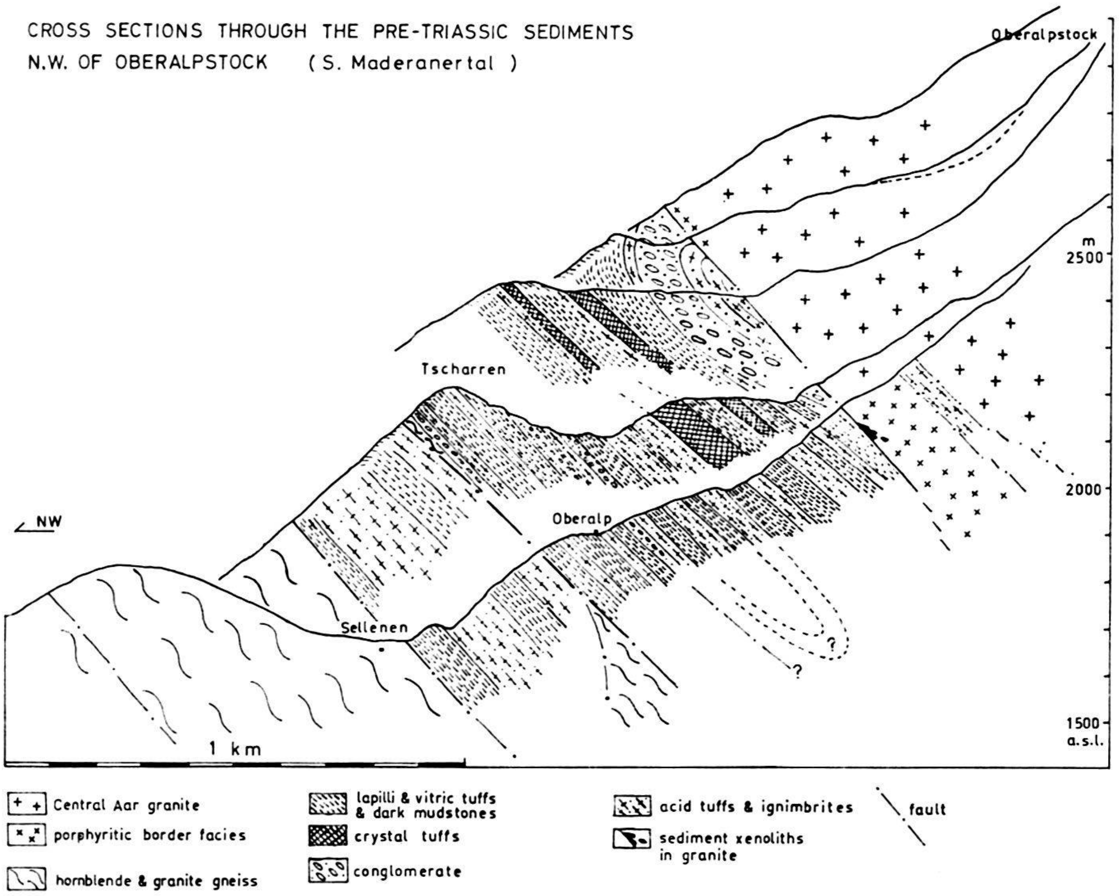


Fig. 25 Geological cross sections through the Upper Palaeozoic volcanics NW of Oberalpstock, 1:20000.

The Ignimbritic Member

Field Relations

These rocks form a succession of acid volcanic flows, interbedded clastic material and tuffs and finer sediments. The coarsest acid beds are microgranodiorites and microgranites of ignimbritic origin.

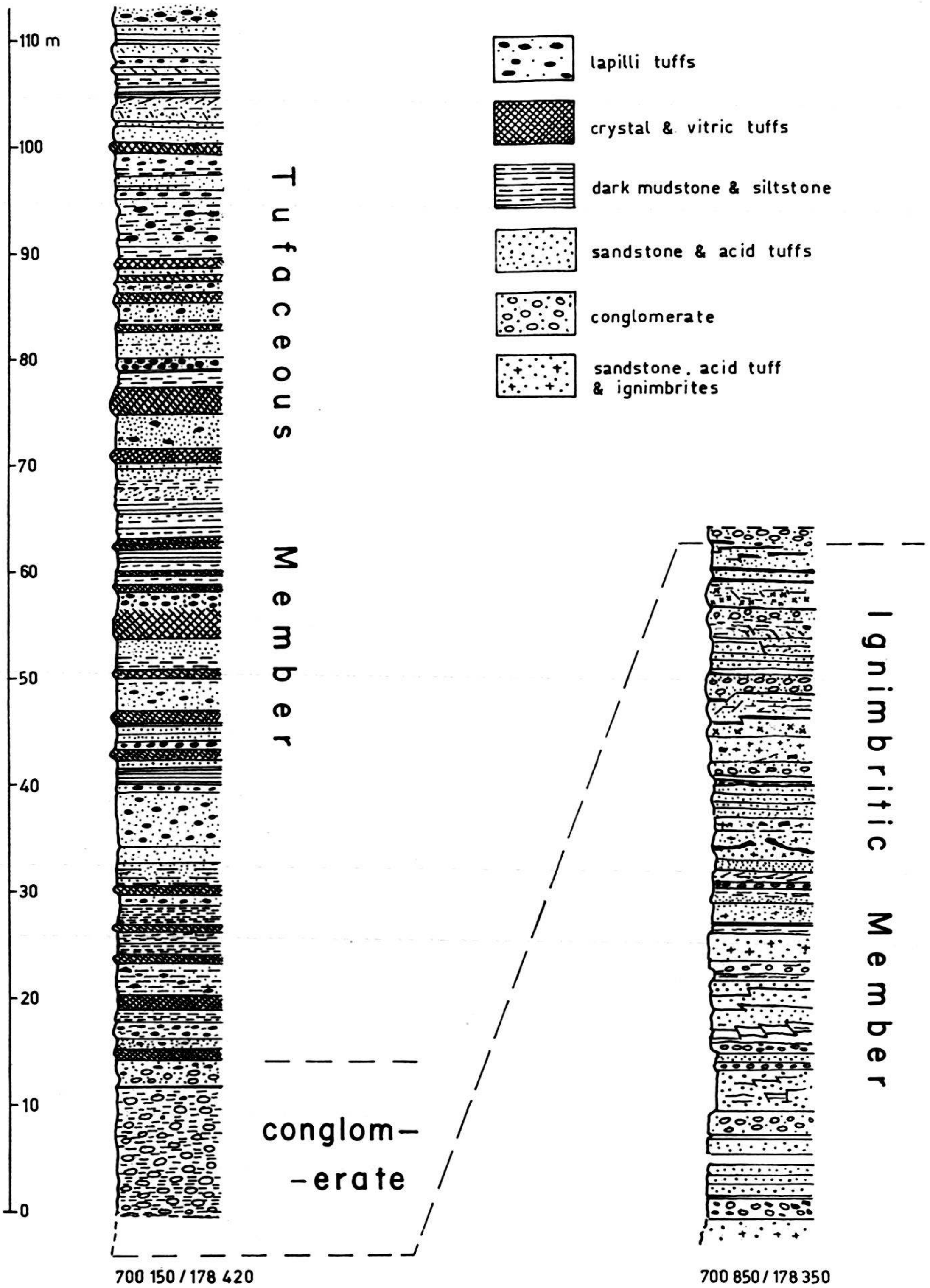


Fig. 26 Measured Section of the Tscharren Formation, southern slopes of Tscharren.

Bedding features are best seen on the hinge of the fold where cleavage and bedding intersect at a large angle; where cleavage and bedding become parallel many of the details are lost. As the coarse light-coloured layers are separated by layers of conglomeratic and finer grained sedimentary material, the vertical variations in composition are regarded as sedimentary stratification and not as magmatic structures. The massive, light-coloured, coarse- to medium-grained, quartzo-feldspathic rocks lie in regular beds of 20 cm to 3 m thickness, and the darker coloured alternating beds are thinner. A faint lamination within the light-coloured beds often shows cross-bedding, and where this is clearly truncated the beds are seen to become younger to the north. The cross-bedding is probably a result of redeposition of the acid tuffs by water, and the graded bedding may prove primary gradation of tuff beds.

Small-scale syn-sedimentary faults are abundant in these beds; they show individual displacements in the order of 10 cm and a constant uplift of the eastern side, often slightly overthrust and thus indicative of a compressive stress on the sediments.

The individual beds are of uniform grain size, and some contain larger elongated fragments (up to 30 cm) of finer grained material similar in composition to the matrix and surrounding beds. No foreign components are found. The fragments are

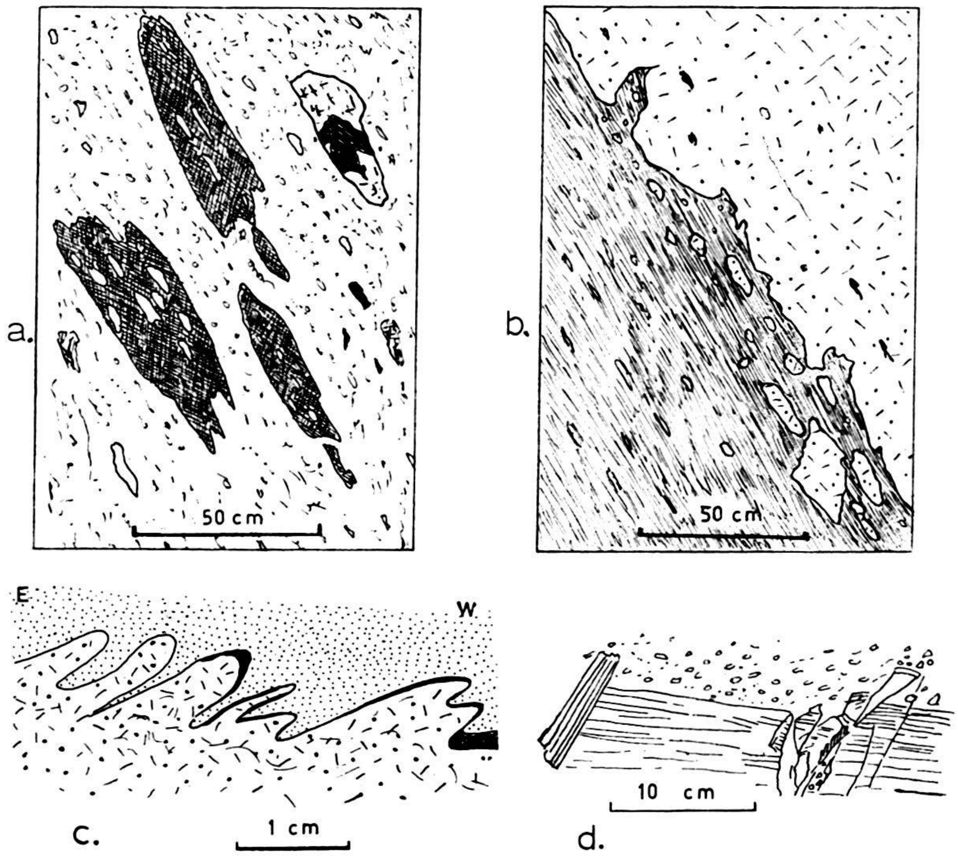


Fig. 27 Details of ignimbrite and banded rhyolite beds. a) fragments of dark-coloured lapilli tuffs and coarse-grained ignimbrites in a pyroclastic matrix. b) inverted ignimbrite bed with fragments in the younger dark-coloured tuffaceous bed. (a & b south Tscharren, 700360/178340; 2300 m). c) Sedimentary load casts of a crystal tuff (below) in an argillaceous bed; indicates inversion of the beds. d) ruptured banded rhyolite, indicating explosive activity associated with the overlying lapilli bed (NE Stöckli, 699830/177860; 2210 m).

elongated tectonically in the cleavage plane, and primary elongation caused by magmatic flow has not been observed. The thinner bands of sediments and conglomerates are of more obviously sedimentary origin, but their components are similar to those of the acid beds. Fragmentary beds formed from the reworking of older ash deposits, lying in the upper part of this section, are shown in fig. 27a, b. The contact of the coarser acid material with the darker fine-grained rock shows no chilling, and farther to the north light-coloured acid beds are seen to contain large blocks of reworked finer grained lapilli tuffs and coarser crystalline tuffs. The available evidence points to an ignimbritic origin of these beds and to the rapid surface erosion of the pyroclastic flows. No glass shards, however, have been observed in these rocks, as later metamorphism has completely recrystallised the matrix.

These homogeneous coarsely crystalline acid tuffs are strongly contrasted in lithology to the finer grained banded rhyolites which are found farther to the west. Lapilli beds comparable to those higher in the section and to those of Klein Tödi are missing in this part of the section.

Petrography

In hand specimens the massive acid tuff beds are light grey to grey-green in colour, with clearly visible glassy quartz grains up to 5 mm which often appear angular or fractured in outline, and strongly altered feldspars with a brown-grey colour on the weathered surfaces. The glassy parts of the groundmass are normally sheared and show the development of micas on the irregular cleavage surfaces.

In thin sections (fig. 28a), the *acid tuffs* are composed of abundant quartz grains and smaller plagioclase with subsidiary potash feldspar set in a fine-grained microcrystalline matrix of quartz, feldspar, and sericite, in which bands of aligned sericite mark discontinuous cleavage surfaces generally about 1 mm apart. The quartz grains are rounded but rarely embayed relics of euhedral crystals of 0.5–4.5 mm in size. They invariably show undulose extinction as a result of strain and often show fractures, some of which are annealed with finer grained quartz. Marginally the crystals are overgrown by finer grained quartz and show some replacement by calcite and sericite.

The plagioclase occurs in two size groups: the most abundant crystals are smaller (0.5–1.0 mm) and euhedral, the other group is less abundant (ca. 2 per slide) and forms rounded grains up to 3 mm. Simple albite twinning, some carlsbad-albite twins, and some poorly developed chessboard twins are present. Most are strongly altered and replaced by very fine sericite and epidote. The microperthitic potash feldspar occurs as rounded crystals up to 1 mm, some of which are composite. Carlsbad and baveno twins are present. Locally they are replaced by recrystallised quartz and calcite of the matrix.

Lens-shaped coarser grained areas of the groundmass consist of an equidimensional mosaic of quartz up to 0.1 mm in size with small sericite flakes and larger areas of calcite. Biotite is locally intergrown within these lenses as plates up to 0.05 mm in size, and may accumulate as composite areas up to 0.2 mm. Within the recrystallized fine-grained quartz areas the biotite is not aligned, but in cleavage

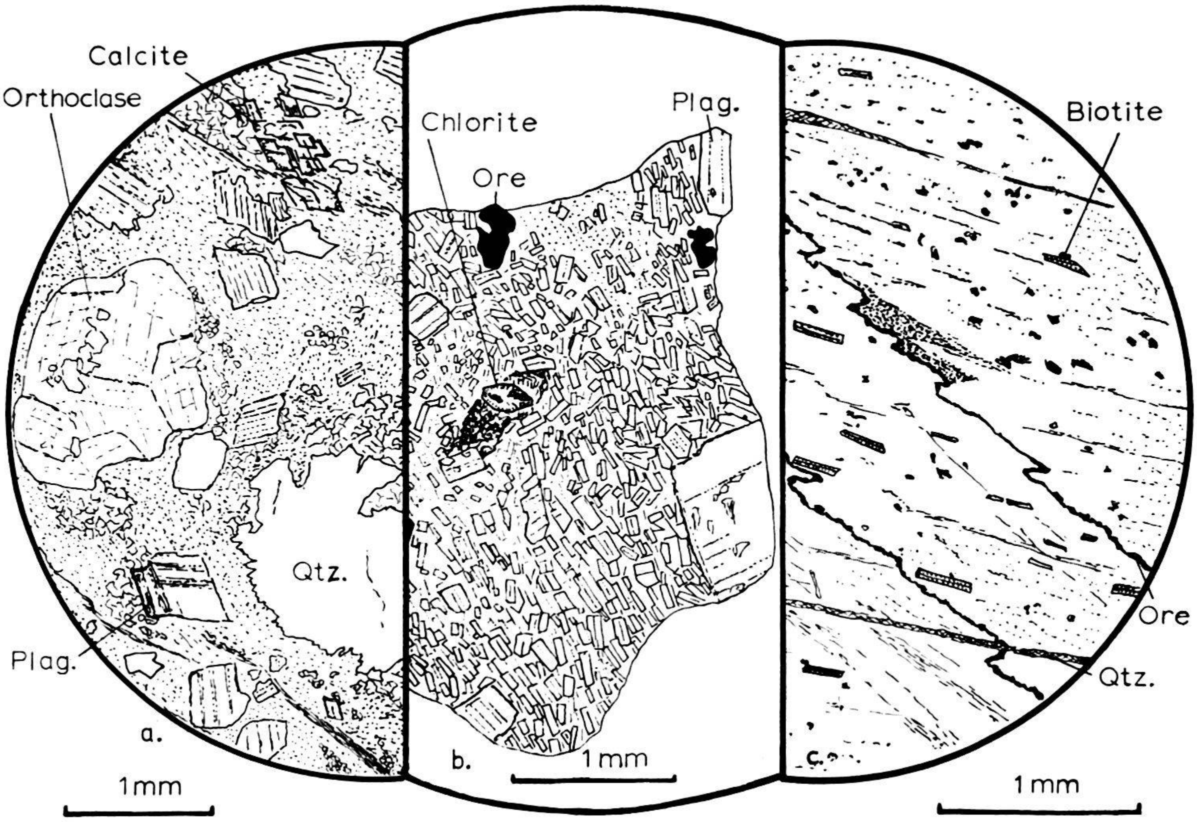


Fig. 28 a) Thin section drawing of a recrystallized acid tuff from ignimbritic member of the Tscharren Formation.

b) Fragment of porphyritic microdiorite with microlithic texture, in tuffs of the ignimbrite section of Witenalp.

c) Banded slaty mudstone from upper slopes of Tscharren. Layers of ore minerals show small-scale folding, with the axial plane marked by the growth of biotite and quartz veinlets.

zones and around plagioclase, which it replaces marginally, it is aligned parallel to the cleavage surfaces. It is strongly pleochroic, with X, yellow-brown (light green); Y, dark brown (green-brown); Z, opaque.

The grain boundaries of the quartz and calcite of the matrix are straight and show no sign of mutual replacement, but both replace the larger crystals of quartz and feldspar. Sericite, other than the very small grains replacing feldspars, lies in parallel discontinuous bands which cut the biotite and the areas of coarser matrix. The finer grained areas of matrix are made up of very fine, aligned sericite and quartz. The degree of alignment of the matrix minerals varies from specimen to specimen. Accessories in the light beds are clinozoisite, some opaque ores, rare zircons and a colourless spinel.

The development of the biotite and the granoblastic texture of parts of the groundmass are thought to be metamorphic effects which took place after the deposition of the rocks, because of the replacement of other minerals, the lack of flow features, and the equal and probably simultaneous metamorphic growth of the matrix minerals. A typical coarse-grained acid bed consists of 30–50% phenocrysts, of which about 50% are quartz, 30% plagioclase and 20% potash feldspar (visual estimates).

The darker interbedded rocks are made up of about 25–30% crystalline material (quartz, plagioclase and potash feldspar) set in a finer grained partly recrystallised matrix. The proportions of the crystalline material vary, but plagioclase (ca. 60% of the coarse material) forms abundant euhedral crystals of up to 0.1 mm, with tabulate or equidimensional outline. They are normally rather fresh and twinned simply in the albite law. Some are enclosed in larger glassy volcanic fragments. They are sometimes replaced partially by quartz and calcite. Quartz forms angular grains of up to 2 mm and shows secondary fracture, strain and replacement. Potash feldspar forms small crystals (up to 1 mm). The groundmass is normally very fine-grained sericite, quartz, with some coarse crystalline areas in which a greenish biotite is present. Some prisms of epidote of up to 0.1 mm and clinozoisite needles are often enclosed in plagioclase.

Conglomerates

Field Relations

Beds of conglomerates and breccias make up a succession of 15 to 20 m, in a small area on E Tscharren. They are composed only of material found in the surrounding beds, and the mud and comminuted fragment matrix gives them a darker colour than the underlying rocks. Bedding is weakly developed and the conglomerates seem to be water-laid deposits with an abundant matrix, but pyroclastic components may have been important. The components consist of coarse silicic ignimbrites (porphyritic micrograpites), glassy lapilli tuffs, finer graded tuffs and dark mudstones. Coarse crystal tuffs and tuffaceous sandstones with thin interbedded shales are present in the section and are seen on the ridge of Tscharren immediately NW of the granite.

Petrography of the Conglomerates

The composition of these clastic and pyroclastic rocks is a mixture of acid material similar to that which predominates in the lower part of the section and of finer grained tuffaceous material which makes up the higher part of the succession. The proportions are variable, and the dark matrix of the conglomerates, composed of mud and crystal tuffs, is normally very abundant. An individual rock type, not found elsewhere in this area is a dark muddy sandstone with potash feldspar grains up to 1 cm in size, quartz, plagioclase and mud fragments. The grains are angular to subangular and are set in a fine-grained matrix (ca. 30%); irregular cleavage surfaces marked by dark clayey layers pass around the grains. The abundant fresh microperthitic potash feldspars show some quartz and plagioclase inclusions and are occasionally fractured, but show little marginal alteration. Quartz, which occurs as angular grains of up to 2 mm, shows strained extinction and is frequently composite. The less abundant plagioclase is more strongly altered, and some fresher chessboard albite is present. The clastic shape and relatively good sorting of the crystal grains as well as the presence of a muddy matrix and of mudstone fragments demonstrate the sedimentary nature of this rock, which in composition resembles a granite. A rather similar rock is observed in the arkosic beds of the Bifertengrätli Formation. Thin interbedded black mudstones resemble those of the dated Carboniferous section.

The Tuffaceous Member

Field Relations

The inverted section of banded fine-grained tuffs, mudstones, crystal tuffs and lapilli tuffs measures 100 m on S Tscharren; a correction of approximately 50% must be added to allow for tectonic deformation, and the minimum thickness of the original sedimentary succession that has been measured would be in the order of 150 m.

The succession consists of an alteration of beds of dark banded slates (max. grain size 0.05 mm), some with about 25% of small feldspar crystals (up to 0.5 mm) which is probably volcanic ash. Some beds contain light-coloured glassy lapilli; their distribution is shown in the section (fig. 26) – no regular rhythms are apparent. The finer grained beds show some mm-banding of grey and black well-indurated beds, but as cross-bedding is rare, load casts are the only criteria of inversion (fig. 27c). Small-scale faults with displacements of up to 2 cm have both reverse and normal displacements.

Crystal tuffs may form very thin bands – sometimes single layers of crystals are seen in the banded slates – or they form massive beds 2–3 m thick which change thickness along their strike. The crystal tuffs are dark fine-grained well-indurated rocks with uniformly scattered angular white feldspars of up to 2 mm. They have been recrystallised and have a massive hemicrystalline texture, but no features indicate that they could have been lava flows. The contacts to the overlying and underlying beds are even and conformable, and no variations of the fabric take place within one bed.

The lapilli beds show variable content and size range of glassy white fragments set in a darker grey matrix. The shape of the fragments is usually ellipsoidal, with the longest axis lying in the cleavage plane. The cleavage in most of the measured section dips at 10–20° less steeply to the south than the bedding. In some areas the lapilli are deformed to unrecognisable white slivers. Normally the median axis of the lapilli varies from 0.5 to 5 cm, and in length they may be stretched to 15 cm. The sizes below 1 cm have usually a simple elliptical outline, but the larger ones may have irregularly angular or lobate outlines depending on the plasticity of the material when it was ejected. Quartz and feldspar crystals are sometimes visible in the lapilli. Angular fragments of black shale up to 3 cm are present in some beds, and others are characterised by the presence of larger bombs of porphyritic rhyolite as well as more abundant feldspar and quartz crystals in the matrix.

Petrography of the Rocks of the Tufaceous Member

Tuffs. In thin section the massive ashy beds consist predominantly of euhedral plagioclase and small quartz crystals embedded in a fine-grained felsitic groundmass of recrystallised quartz, feldspar, biotite, sericite and chlorite (see fig. 29). The plagioclase (An_{0-10}), up to 2 mm in size, shows albite, carlsbad and some pericline twinning, and some grains are composite. Slight alteration affects all the grains uniformly, and some have a narrow rim of clear albite. The crystals show no preferred orientation, but they are often surrounded by strain-shadows of xenoblastic quartz and biotite.

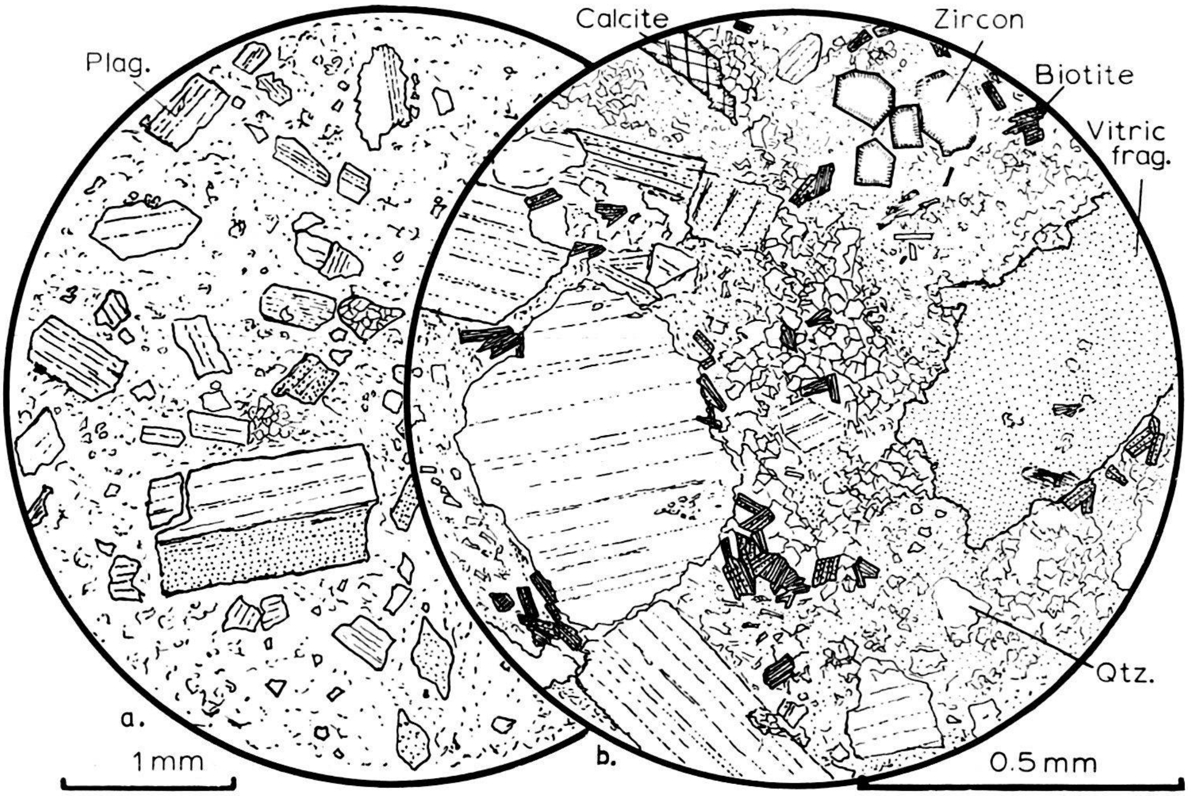


Fig. 29 Thin section of crystal tuff, Tufaceous Member of Tscharren Formation. a) showing altered plagioclase and recrystallized matrix, b) detail of recrystallized matrix with granoblastic quartz-biotite mosaic: note local patches of calcite and idiomorphic zircons.

The single quartz grains are small (up to 0.5 mm) and rounded, but quartz forms the most important part of the matrix and in parts has recrystallised to a mosaic of grains of 0.05–0.1 mm in size with plates of biotite. The biotite is strongly pleochroic (X, yellow-green; Y, green-brown; Z, dark brown). Epidote, chlorite, sericite, clinozoisite and calcite are present as widely distributed secondary alteration minerals. Apatite and zircon are present as accessories. Occasional glass fragments and fragments containing plagioclase illustrate the tuffaceous origin of these rocks.

The lapilli beds are made up of a matrix similar to that of the crystal tuffs, in which glassy fragments and rock fragments are embedded. The glass fragments are distinguished in plain light be their uniform appearance and their smaller amount of biotite, epidote and ore minerals; they are made up of a uniform fine-grained (up to 0.05 mm) mosaic of quartz, feldspar and some sericite, and enclose occasional larger plagioclase phenocrysts (up to 0.6 mm). The lapilli are markedly elliptical, their longest axes parallel to the cleavage which cuts all the rocks. The groundmass of the lapilli-bearing beds is richer in alteration minerals than that of the crystal tuff; slightly pleochroic epidote forms prisms up to 0.1 mm; biotite may occur in clusters of small flakes, and sericite and small ore minerals are abundant.

The mudstones consist of recrystallised quartz (0.002 mm), together with sericite, larger biotite, epidote and opaque grains. Bedding is marked by thin darker layers and bands of opaque grains which are folded about an axial plane marked as the schistosity of the rocks, the plane of growth of most of the biotite, and the direction of quartz veinlets (fig. 28c). The growth of the metamorphic minerals in this direction demonstrates the contemporaneous activity of deformation and metamorphism. There is no indication that this is a regional type of metamorphism; the temperature rise was probably caused by the intrusion of the Central Aar granite, which would hence be of post-Tscharren Formation age, and the stress field responsible for the alignment of the minerals was probably established during the rather complex emplacement movements.

Discussion of the Tscharren Formation

Rocks outside the measured section on Tscharren can be placed in one of the described rock types; frequently the bedding features and much of the characteristic aspect of the rocks have been destroyed by deformation. Some black carbonaceous mudstones and siltstones are found locally as discontinuous beds or in strongly sheared zones between more competent beds. These are the best, but very inconclusive evidence of a correlation with the Bifertengrätli Formation of the NE Tödi area. The explosive type of volcanic activity recorded in the Tscharren Formation suggests that it may have been coeval with the later explosive eruptions of the Biferten inlier and Klein Tödi areas.

The volcanic rocks were deposited in a terrestrial environment, where they suffered rapid erosion. They must have formed an extensive blanket over the older gneisses, as these form only a small part of the components. The early phase of the activity produced the acid tuffs and ignimbrites of the lower member. The thinness of these beds and the extensive reworking between the eruptions suggest that they were some distance (2–10 km?) from the volcanic centre, and that they form the ends of ignimbritic flows. The rocks have been recrystallised by later metamorphism, but the silicic tuffs probably formed partially or non-welded zones (SMITH 1960) of larger ignimbrite units.

After the period of strong erosion marked by the conglomerates, a period of ash/tuff deposition commenced; this continued uninterrupted by erosion or catastrophic explosion throughout the upper part of the Formation. The bedding features indicate a much more gentle volcanic activity, and the upper part of the Tscharren Formation is thought to mark a period of waning volcanic activity.

The intrusion of the Central Aar granite is a later phenomena. Although there may be a fundamental connection between the volcanic activity and the granite intrusion, the field evidence shows that the two are clearly separated. The folding of the Tscharren Formation probably owes its origin to the intrusion of the granite, as the metamorphism indicates contemporaneous increase in stress and temperature.

WITENALP

To the south-east of Tscharren, the Witenalp area exposes porphyritic acid rocks interbedded with dark shales and lapilli tuffs, coarse volcanic conglomerates and rhyolite breccias. The rocks lie south of the massive porphyritic microgranite which extends from Stöckli to the Etzlital north of the main Aar granite and which is thought to be a subsidiary intrusive mass. The most prominent structure seen in this area is a strong cleavage that dips with 70–80° to the SE and contains the long axes of the strongly deformed fragments of the breccias.

Ignimbrite section of Witenalp

Below and east of the Witenalp huts several units of light-coloured porphyritic acid tuffs and darker lapilli tuffs form a section of at least 50 m. This thickness is tectonically reduced to about 50% of the original one. A measured section 200 m SE of the huts is given below. Base of section: grid reference 698.330/186.250; height 2015 m. Bedding and cleavage are roughly parallel, dipping SE with 70°.

1. + 1 m light-coloured homogeneous porphyritic acid rocks with visible quartz and feldspars in an aphanatic groundmass. Large rounded fragments of similar material up to 10 cm in size near the southern (lower?) border. This rock has a similar appearance in thin section to type (6).
2. 5 cm black slates.
3. 25 cm dark fine-grained lapilli tuff. In hand specimen it is a dark aphanatic rock with some scattered larger crystals, whitish grey lenses up to 1.5 cm, and is cut by a weak cleavage. In thin section occasional quartz, microcline and rock fragments are set in a recrystallised felsitic matrix in which glass shards are still recognisable. Quartz occurs as rounded embayed grains, and also in some euhedral crystals up to 1.5 mm; it shows strained extinction and some fracturing. Composite rounded grains are common, and the recrystallised groundmass consists mainly of quartz together with biotite. Microperthitic potash feldspar occurs as euhedral or rounded grains up to 2 mm. Alteration is sometimes strong, and inclusions of epidote, sericite and quartz are common. Plagioclase is absent. The groundmass consists of very fine-grained quartz and sericite (up to 0.02 mm) in the less strongly recrystallised areas, and in plane polarised light glass shards and feldspar-bearing lapilli up to 5 mm are seen, together with smaller black shale fragments of non-volcanic origin. Small ore grains are abundant.
4. 60 cm sheared fine-grained grey, dense tuffs with large deformed lapilli up to 3 cm. In thin section the rocks consist of subrounded to euhedral crystals of plagioclase, quartz and microperthitic potash feldspar, together with porphyritic lapilli in a fine-grained groundmass (up to 0.02 mm). Epidote is very common in single prismatic grains up to 0.4 mm or as inclusions in the feldspar. A greenish-brown, strongly pleochroic biotite in 0.05 mm laths sometimes forms lenses. Sphene and ore minerals are also present. The epidote, biotite and sphene are metamorphic minerals, and locally form xenoblastic mosaics with quartz. The lapilli or volcanic rock fragments consist of (a) glassy material, (b) porphyritic microdiorite with euhedral plagioclase up to 0.6 mm (An_{0-10}) set in a groundmass of tabular plagioclase up to 0.2 mm with a parallel microlithic texture (fig. 28b). Ores, epidote and small green-brown biotite are abundant, and pseudomorphs of semi-opaque material probably represent original amphibole.
5. 5 cm deeply weathered shear zone in softer rocks.
6. 3 m massive sheared grey porphyritic rhyolite with sedimentary fragments and some lapilli, indicating an ignimbritic origin. Many quartz grains are seen on sections across the cleavage, and lens-shaped and folded glassy fragments are present. Brownish mica is seen on the cleavage surfaces. In thin section the rock is composed of approximately 15% quartz, 15% plagioclase, 10% microperthite and 60% matrix. Darker, finer grained glassy fragments with small tabular plagioclase are less abundant than in (4). Euhedral plagioclase up to 2 mm with albite and carlsbad-albite twinning is slightly altered and sometimes fractured. The grains are scattered irregularly in a matrix rich in small opaque grains, small brown-green pleochroic biotite (up to 0.1 mm) with some sericite and epidote. Some of the subspherical lithic fragments are made up of radiating aggregates of quartz needles, probably a spherolitic texture resulting from the recrystallisation of a volcanic glass.
7. 1 m glassy, light-coloured tuff with deformed glass fragments.
8. 5 m light grey lapilli tuff with deformed glassy fragments up to 20 cm in length. In thin section it contains roughly 30% quartz, 5% plagioclase, 5% microcline and 60% matrix, with fragments of coarser grained granodiorite. The quartz occurs as angular to subrounded fractured and strained

grains up to 2 mm with marginal growths, as composite rounded grains and as blastocrystalline mosaics (up to 0.5 mm) in parts of the groundmass. The feldspars are smaller, fractured, slightly altered and corroded subhedral crystals. The groundmass is made up of fine-grained quartz, feldspar and sericite, locally recrystallised and with interstitial biotite, or as larger areas of fine-grained sericitic material. Epidote and apatite are present. The coarser grained granodioritic rock fragments contain subhedral plagioclase up to 1 mm and a holocrystalline groundmass of anhedral quartz up to 0.4 mm: the plagioclase contains small sericite flakes and is bordered by a rim of clear plagioclase in optical continuity. Narrow sericite and biotite zones cut the rock.

Volcanic Conglomerates

Above Witenalp (Ref. 698.820/176.910; 2280 m) a succession of coarse clastic volcanic rocks and volcanic conglomerates is seen, the structures of which lie parallel to those of the section described above. Cleavage and bedding are parallel, but age relations cannot be determined. The conglomerates are strongly deformed, stretched in a direction plunging to the SSE (65° to 165°). The coarsest conglomerates, with angular and rounded blocks up to 1 m, measure at least 6 m across their strike. The beds farther north are also composed of coarse volcanic débris, and some beds consist of angular blocks of banded rhyolite. Most of the components of the conglomerate are coarse quartz-bearing rocks with a fine-grained matrix. In thin section they contain quartz, plagioclase and potash feldspar in an abundant matrix. The rocks appear to be either well indurated recrystallised arkoses and sandstones or metamorphic ignimbrites. Quartz occurs as equidimensional subangular to subrounded grains up to 1.5 mm with marginal outgrowths and strained extinction. Plagioclase shows a little alteration, and the microperthite may show strained extinction and large inclusions of sericite and epidote. Parts of the groundmass are granoblastic; new growths of epidote reach 0.3 mm and the biotite, of two colours (X, light yellow, golden yellow; Y, grass green, green-brown; Z, grass green, opaque), may accumulate as small aggregates. Clinozoisite, sericite, some calcite and rounded zircons are present. The approximate composition is quartz 50%, feldspar 20%, matrix 30%, and is similar to some of the coarser light-coloured beds of the lower part of the Tscharren Formation. The associated lapilli tuffs and volcanic breccias are of the acid variety, and in thin section show a weak banding of the glassy groundmass caused by the devitrification of relic glass shards and lapilli. The phenocrysts of quartz, plagioclase and microperthite are concentrated in layers and lenses. Metamorphic products in the groundmass are abundant (epidote, biotite, sericite) but the feldspars are relatively fresh. A pyroclastic origin is ascribed to the greater part of these rocks.

Rhyolites and Rhyolite Breccias of Witenalp

Field Relations

Fine-grained acid rocks are exposed above Witenalp in the rock faces south-west of Etzlistock (Ref. 698.940/176.930; 2350 m), somewhat above and NE of the main exposures of conglomerates. They adjoin the granite in the south along a sheared contact: a deformed glassy lapilli tuff is separated from the massive porphyritic granite by a shear zone, 10–15 cm wide, and by 8–10 cm of glassy material which

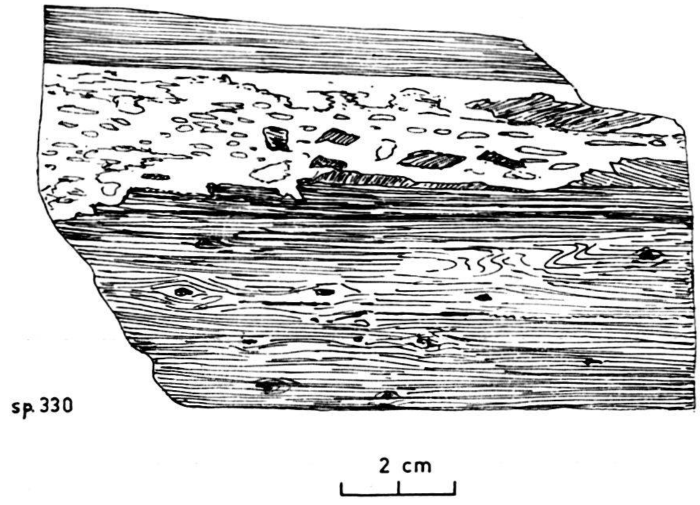


Fig. 30 Flow banded rhyolite and breccia-lapilli bed.

is possibly a flinty crush rock. The shape of the rhyolite body is not clear, but it appears to extend to the east in the direction of the cleavage and bedding strike, and it is probably a stratigraphical unit of acid flows and breccias lying below the volcanic conglomerates and lapilli tuffs. This section is probably inverted on the evidence of the ignimbrite section below Witenalp.

The banded rhyolites and dacites are light grey in colour on weathered surfaces, and darker grey on fresh surfaces. Flow banding and scattered quartz phenocrysts are clearly visible (fig. 30). In non-banded glassy types, microlites may develop rod and radial patterns, usually centred on a larger phenocryst. The breccias are made up

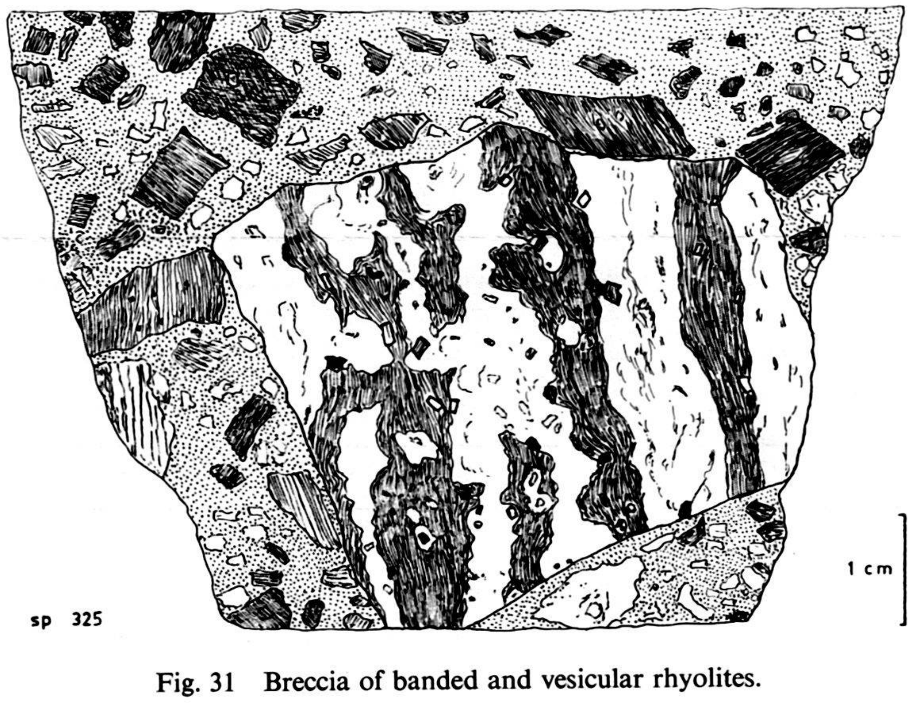


Fig. 31 Breccia of banded and vesicular rhyolites.

of parallel-sided blocks of banded rhyolite up to 10 cm set in a dark consolidated aphanatic matrix. Some of the blocks show a vesicular texture (fig. 31), the vesicles being filled with light-coloured recrystallised glass. The development of a breccia above a banded rhyolite is shown in fig. 30. This is conclusive proof of the surface nature of the acid volcanic activity.

Petrography

In thin section the banded dacites consist of a felsitic matrix containing phenocrysts of euhedral plagioclase, quartz and some rare potash feldspar. The plagioclase forms euhedral tabulate crystals up to 3 mm in length; some are slightly rounded, and all contain alteration products of sericite and epidote. Epidote is well developed as single grains up to 0.2 mm, or may form veinlets in the groundmass, or fill fractures in the feldspar. Quartz is restricted mainly to the groundmass, and forms microcrystalline recrystallised layers up to 0.2 mm in thickness which mark the banding. Larger areas (up to 2 mm) of composite quartz mosaics may represent recrystallised phenocrysts. The original flow banding, which shows tight folding in places, is marked by thin layers of finely disseminated ores and darker minerals and has been accentuated by devitrification and recrystallisation of some bands. Most of the matrix is a dark devitrified glass made up of quartz and sericite up to 0.01 mm. The microlites, where present, consist of tubes and rods of devitrified glass up to 0.3 mm in width; they are often filled with small ore grains and are separated by areas of coarser microcrystalline matrix.

The breccias in thin section show blocks of banded rhyolite and dacite in a coarser microcrystalline matrix of quartz, feldspar, with scattered ore-minerals, sericite, epidote and clinozoisite. The darker colour of the lava fragments is produced by the disperse ore dust and the finer grain size. The margins of the blocks against the groundmass are strongly recrystallised.

ROSSBODENSTOCK AND THE WESTERN EXTENSION OF THE VOLCANICS

The contact of granite to the south with dark slates and acid tuffs to the north is well seen on the upper part of Rossbodenstock (10 m SE of p. 2460.8). The volcanic rocks are made up of porphyritic silicic rocks in beds 1–1.5 m thick and interbedded thinner black shales 20–30 cm in thickness. Blocks of shale are seen in the acid porphyritic beds close to the contact with shale horizons, and suggests that the succession is inverted. The bedding is generally steep and trends parallel to the ridge.

Further west the continuation of the belt of pre-Triassic sediments and volcanics is made up of a large area of deformed ignimbrite conglomerates. These are well seen 200 m NE of the Spillaui Seeli. They are rather uniform in composition, and almost all the blocks are of acid tuffaceous or ignimbritic material of a darkish green colour with visible large angular quartz and feldspars. The largest blocks reach 80 cm in length (elongated) and about 30 cm median diameter.

The contact of these sediments with the gneisses in the north is a strongly sheared zone, with boundinage and abundant quartz veining.

THE BASEMENT ROCKS OF THE WINDGÄLLEN

Introduction

Most of the rocks of the crystalline core of the Windgällen fold are fine-grained to microcrystalline porphyritic silicic rocks. Since their discovery in the 1840s by ARNOLD ESCHER they have been known as "quartz porphyries" and have received a respected place in Alpine literature (SCHMIDT 1886; HEIM 1887; W. STAUB 1911; SIGRIST 1947). They have generally been regarded as intrusive (HEIM 1922, vol. 2/2, p. 135; SIGRIST 1947), although they have sometimes been drawn into comparison with similar rocks from the Carboniferous of Northern Germany and from the Lower Paleozoic of North Wales (MUEGGE 1893), for which a tuffaceous and effusive origin had been suggested on the grounds of ashy structures and geological relationship.

Of the 20 thin sections examined in the present study, 14 showed a significant pyroclastic character, 4 were strongly sheared so that groundmass textures were unrecognisable, and 2 were of a mircoquartzdiorite composition, the appearance of which was in marked contrast to the other more acid rocks. Although ignimbritic rocks and fine-grained granitic intrusions may approach each other in petrographical appearance, the difference in genesis which the two modes of emplacement imply is sufficiently great to warrant a discussion of the available evidence. The most important question is the age of the surface pyroclastic deposits and their age relationship to the associated intrusive microquartzdiorite.

Fossil plants or anthracite deposits have not been found in the basement sediments of the Windgällen, and the only suggestion of their age is a lithological similarity of some of the rocks with the anthracite-bearing beds of Bristenstäfeli or the Biferten inlier. This is not strong evidence in itself, for carbonaceous shales are not restricted in age. The association with acid volcanic rocks, and particularly a similarity with the Klein Tödi volcanics, is probably more suggestive. Volcanic outbursts, although spread out over a large time span, are events which may be used for rough stratigraphical correlation, and the study of the areas to the east shows that important volcanism took place before and during the deposition of the Upper Westphalian and Stephanian.

The red or purple colouration of some of the rocks is very weak evidence of Permian age of these rocks, for it affects both pyroclastic rocks and the intrusive rocks which are thought to be younger in age. The oxidation colour of irregular parts of this complex is probably a result of pre-Triassic weathering of the basement; part of the colouration may stem from weathering during the Lower to Middle Jurassic, in which the Windgällen area stood out as an island. If the pyroclastic rocks of this area were formed during the same volcanic episode as that of the Tödi area it seems probable that their age is Westphalian or Lower Stephanian.

Field Relations

The rocks which have been regarded as Carboniferous are best exposed SE of the Gross Windgällen, between Schwarzberg and Furggelihorn. Small exposures of black mudstones and conglomerates with a black fine-grained matrix (Ref. 699.450/184.100; 2310 m) lie in an inverted position above sandstones of the Middle Jurassic. Bedding is seen to dip steeply to the north in the exposures 20 m farther to the east. No stratigraphical section can be measured as the dark rocks pass into light-coloured massive unbedded acid flows or ash beds which are thought to be ignimbrites.

The darkest fine-grained mudstones contain varying amounts of visible quartz ranging from isolated angular sand-size grains to larger rounded pebbles, and passing into rounded or angular boulders of light-coloured acid rock in the conglomerates and breccias. The term conglomeratic is here used for beds which may be agglomeratic, but which cannot be distinguished from water-worn boulder conglomerates in the field. The coarser clastic components are mainly grey hemicrystalline or microcrystalline fragments of irregular subangular shapes which are flattened in the cleavage. Some smaller darker mudstone components are also present, and many of the rocks are spotted with small carbonate points.

Black bands are seen in places between thicker light-coloured massive or boulder-bearing acid beds; they are usually formed by fine sand-sized components, and the bedding contacts against the conglomerates or acid tuffs are best seen in polished specimens. In the field many of the contacts appear to be gradational because of the similarity of the uniform fine sandy or muddy layers to the matrix of the conglomerates. The continuity of the section of these dark-coloured fine-grained rocks and the more massive acid beds of igneous appearance is evidence of the volcano-sedimentary character of the acid rocks.

Farther east, on Schwarzberg and on the Alpgnofer Platten, the core of the Windgällen fold is composed mainly of finer grained microcrystalline porphyritic acid rocks which show little or no bedding; parts contain isolated lighter coloured quartzite boulders or lenses. Massive porphyritic greenish-grey rocks with a cryptocrystalline matrix on the lower slopes of Schwarzberg often show local red colouration of irregular areas of restricted narrow bands; the red colour may be bleached along a closely spaced regular pattern of parallel joints.

The Alpgnofer Platten in the east shows mainly rocks of greenish colour with two prominent sets of foliation, the earlier one, generally steeply dipping or vertical, being marked by flattened glassy lenses about 1 cm in length. Parts of the rather uniform rock contain large angular blocks up to 40 cm, and parts show more abundant feldspars. Lenses of up to 30 cm of carbonate with brown weathering surfaces are found (carbonate lenses are also found in the Bifertengrätli Formation). Faults, probably of Alpine age, are thought to control the structures of the basement rocks, and to be responsible for bringing more massive crystalline parts against conglomeratic beds, but lack of bedding and distinctive petrographic types in the field make a more exact description of the configuration difficult.

The rocks in the core of the Windgällen fold in the west make up the upper part of the Klein Windgällen. These rest in an inverted position above thin boudinage dolomites of uncertain stratigraphical position and Jurassic limestones. Pyroclastic deposits are seen in most of the basement rocks, and bands of conglomerate with fragments of pyroclastic rocks in a black matrix up to 1 m thick and some black carbonaceous mudstones are found near the lower contact of the basement rocks.

North of the Klein Windgällen, a body of microquartzdiorite, often showing local red colouration, is exposed. The shape of the body has not been determined, but it appears to be intrusive into the ignimbrites and conglomerates and thus of younger age. No fragments of this rock have been found in the clastic or pyroclastic beds.

Petrography of the Basement Rocks of the Windgällen Fold

In place of the five petrographic types described by SCHMIDT (1886), three broad groups are here distinguished:

(1) Acid (silicic) tuffs, ignimbrites and ignimbrite breccias and conglomerates.

(2) Rocks with a darker matrix, probably indicative of resedimentation of the acid rocks by water. Mixed sedimentary rocks.

(3) Porphyritic microquartzdiorite.

Acid (Silicic) Tuffs, Ignimbrites and Ignimbrite Breccias and Conglomerates

These rocks, which form the greater part of the Windgällen basement rocks, are variable in appearance and composition, but complete gradation exists between the individual types. They include types 2–5 of SCHMIDT's (1886) classification. The colour of the rocks in hand specimens is normally grey-green, but sometimes reddish-purple; small quartz and feldspar crystals are usually clearly visible.

The clearest evidence of the pyroclastic origin of these rocks is their content of darker coloured lapilli, bombs and blocks which may be seen on weathered surfaces of almost all the less deformed types. Many of the fragments have an angular outline and indicate eruption of solidified magma; others have rounded or ovoid shapes and were probably plastic at the time of eruption. Deformation and the development of sericite-coated cleavage surfaces reduces the fragments to darker chloritic lenses which may be visible only on polished specimens.

Three main varieties may be distinguished, but these do not correspond to the types which SCHMIDT (1886) separated on the basis of grain size and colour. The varieties separated are (a) massive types, (b) fragmentary types, and (c) laminated fragmentary types. They are completely gradational into each other, and cannot easily be separated into distinct units in the field. The petrographical differences imply slight differences in the eruptive mechanism and represent different stages in the progressive welding of acid tuff deposits or ash-flows.

(a) *The massive types* show no structural alignment in hand specimens; only quartz and feldspar phenocrysts are seen in a dense or sheared matrix. In thin sections of undeformed specimens they show a clear vitroclastic texture of recrystallised arcuate glass shards (fig. 32a). Some of the shards are still completely spherical and preserve the hollow space of the glass bubble, now filled with recrystallised glass – a remarkable feat considering their history. The phenocrysts make up about 20% of the rock; quartz forms rounded embayed crystals which reach about 3 mm in some specimens; potash feldspar and some plagioclase are present in smaller slightly rounded grains. Potash feldspar forms rounded grains up to 2 mm with some microperthitic areas and carlsbad twinning; they are often strongly altered or completely replaced by fine-grained sericite. Plagioclase, much of it strongly altered and some showing chessboard twinning, is less abundant in these rocks than in varieties con-

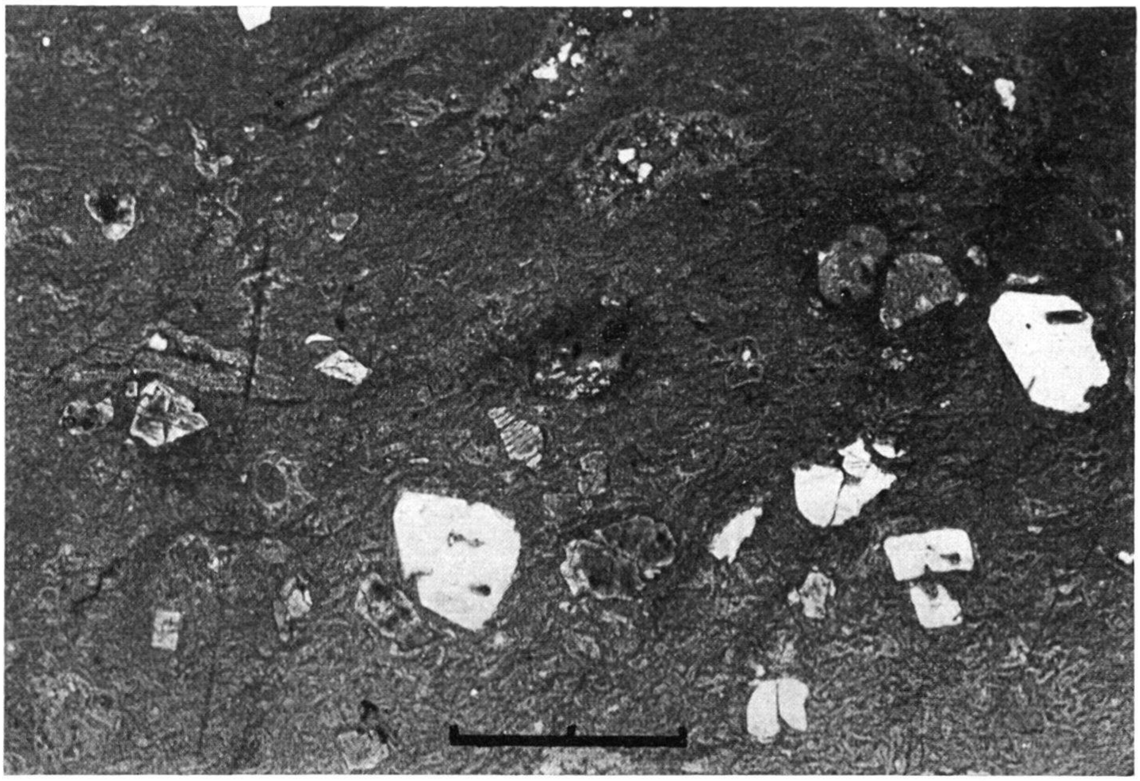


Fig. 32a Vitric acid tuff with undeformed arcuate glass shards. Note the section through the unbroken gas bubble, lower left. Scale is 2 mm.

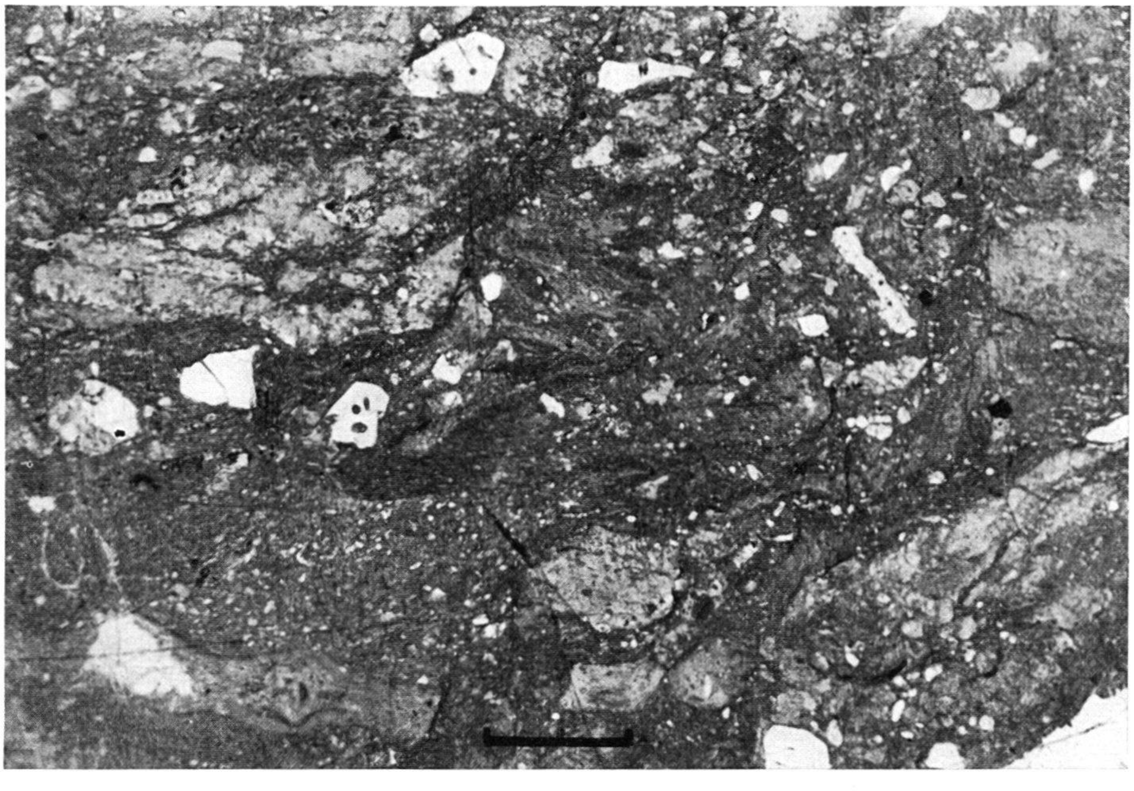


Fig. 32b Fragmentary acid tuff with ataxitic texture. Only slight deformation of the fragments. Scale is 2 mm.

taining lapilli and blocks. The matrix, seen to be composed mainly of shards in plain light, is seen under crossed nicols to consist of an indeterminable aggregate of quartz, feldspar and sericite (ca. 0.005 mm grain size).

(b) *Pyroclastic types:* the fragments that characterise this type are best seen on smooth weathered surfaces. They are blocks and lapilli of rather darker coloured material than the matrix. Most are angular and roughly parallel-sided in shape, giving the rock a brecciose appearance which may be described as ataxitic (HARKER 1928). Their shape demonstrates that although the fragments are of the same composition as the matrix, they were already crystallised at the time of deposition of the tuff. The rocks probably formed as a glowing avalanche deposit of rhyolitic to rhyodacitic composition.

The matrix is very fine-grained, cryptocrystalline, and in thin sections (fig. 32b) is seen to contain a large amount of disperse sericite. No shards or relic glassy outlines are present as part of the matrix. Phenocrysts of quartz and feldspar are present in amounts varying from 5 to 20%. Plagioclase is more abundant than potash feldspar and, although strongly altered and often fractured, shows good albite twinning. The fragments consist of three main types:

Rounded to subrounded fragments of equigranular fine-grained or microcrystalline (normally about 0.2 mm grain size) quartz-feldspar rocks, sometimes with isolated phenocrysts of quartz or feldspar. A rough banding or lenticular structure is seen in some of the rocks in plain light; this may indicate that the fragments were pumiceous and have been recrystallised more completely than the groundmass.

Lenticular or angular blocks: these are the most abundant fragments. They show similar mineral composition to the other fragments but possess a completely different texture. Few large well-developed phenocrysts occur and the general grain size is 0.05 to 0.2 mm, in irregular interlocking grains with complex shapes. Areas of sericite (up to 0.1 mm) are abundant, and some fragments are rich in ores. Some areas of spherolitic quartz needles are present in most fragments, and may be dominant in some; they seem to be the effects of recrystallisation of a glassy, degasified material. A characteristic feature is the dull colour of the quartz and feldspar aggregates. Flattening of the fragments shows a progressive change towards the laminated type of rocks, and slight marginal extensions of the more elongated fragments may cut the matrix and are illustrative of typical welded tuffs or ignimbrites (fig. 32b).

Cryptocrystalline fragments with quartz and feldspar phenocrysts. These are similar in composition to the matrix but are distinguished by their lower content of small sericite flakes, and their consequent more uniform appearance.

(c) *Laminated pyroclastic types* develop from the fragmentary types as the components become more elongated and flattened (fig. 32c, d). The components which can be recognised are similar to those of the non-laminated types. The foliation which is thus developed is marked also by bands of recrystallisation of the quartz and feldspar matrix and by distinctly sericite-rich bands. Many of the larger quartz and feldspar grains are cracked, pulled apart and slightly rotated in the foliation. Some of the more coarsely crystalline bands cut across the foliation (fig. 32d) and show that the material became locally sufficiently fluid to intrude the more viscous parts.

Fig. 32c Laminated acid tuff with eutaxitic texture. Folding of the elongated fragments is Alpine. Scale is 2 mm.

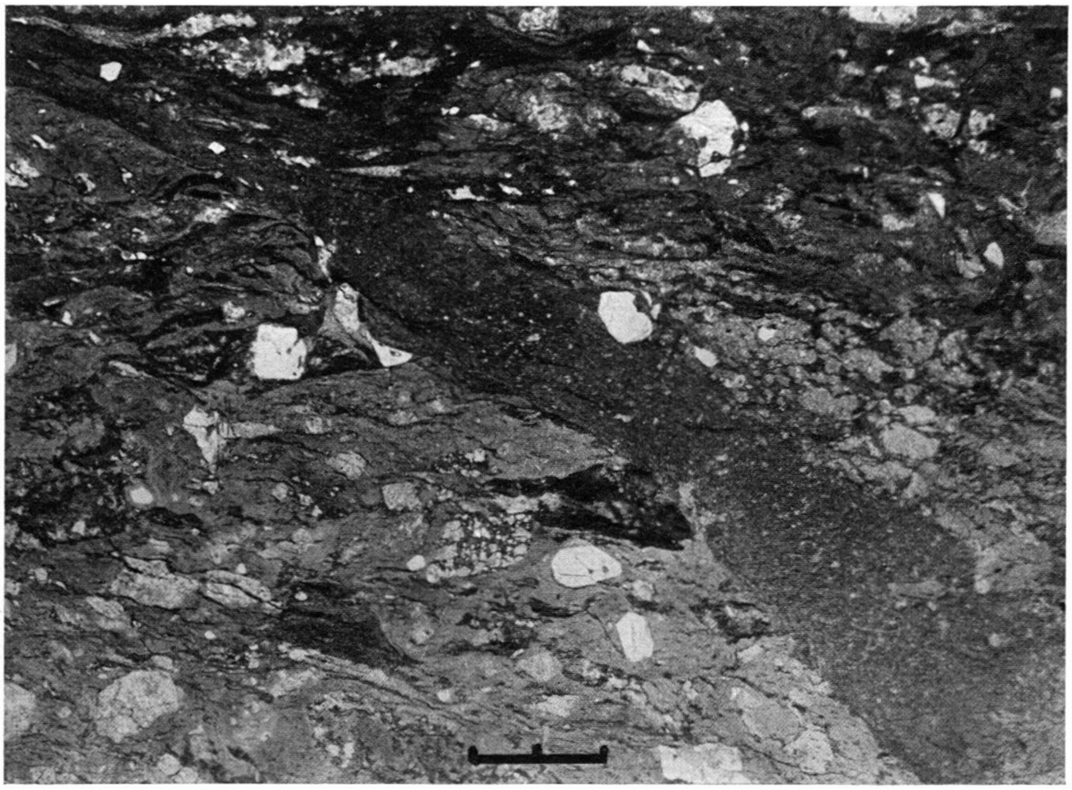


Fig. 32d Ignimbritic texture of rhyodacitic tuff: the elongated pyroclastic fragments are cut by partially remelted groundmass. Scale is 2 mm.

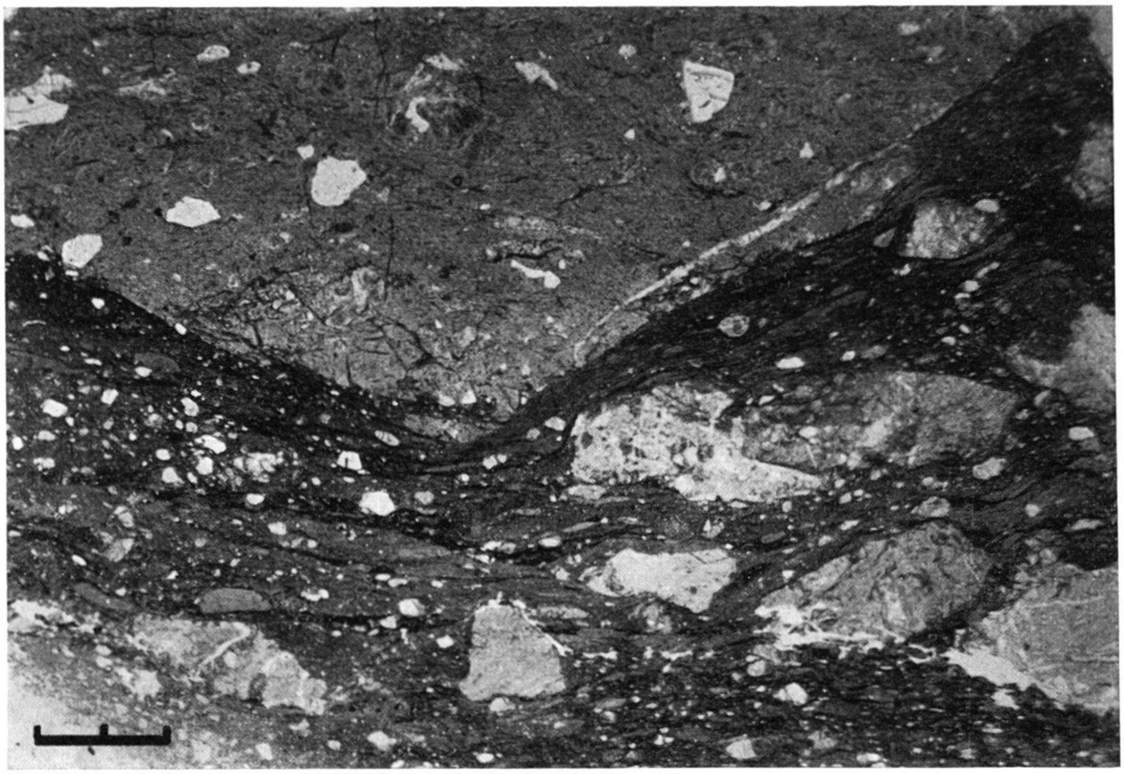


Fig. 32e Reworked pyroclastic rocks: the fragments are mainly vitric tuffs with recrystallised glass shards. Scale is 2 mm.

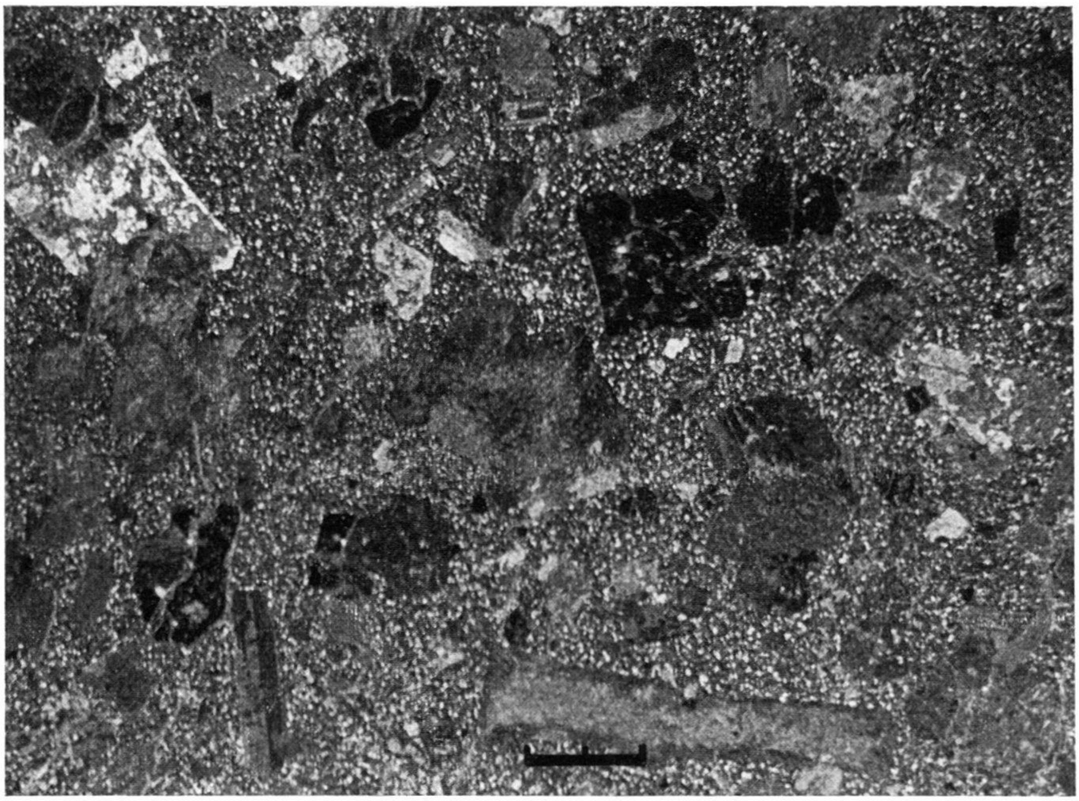


Fig. 32f Porphyritic micro-quartzdiorite from Klein Windgällen. Scale is 2 mm.

Folding and thickening and thinning of the laminae took place whilst the rock was in a plastic, semi-molten condition. Small-scale Alpine folds are superimposed on these structures and form clear kink bands in the sericite-rich layers. The streaky, foliated structure and its primary deformations are typical eutaxitic structures of ignimbritic deposits, and formed during the flowing of a superheated, partially reliquified acid tuff ejection.

Mixed Sedimentary Rocks (Fig. 32e)

These can be described rather briefly as they are made up entirely of fragments of rocks as described above. Most are massive types which show glass shards and comminuted glass which has been recrystallised to a cryptocrystalline matrix. Microcrystalline and fine-grained granular types do occur, but usually as smaller fragments. No foreign components have been observed. The size of the components is very diverse, and boulders up to 30 cm are seen in the field. Most are rounded in shape and deformed to oval outlines. The matrix is composed of fine-grained comminuted crystals, dark recrystallised glass and abundant sericite on the cleavage surfaces. Some of the darker parts of the matrix appear to be distinctly carbonaceous.

Porphyritic Microquartzdiorite (to Granodiorite)

The field occurrence of this rock is limited to the area of the Klein Windgällen. It includes types 1 and 2 of SCHMIDT's classification, and types which he named as granites and granophyres.

In hand specimens the rock is porphyritic hemicrystalline, with tabular euhedral plagioclase, sometimes light-red in colour, up to 8 mm in length, and green chloritic areas up to 2 mm set unoriented in a grey aphanatic groundmass. Thin sections (fig. 32f) show plagioclase ($An_{0\text{-}10}$) as euhedral or slightly rounded phenocrysts which compose about 30% of the rock. Rare and small, deeply embayed quartz grains (up to 0.7 mm) are present, but quartz is mainly restricted to the groundmass, and makes up, as accurately as can be estimated, about 10–20% of the rock. Euhedral pseudomorphs of sericite, chlorite and ores after biotite and hornblende reach 1 mm in size. The anhedral mosaic of the groundmass consists of quartz, feldspars, and small sericite (up to 0.1 mm) with zircon and ores as accessories.

The Metamorphism of the Windgällen Basement Rocks

The alteration products seen in all specimens are sericitic replacement of the feldspars, small irregular patches of epidote, and vaguely defined chloritic areas. Chlorite forming pseudomorphs after hornblende is very scarce in the acid tuffs, and plays the prominent role ascribed to it by SCHMIDT (1886) only in the microquartzdiorite. Ferromagnesian minerals are lacking in most of the acid tuffs, and only indistinctive shapes of very small amphibole or pyroxene grains (0.1 mm) replaced by epidote survive. In contrast to the rocks of Tscharren and the Witenalp areas, biotite is absent from the groundmass of these tuffs, and the secondary recrystallisation and granoblastic growth of new minerals is in general much less. This may be a result of the greater distance from the Central Aar granite, and strengthens the view that the Tscharren rocks have suffered only local contact metamorphism.

Discussion of the Windgällen Volcanics

The Windgällen volcanics, although in an overthrust position on the northern margin of the Aar Massif, still preserve very clear evidence of their pyroclastic origin. The pyroclastics are all silicic, and most are ignimbrites. Gradations between rocks with different degrees of welding are seen, but much of the original welded texture is masked by later recrystallisation and Alpine dislocation metamorphism (shearing). Varieties with undeformed glass shards were probably unwelded deposits, or the unwelded parts of ignimbrite flows. The types which are clearly welded are rhyolitic and rhyodacitic in composition and were formed in the central and lower parts of ignimbrite flows.

The original thickness of the volcanics cannot be estimated accurately, but was probably of the order of 400–500 m. This was formed by repeated eruptions, separated by short periods of erosion and reworking of the surface parts of the flows. The predominance of types containing undeformed glass shards in the conglomerates suggests that they were derived from the upper unwelded parts of ignimbrites. Periods of erosion were probably of so short duration that the lower welded parts of the flows were rarely attacked; rocks from the older basement are not found in the reworked beds. The black carbonaceous slates were probably formed as muds in shallow depressions, but their small exposures suggest that these were of very restricted extent.

The microquartzdiorite which is found north of the Klein Windgällen is not related directly to the acid pyroclastic flows, and is interpreted as a later intrusion. How deep the intrusion lay cannot be determined, but it is probable that it belongs to the subvolcanic apparatus of a later rhyodacitic volcanic episode.

In comparison to the volcanics south of the Maderanertal, the Windgällen pyroclastics are monotonous and more extensive. The uniform thickness of ignimbritic rocks distinguished the Windgällen rocks from those of the other areas; they contain neither the crystal and lithic tuffs that characterise the upper part of the Tscharren Formation nor the well-bedded tuffs and reworked ignimbrites of its lower part. They differ from the Witenalp rocks by their lack of interbedded lithic tuffs between the ignimbrites and the lack of flow-banded rhyolites. The Rossbodenstock and more westerly volcanics are of uniform silicic types, but contain more abundant conglomerates of reworked ignimbrite components than the Windgällen rocks.

The variations in the volcanic rocks which are seen in the area between the Windgällen in the north and the Rossbodenstock in the south may reflect slight age differences and changing volcanic activity. This, however, probably cannot explain all the differences in this rather small area, and part of the variations may be geographical changes in the lithology of a single pyroclastic unit, depending on the distance from the explosive centre. The Tscharren Formation shows that a major ignimbritic period preceded a more gentle and less acid (moderately silicic) volcanic pyroclastic period. The earlier explosive phase was probably responsible for the Windgällen rocks, the lower Tscharren Formation and the Witenalp-Rossbodenstock volcanics. The later phase, more andesitic to dacitic in character, formed the tuffs of the upper Tscharren Formation, and may have been related to the intrusion of the microquartzdiorite in the Windgällen area. A possible reconstruction of the volcanic sections of the Maderanertal is shown in fig. 33.

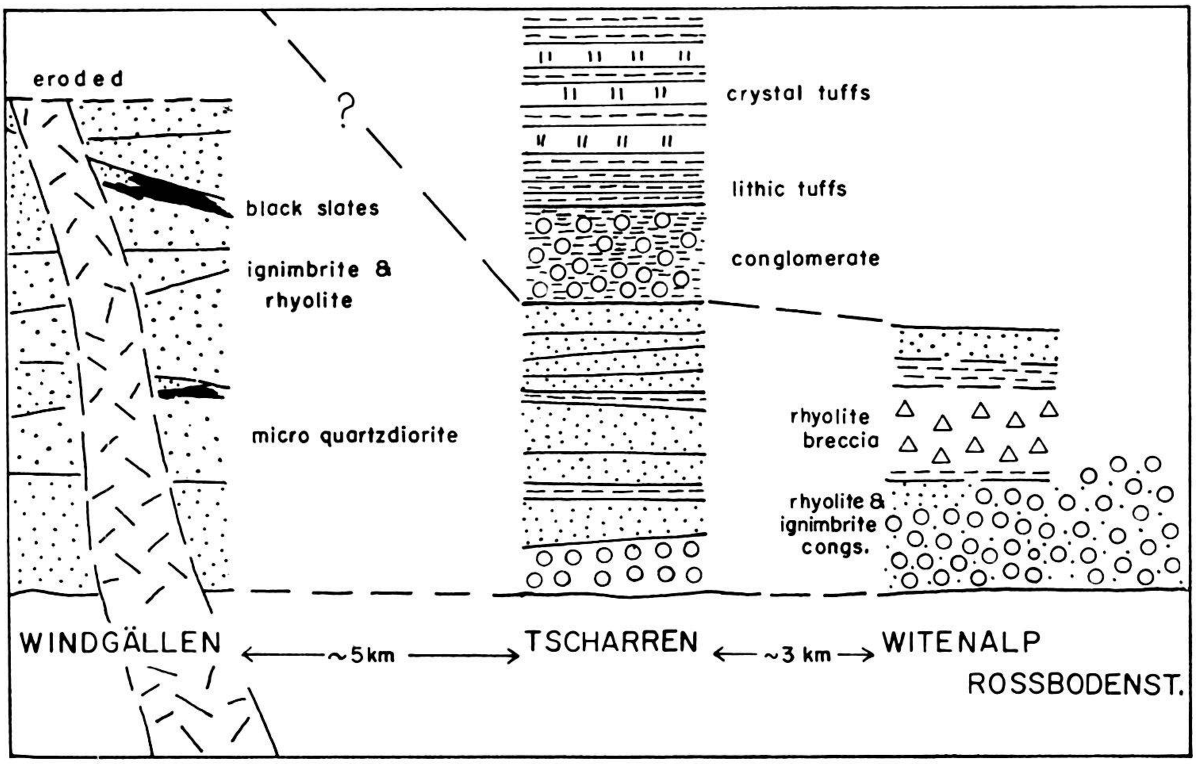


Fig. 33 Reconstruction of the volcanic sections of the Maderanertal.

The extrusion centre of the volcanics must have lain very close to the Maderanertal. There may have been several vents, but none has been observed in the crystalline basement rocks; it is possible that some lay to the north under the cover of Mesozoic rocks, but we rather suspect that the location of the Central Aar granite of Oberalpstock, intruded later than the volcanic episode, may give some indication of the position of the principal magmatic upsurge of both volcanic and later granite-intrusion episodes.

STRUCTURES OF THE UPPER PALEOZOIC ROCKS OF THE MADERANERTAL

The Area of Volcanic Sediments South of the Maderanertal

Alpine structures are dominant in the Maderanertal. The principal structure in the basement rocks is a strong foliation which strikes ENE–WSW and which is especially well developed in certain zones. The Maderanertal itself follows one such zone, and exposures in the soft phyllonitic rocks of the valley floor are not numerous. The strong zone of deformation along the valley floor and on the lower slopes of the southern valley side is the root zone of the recumbent fold of the Windgällen in the north. The cleavage of the basement rocks is shown in the stereograms in fig. 34. Towards the southern margin of the Aar Massif the dip of the cleavage becomes steeper, and as pointed out by HUBER (1947) forms a slight fan structure.

Mapping of the sediments and volcanics of Tscharren (Scharren of the new Landeskarte) reveals a poorly preserved anticlinal structure with an overturned limb resting on a sheared zone, and a partly preserved southern normal limb which is cut

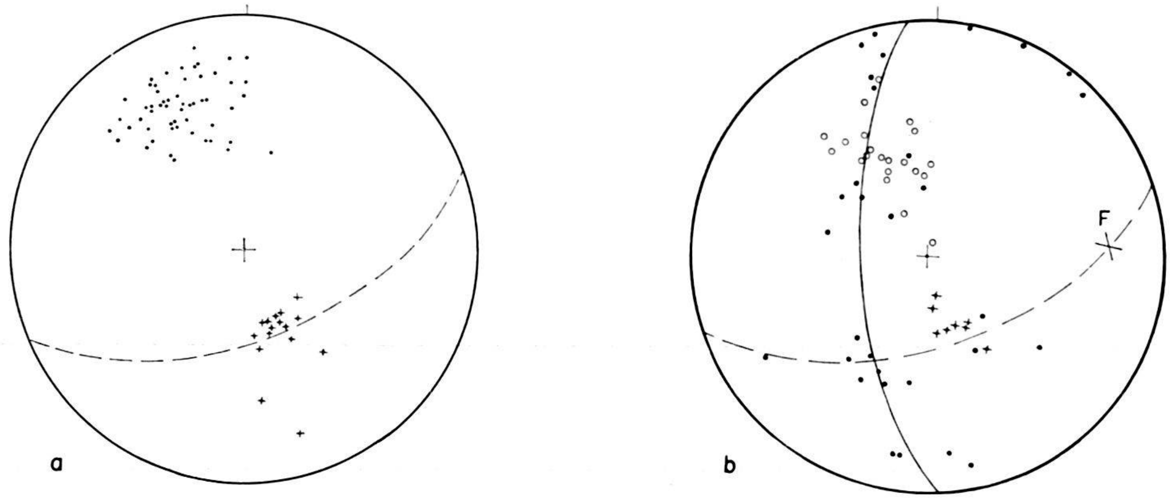


Fig. 34 Stereograms of structural measurements from the Upper Palaeozoic rocks of the Maderanertal:
a) cleavage (•) and elongation direction (+) in the Tscharren Formation: great circle is the general cleavage surface.
b) poles to first cleavage (•), poles to second cleavage (o) and elongation direction from the rocks of the core of the Windgällen fold. Full great circle-plane of poles of the folded early cleavage: dashed great circle-general surface of second cleavage. F = constructed fold axis.

off abruptly by the contact to the granite (fig. 25). The fold structure is not well enough exposed to allow a detailed description of its geometry; the crest of the fold is exposed north of the granite contact on east Tscharren, where sedimentary structures indicate the way-up of the beds. The fold axis is roughly horizontal and strikes ENE. The cleavage lies in the axial plane of the fold and dips less steeply than the bedding through most of the section of the southern slopes of Tscharren.

The Tscharren fold cannot be extended to the west; the volcanics of Witenalp and Rossbodenstock show bedding which maintains a constant dip almost parallel to the cleavage. The ignimbrite beds of Witenalp seem to be inverted, and most of this area may correspond to the inverted limb of a fold comparable to that of Tscharren.

Lapilli and components of the volcanic conglomerates and tuffs are strongly elongated in the cleavage, and measurements show a shortening of about 50% perpendicular to the cleavage, assuming no volume change (fig. 35). This requires that the thickness of the measured sections be increased by up to one half, as bedding and cleavage are roughly parallel through most of the section.

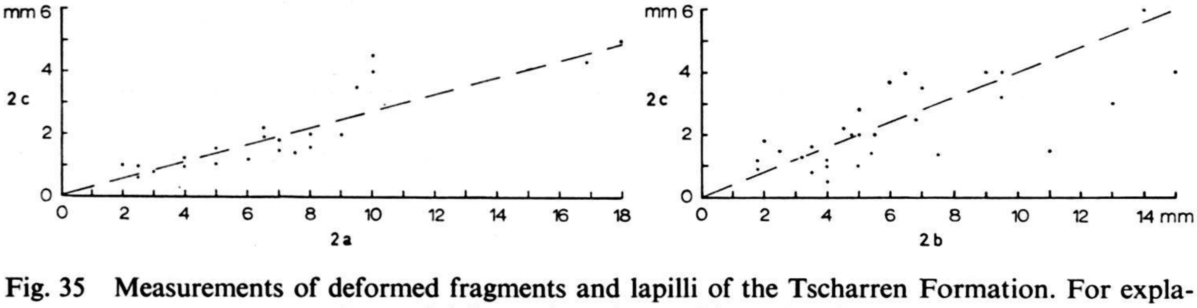


Fig. 35 Measurements of deformed fragments and lapilli of the Tscharren Formation. For explanation and deformation plot see Figs. 16 and 17.

The older rocks that formed the foundations of the volcanic rocks have suffered intense deformation in the areas of infolding of the younger sediments. A sheared wedge of gneiss is seen south of Sellenen in the northern sheared zone of the volcanics. Farther away from the strongly sheared belts, towards the east and north, the rocks are typical Altkristallin gneisses of the northern zone of the Aar Massif, with prominent banding and basic and ultrabasic lenses. Petrographical descriptions of the northern gneisses are given by PFLUGSHAUPT (1927) and SIGRIST (1947). Gneisses south of the volcanic belt which must also be considered as part of the basement of the volcanics are those of the Piz Giuf area, described by WEBER (1904) and HUBER (1947); these rocks, however, are separated from the volcanics by an important structural break and belong to the southern igneous complex of the Aar Massif.

The Contact of the Volcanics with the Granite

Between Staldenfirn in the east and the southern part of the Etzlital in the west, over a distance of 6 km, the northern contact of the Central Aar granite is a planar structure with a strike of N 55°–60° E and a southerly dip of about 60°. The outcrop of volcanics immediately to the north follows the same trend, and their contact with the gneisses in the north runs roughly parallel to the granite contact. The Alpine structures strike more nearly E–W (N 70°–85° E), and the strong zones of deformation on the southern slopes of the Maderanertal, which cut the granites and volcanics north-east of Tscharren, reduce the width of the volcanic outcrops and disturb the contact with the granite.

Contacts of the granite with the volcanics that show no tectonic disturbances are rare; the section exposed on the saddle of Tscharren ridge is the most instructive, although it shows an abnormally flat dip because of surface creep. The granite here develops a very clear porphyritic marginal facies of about 3 m in width, south of which a normal coarse-grained biotite granite is exposed.

The porphyritic marginal facies of the granite, described also by SIGRIST (1947), is the best evidence for the intrusive contact of the Central Aar granite of this area. In hand specimens, large porphyritic feldspars and quartz are seen in a dense matrix. The rock is not normally strongly sheared, and shows little effect of cataclasis, thus excluding a blastomylonitic origin. In thin sections the large orthoclase are slightly rounded, and often show fresh margins and irregularly outlined cores of microcline with polysynthetic twinning. Quartz forms rounded and embayed grains which always show strained extinction but little fracturing; plagioclase is less abundant. The matrix of the rock is a microcrystalline aggregate of quartz, feldspar and biotite; the greenish biotite may form some areas of about 1.5 mm consisting of small irregularly oriented flakes (ca. 0.1 mm). Some rounded areas of coarser granite are present, and were probably parts which became crystalline before final emplacement of the granite.

At a distance of 3 to 4 m from the margin, the granite is coarse-grained holocrystalline with frequently zoned orthoclase crystals, less abundant plagioclase and interstitial equidimensional quartz. Biotite is abundant, but forms only small green flakes up to 0.1 mm associated with chlorite, as it does in the matrix of the marginal facies; the appearance of the biotite – its size, colour and mode of occurrence – is very similar to the biotite in the matrix of the recrystallised tuffs of the Tscharren

Formation. It is possible that the mode of occurrence of the biotite, and the lack of larger crystals, is an effect of its late crystallisation, or recrystallisation during a late magmatic stage. Large euhedral orthite (allanite) crystals up to 0.5 mm are common, and are normally somewhat altered to epidote. Further descriptions and chemical analyses of the granites are given by SIGRIST (1947) and HUBER (1949).

Other contacts of the granite to the volcanics are more strongly sheared, and frequently show a less clear porphyritic marginal facies. The contact seen in the Etzlital is marked by a 2 mm broad mylonite zone with strongly phyllonitic rocks.

A body of porphyritic microgranite that is petrographically comparable to the marginal facies of Tscharren extends from Stöckli, NW of Oberalpstock in the east, where it merges into the main granite, to the Etzlital in the west. It separates the volcanics of the Tscharren Formation from those of the Witenalp, and is interpreted as a marginal subsidiary intrusion of the granite. Its contacts with both the main granite and the volcanics are, however, sheared.

The contact of the granite with volcanics which is exposed in the area south of the Maderanertal is of greatest importance, as this is the only area of the Aar Massif in which the Central Aar granite comes in contact with a clear stratigraphical section of Upper Paleozoic rocks. It is an unusual contact in many respects. Its lack of small apophyses and cross-cutting pegmatites, its planar shape, the lack of xenoliths of country rock in the granite and the absence of pneumatolitic and hydrothermal activity on a large scale are features which are readily apprehended. Regional characteristics of the granite are discussed by E. HUGI (1934).

The metamorphism of the adjacent rocks has produced biotite, epidote, chorite and albite. The local orientation of the biotite indicates that the rise in temperature caused by the granite was accompanied by stress (fig. 55). A possible explanation of the features of the contact zone is that the granite was emplaced along a fault zone as a rather dry, low-temperature magma which cooled quickly during its uplift. HUTTENLOCHER (1947) suggested that the emplacement took place at a very shallow depth. The stresses evoked during the granite emplacement caused the folding of the volcanics and accentuated the planar surface of the granite contact.

The Mont Blanc granite, which is thought to be comparable in age to the Central Aar granite, shows a strongly tectonised contact on its NW border along a fault zone parallel to the Alpine Chamonix syncline (OULIANOFF 1965). This is comparable to the strongly sheared zones of the Maderanertal, but the undisturbed contacts of the Mont Blanc granite (the "protogine") show greater metamorphic effects and resorption of country rock than the eastern Aar Massif granites (CORBIN & OULIANOFF 1926).

The Area of Volcanics North of the Maderanertal

North of the Maderanertal the basement volcanics lie in the core of the Windgällen recumbent anticline and are part of a parautochtonous unit resting on Mesozoic and Tertiary sediments. A connection with the phyllonitic basement rocks of one of the strongly deformed zones of the southern slopes of the Maderanertal is seen at the eastern end of the fold in the Hüfifirn area. The dark-coloured sediments which have been described as Carboniferous occur near the centre of the parautochtonous body amongst light-coloured acid tuffs. The tectonic structure and alteration of these rocks is largely Alpine; no definitely earlier structures have been observed other than a weakly developed bedding in some tufaceous conglomerates.

Two distinct cleavages are present in the basement rocks; the earlier one dips generally to the south at a low angle and is concentrated especially near the inverted limb of the fold. The second cleavage dips steeply to the south-east and lies in the axial planes of minor folds; it is especially well developed east of the Untere Furggeli, immediately north of a larger fold (100 m amplitude) which probably belongs to the same deformation phase (see stereograms, fig. 34).

The tectonic history of these basement rocks during the Alpine folding appears to have been (1) lateral transport of part of the Aar Massif as the core of the Windgällen recumbent fold, and (2) folding about steeply south-dipping axial planes. This corresponds to the structural development seen in the Mesozoic rocks of the N. Tödi area. The repeated deformations of the autochtonous massif produced movements on the same steeply south-dipping cleavage and gave no individual interfering structures.

CONCLUSIONS

The studies of the Tödi and Maderanertal areas show that the Upper Paleozoic formations contain a well-developed and varied volcanic suite of silicic to moderately silicic rocks which stretches for a distance of at least 20 km in an E–W direction. The estuarine and lacustrine beds that are seen in the eastern exposures were presumably laid down in small inland basins which formed in local areas of subsidence. Heavy rainfalls caused the rapid erosion of the volcanics and permitted the growth of a rich vegetation around the basins. Vegetation probably covered the greater part of the area and gave rise to the local carbonaceous beds found in the Maderanertal as well as to the thin anthracites of the NE Tödi area.

The older rocks below the volcanics formed a land surface during the early volcanic episode and had delivered components to the basal conglomerates of the Biferten inlier. During the main volcanic episode, lavas, lava débris, tuffs and explosive breccias formed an extensive blanket over the older rocks so that pebbles of gneisses, hornfelses and granites are not abundant; they are seen in the volcanics of the Klein Tödi and in one bed on W. Tscharren. In the Bifertengrätli Formation of the NE Tödi area the older rocks are again found as components in the Estuarine Member, as by this time rivers had worn through the volcanic blanket into the older rocks. Even during this period, however, volcanic explosions gave rise to crystal tuffs.

The acid volcanics of the Maderanertal area originated during violently explosive activity which is thought to be roughly coeval with the explosions of Klein Tödi and the Biferten inlier. The acid explosions gave rise to extensive ignimbritic flows which became rapidly eroded in more exposed areas. Crystal tuffs of more intermediate composition in the upper part of the Tscharren Formation support the correlation with the volcanic activity of the Bifertengrätli Formation, but no plants have been found in the former succession to make this correlation certain.

THE EXTENSION OF THE TÖDI-MADERANERTAL ZONE

The direct continuation of the Tödi-Windgällen-Bristenstäfeli zone of Upper Carboniferous formations to the west crosses the Reuss valley at Intschi and extends to the Sustenpass area, where it appears to enter the basement rocks below the Färnigen syncline (ALB. & ARN. HEIM 1916; MORGENTHALER 1920). Farther west this belt forms the so-called zone of envelope-schists of the Central Aar granite (E. HUGI 1934) which extends into the Lötschental and continues along the root zone of the Morcles nappe. Many of the rocks of this schist belt are older paragneisses with a complex history of intrusion of basic and acid rocks (LEDERMANN 1946), and hornfelses of possible Paleozoic age (MORGENTHALER 1920).

A narrow belt containing probable Carboniferous sediments is seen in the northern part of the central Aar Massif between the Gastern-Innertkirchen granites and the Erstfeld granite zone: this forms the frequently mentioned exposures of the Wendenjoch (HUEGGLY 1927; KOENIGSBERGER 1926; TH. HÜGI 1947, 1956) and was encountered in the Lötschberg tunnel (BRUECKNER 1943).

After a gap of some 50 km, dated Upper Carboniferous rocks reappear in the Salvan-Dorénaz syncline of the Aiguilles-Rouges Massif. The most marked contrasts of these sediments with those of the eastern Aar Massif are the predominance of locally derived older gneisses and granites in the conglomerates and the fact that they pass upwards into purple-coloured beds of supposed Permian age (OULIANOFF 1924; SUBLET 1962). Contemporaneous volcanic activity has not been described from the northern Aiguilles-Rouges Carboniferous (LAURENT 1965), although SUBLET (1962) describes rhyolites and quartz diorites from the Upper Carboniferous conglomerates which may indicate earlier volcanic activity. The lack of typical Mt-Blanc granites ("protogine") from these conglomerates is a suggestion of the post-Upper Carboniferous age of this granite, which may thus be of the same age as the similar Central Aar granite.

The Upper Paleozoic rocks of the Tödi-Maderanertal belt along the northern border of the eastern Aar Massif are the northernmost dated pre-Triassic sediments of the autochtonous units of the western Alps. To the south, Upper Paleozoic rocks are known from the internal areas of the Alps, but these lie in more complicated structural positions. The numerous and isolated outcrops of Upper Carboniferous sediments of the Swiss Alpine region are reviewed by RITTER (in JONGMANS 1960), and many further references are to be found in that work. The review of RITTER and a summary of the Verrucano (Permian) question by TRÜMPY (1966) make it clear that it is impossible to establish any detailed stratigraphical correlations between the widespread areas. The striking fact which emerges from the literature on the Upper Carboniferous and Permian sediments of the western, central, southern, and parts of the eastern Alpine regions is that during the whole of the later part of the Upper Paleozoic, continental conditions ruled over a large tract which was then to subside during the Mesozoic into a complicated geosynclinal area. Volcanic activity was widespread during the Upper Paleozoic, and to discuss the history and paleogeography one will have to clearly analyse the volcanic activity of the area which extends from the Massif Central (LETOURNER 1952), the French external massifs (LAMEYRE 1957, 1958; SARROT-REYNAULD 1964; TERMIER 1894; TOBI 1958, 1959), the Briançonnais area

(DEBELMAS et al. 1964), the Pennine nappes (SCHAER 1959), the Helvetic root zone (NIGGLI 1944) and the eastern Helvetic nappes (AMSTUTZ 1954) and into large areas of the southern Alps. At the moment only vague correlations invoking the use of hypothetical ancient structural lines are possible (STAUB 1956; TRÜMPY 1966).

VAL GLIEMS

The exposures of undated pre-Triassic sediments closest to the Biferten area lie directly south of Tödi in Val Gliems, near the eastern end of the Aar Massif. Metamorphic sediments from this area were described by EUGSTER (1951) as equivalents of the Bifertengrätli Formation; the metamorphic conglomerates of Val Gliems were correlated with the coarse breccias of WIDMER's Grünhorn Formation. The area was restudied to verify this correlation, but with negative results. Further results of this study will be published elsewhere (FRANKS 1968).

The rocks that make up Val Gliems and its extension to the west are metamorphic conglomerates, knotenschiefer and hornfelses with thin calc-silicate layers which form a distinct stratigraphical sequence. This sequence cannot be correlated with the Bifertengrätli Formation or any of the volcanic formations on the nothern border of the Aar Massif. Its older age is indicated by components of similar rock types in the conglomerates of the Bifertengrätli Formation. A Paleozoic age (possibly Lower Carboniferous) is probable for these sediments because of local graphitic horizons, the calc-silicate layers and the massive marbles that are found as components in the conglomerates. On the basis of the structural and metamorphic development of these rocks, we may assume that they were folded and metamorphosed at the same time as the Bifertenfirn metasediments; their higher grade of metamorphism is thought to be due to their proximity to the pre-Westphalian intrusive body (within the southern igneous complex of the Aar Massif?). The Bifertenfirn metasediments and the Val Gliems formations thus comprise, as proposed by WEBER (in HEIM 1922), a sequence of older "Carboniferous" sediments which are separated by a stratigraphical, structural and metamorphic break from the dated Upper Westphalian and Stephanian formations.

GENERAL AGE RELATIONSHIPS

The older rocks on which the Upper Paleozoic sediments were laid down consist in the eastern Aar Massif of two major units, (1) an older complex of gneisses, and (2) a younger series of metasediments (the Bifertenfirn and Val Gliems metasediments) and intrusives. The suggested relationships of the various areas are shown in fig. 65.

Age dating of rocks of the Aar Massif has not yet provided sufficient data to clarify the magmatic and metamorphic history that preceded the Upper Carboniferous sediments. Dates from the Aar Massif are concentrated in the Central Aar granite, and little is available for the older rocks. The late Hercynian age of the Central Aar granite, seen in the field to intrude the volcanics of the Tscharren Formation, is well established; the lead isotope ages (PASTEELS 1964) tend to give a slightly older average age – 230 to 300 million years – than the Rb/Sr ages of between 190 ± 21 and 250 ± 22 million years (JAEGER 1962; JAEGER & FAUL 1962; WÜTHRICH 1963, 1965).

The older history is not reflected in the dates available at present, but significance may be attached to the slightly older Rb/Sr dates from pegmatites in the Tödi granite (312 ± 12), the Etzlital (287 ± 12) and Lötschental (309 ± 30), from the Erstfeld gneiss (298 ± 12; 305 ± 12) and from the Gastern granite (271 ± 19). WÜTHRICH (1965) suggested that these slightly older dates may result from a "re-juvenation" of older minerals by heating just before the intrusion of the Central Aar granite; he rejects the possibility of distinguishing more than one orogenic phase.

The top of the Stephanian is generally accepted as ca. 280 million years (KULP 1961; SMITH 1964), but the base of the Stephanian and Westphalian stages are less well defined. FAUL & JAEGER (1963) suggest a revised age of 300 million years for the base of the Stephanian, but a somewhat younger age is more generally accepted (FRANCIS & WOODLAND 1964); an age of 300 million years would probably lie near the Namurian-Westphalian boundary. If this is correct, and if the ages of around 300 million years are significantly older than the ages of the Central Aar granite, the main Hercynian movements, metamorphism and intrusion took place after the Lower Carboniferous and before the Stephanian. The Central Aar granites would thus be unrelated to this episode, having intruded at a later date in the upper Stephanian or Permian. The Devonian and the lower part of the Carboniferous (Tournaisian to

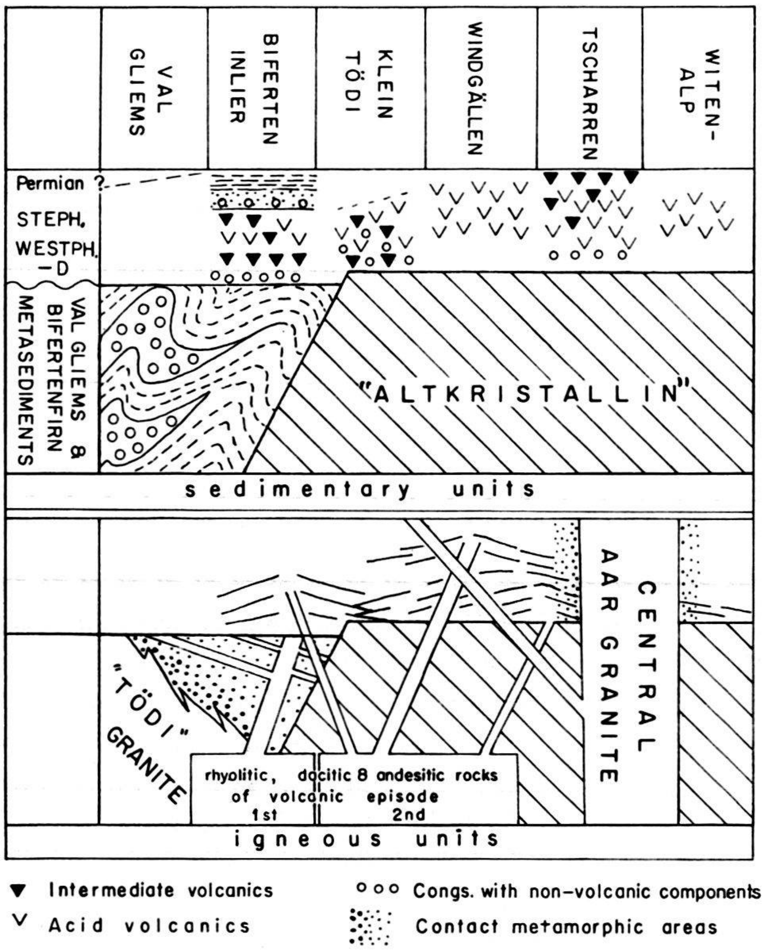


Fig. 36 Schematic reconstruction of the sedimentary and magmatic history of the eastern Aar Massif.

Namurian?) are open as a possible age for the Bifertenfirn and Val Gliems metasediments, but of course, a still older age cannot be excluded.

The pre-Westphalian-D movements and intrusions that are seen in the eastern Aar Massif are equivalent to the Segalunian phase of LUGEON (1911) in the western Alps, a term which is preferable to that of Asturian (STILLE 1924), as the former is imprecisely defined whilst the latter was intended by STILLE to mark a brief, sharply defined folding episode. The movements which preceded the deposition of the volcanic sediments of the eastern Aar Massif may prove to be the equivalent of the main Hercynian orogeny of this area.

ZUSAMMENFASSUNG

Die Zone der oberkarbonischen Sedimente, welche sich über eine Distanz von etwa 40 km vom Tödi im Osten zum Bristenstäfeli im Westen erstreckt, enthält eine Vielfalt an vulkanischen Gesteinen und damit assoziierten Sedimenten. Stratigraphie und Struktur dieser sedimentären und vulkanosedimentären Einheiten wurden einer Neuüberprüfung unterzogen, aus welcher eine Revision der Stratigraphie hervorgegangen ist. Folgende drei Gebiete stehen zur Diskussion:

1) Der NE-Abfall des Tödi,
2) Der Klein-Tödi,
3) Das Maderanertal.

Einzig der nordöstliche Tödi weist eine gut datierte Gesteinsfolge auf; die beiden westlicheren Gebiete wurden nur auf Grund ihrer Lithologie mit ersterem korreliert und damit als gleichaltrig angenommen.

Im NE-Tödi-Gebiet konnte nun eindeutig bestätigt werden, dass das Westphal-D und Stephan diskordant auf dem Tödigranit und älteren Hornfelsen liegt. Die Annahme WIDMERS (1949), wonach die Hornfelse ein metamorphosiertes Oberkarbon darstellen, musste aufgegeben und die frühere Auffassung WEBERS (1922) und HÜGIS (1941) gutgeheissen werden. Die Prä-Oberkarbon-Hornfelse zeigen eine leichte Kontaktmetamorphose (Albit-Epidot-Hornfels-Fazies erstreckt sich über den grössten Teil des Gebietes). Die Metamorphose wird als vom Tödigranit ausgehende Kontaktmetamorphose gedeutet. Die zahlreichen mikrogranodioritischen und mikroquarzdioritischen Lagergänge, die den gefalteten Hornfels durchschneiden, sind postmetamorphe Intrusionen, welche wohl viel eher mit einer späteren vulkanischen Tätigkeit als mit dem Tödigranit im Zusammenhang stehen.

Die aus oberkarbonischen Sedimenten bestehende *Bifertengrätli-Serie* besitzt lokal entwickelte Basiskonglomerate und -breccien aus Hornfels-, Granit- und Quarzitkomponenten. Es folgt ein rascher Übergang in vulkanische Breccien und Tuffe der unteren Abteilung, das «Volcanic Member». Diese klastische und pyroklastische Einheit wurde von WIDMER «Grünhorn-Serie» benannt und als jüngstes Glied aufgefasst; der Name «Grünhorn-Serie» soll aber nicht mehr verwendet werden. Die zwei oberen Abteilungen deuten auf die allmähliche Absenkung eines Beckens: Das «Estuarine Member» enthält kreuzgeschichtete Sandsteine und Arkosen, ferner Konglomerate mit sowohl älteren granitischen als auch vulkanischen Komponenten. Aus diesen Schichten stammen zudem die Pflanzenreste und die

Anthrazitlagen. Ein vollständiges Vorherrschen der aquatischen Sedimentation in einem limnischen Becken, wobei auch Kristalltuffe zur Ablagerung gelangten, kennzeichnet die oberste Abteilung, das «Lacustrine Member».

Poststephanisch-prätriasische Bewegungen setzen die Oberkarbonsedimente längs einer E–W verlaufenden wichtigen Bruchzone in die Tiefe, welche sowohl zu den präalpinen als auch zu den alpinen Faltenachsen schief verläuft. Die Faltung der Sedimente, die auch die älteren Hornfelse beeinflusste, verursachte eine nach Norden gerichtete Falte, wobei die interne Deformation der Gesteine vorwiegend im senkrechten bis überkippten Verkehrschenkel lokalisiert ist.

Das Klein-Tödi-Gebiet zeigt ein weniger umfangreiches Profil. Da aber Lapilli, Tuffe und grobvulkanische Breccien vorhanden sind, bildet es ein wichtiges Bindeglied zum westlichen Gebiet des Maderanertals. Die Breccien führen meist eine dunkle Grundmasse und scheinen in Verwandtschaft mit der Bifertengrätli-Serie zu stehen. Rhyolith-, Tuff- und Ignimbrit-Komponenten in den Breccien weisen auf saure, die Zusammensetzung der Lapilli und anderer Fragmente der Breccien auf eine etwas mehr intermediäre vulkanische Tätigkeit. Gneis- und Hornfels-Komponenten der Breccien stammen von benachbarten älteren Gesteinen. Diese Vulkanite sind sehr deutlich durchsetzt von drei Mikrogranit-Gängen, welche vielleicht mit den späten Intrusionen des zentralen Aaregranits zusammenhängen.

Die oberpaläozoischen Vulkanite des Maderanertales liegen im Norden, im Kern der Windgällenfalte; der grössere Teil befindet sich im Süden, in einer Zone vom Tscharren bis zum Spillauiseeli im oberen Etzlital. Diese zwei Gebiete sind durch die stark deformierte Wurzelzone der Windgällenfalte und das Maderanertal getrennt, doch bilden die Vulkanite ein solch einheitliches Bild von rhyolithischen und vor allem ignimbritischen Ergüssen, dass von einem vulkanischen Zentrum gesprochen chen werden kann.

Die Serie des Tscharren enthält im untersten Teil des Profils ignimbritische Glieder, die über Konglomerate zu einer weniger sauren, tuffogenen Abfolge überleiten. Das Profil liegt grossenteils verkehrt und wird abgeschnitten durch den Kontakt zum zentralen Aaregranit. Eine schwache Metamorphose dieser tuffogenen Schichten (Biotit-Chlorit) in der Nähe des Granitkontaktes stammt von einer Kontaktmetamorphose während der Faltung der Sedimente und der gleichzeitigen Intrusion des Granits, welcher jünger ist als die Tscharren-Windgällen-Vulkanite. Dieselbe Zone enthält an der Witenalp sowohl Rhyolith-Breccien als auch ignimbritische Teile, die gegen SW vorwiegend in Breccien und saure Agglomerate übergehen. Die Gesteine im Norden, die sog. Quarzporphyre, im Kern der Windgällenfalte sind mehrheitlich pyroklastischer und ignimbritischer Natur, und die verschiedenen Stadien des Schmelzvorganges sind teilweise erhalten geblieben. Im Gegensatz zu diesen Gesteinen der Rhyolithfamilie lässt der Mikroquarzdiorit (Granit von C. SCHMIDT 1886) der kleinen Windgälle auf eine späte subvulkanische Intrusion schliessen. Die Tektonik dieses Gebietes ist durch die alpine Dislokation – Nordbewegung und sekundäre Faltung – beherrscht, doch ist die Gesteinsdeformation so inhomogen und teilweise so schwach, dass man noch kaum deformierte pyroklastische Anteile erkennt.

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