# The NE Tödi area

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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

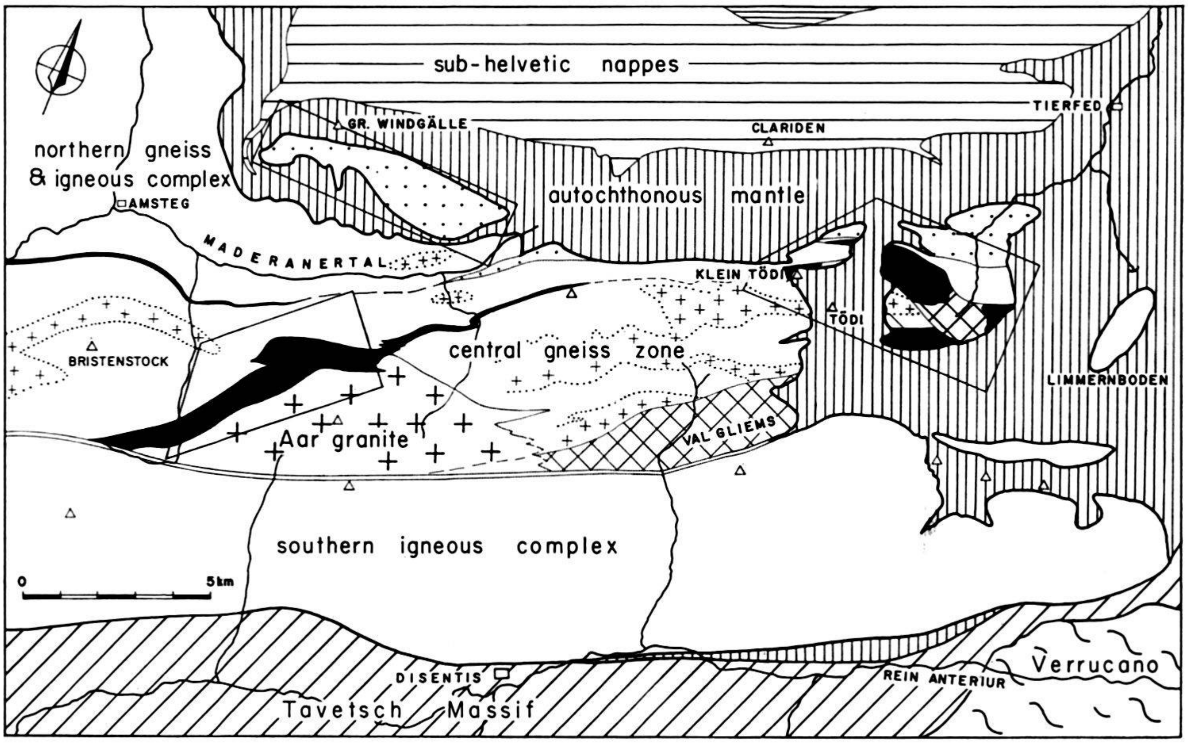

Fig. 1 Locality map of the pre-Triassic sediments of the eastern Aar Massif: black, areas of Upper Carboniferous sediments and volcanics; dots, Windgällen volcanics; cross-hatching, pre-Upper Carboniferous (Lower Palaeozoic?) sediments. Described areas outlined.

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

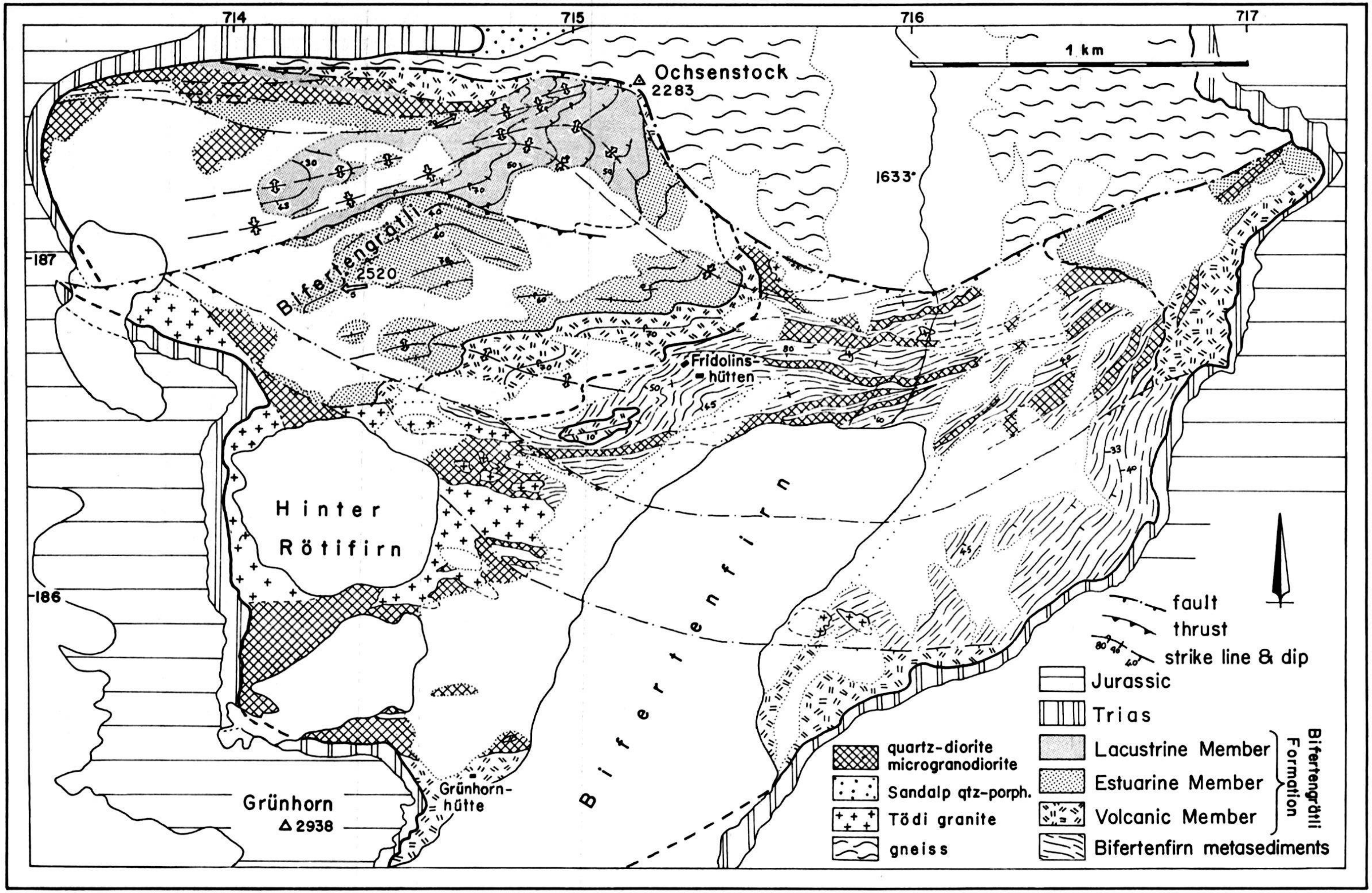

Fig. 2 Geological Map of the southern part of the Biferten inlier.

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.

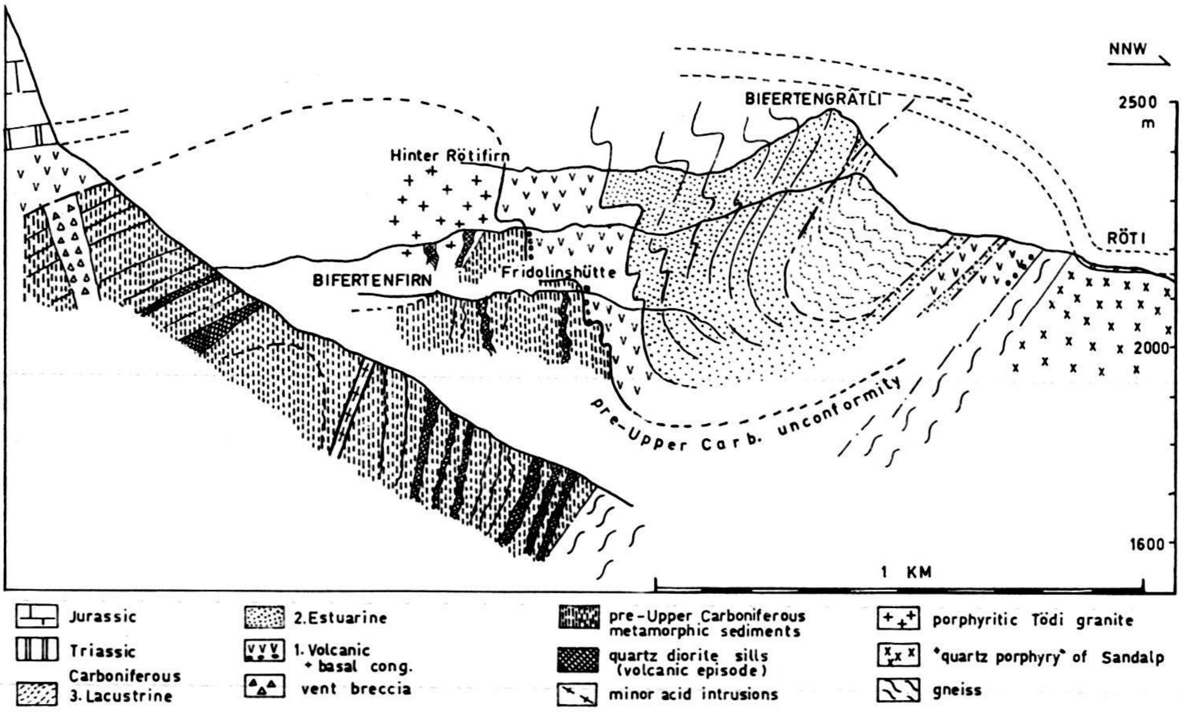

Fig. 3 Simplified section through the pre-Triassic sediments of the Biferten inlier.

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

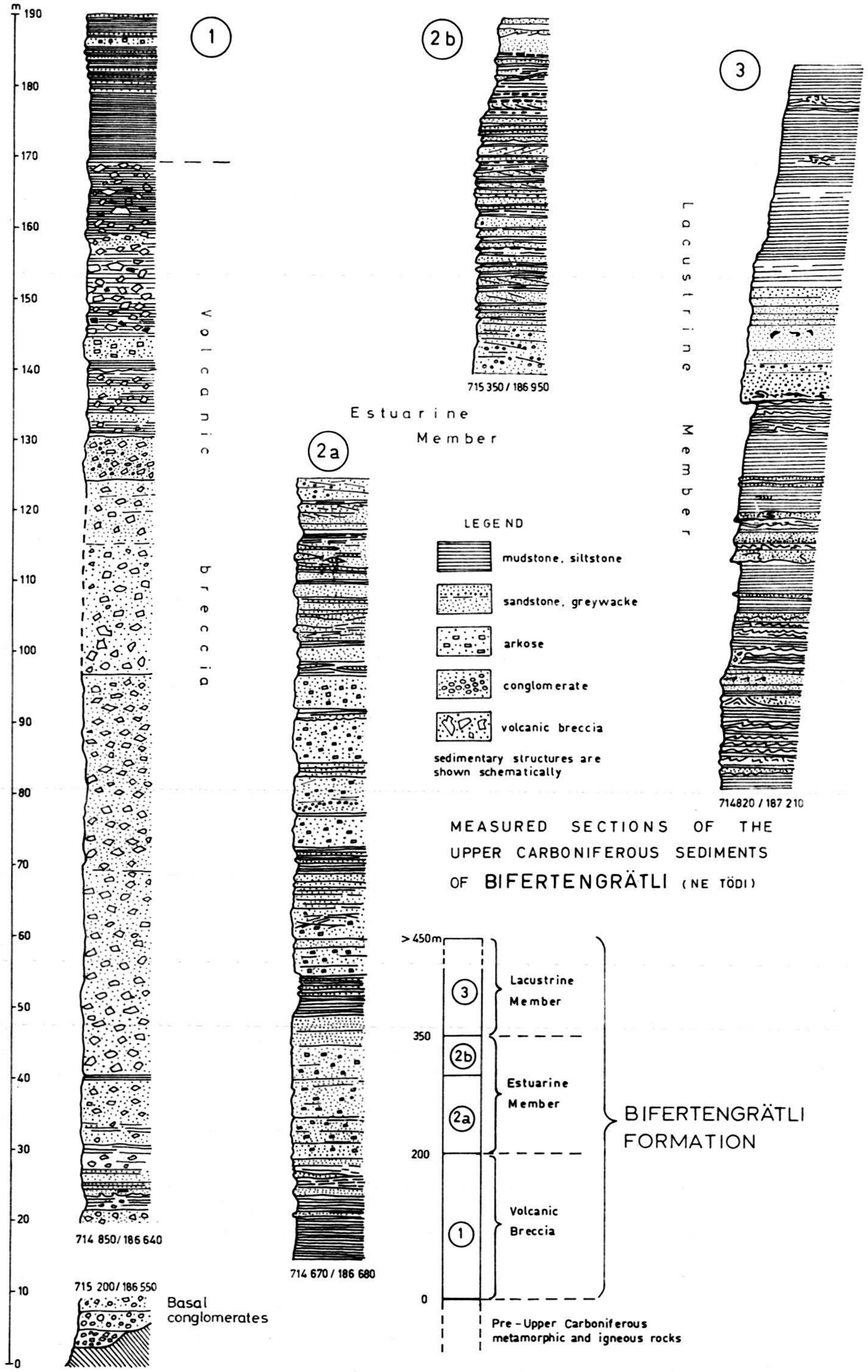
m
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
①
Volcanic breccia
714 850/186 640
715 200/186 550
Basal conglomerates
2a
714 670/186 680
2b
715 350/186 950
Estuarine Member
3
Lacustrine Member
714820/187 210
LEGEND
mudstone, siltstone
sandstone, greywacke
arkose
conglomerate
volcanic breccia
sedimentary structures are shown schematically
MEASURED SECTIONS OF THE UPPER CARBONIFEROUS SEDIMENTS OF BIFERTENGRÄTLI (NE TÖDI)
>450m
350
200
0
③
Lacustrine Member
2b
Estuarine Member
2a
①
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

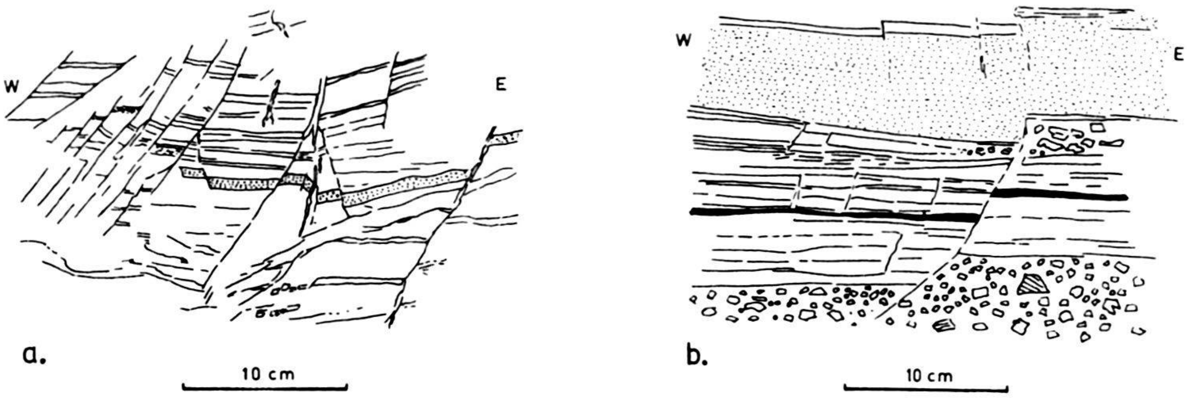

Fig. 5 *a.* Small-scale faults in the hornfelses SW of the Fridolinshütten. *b.* Small-scale syngenetic faults in the basal breccies of the Bifertengrätli Formation, SW of the Fridolinshütten.

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.

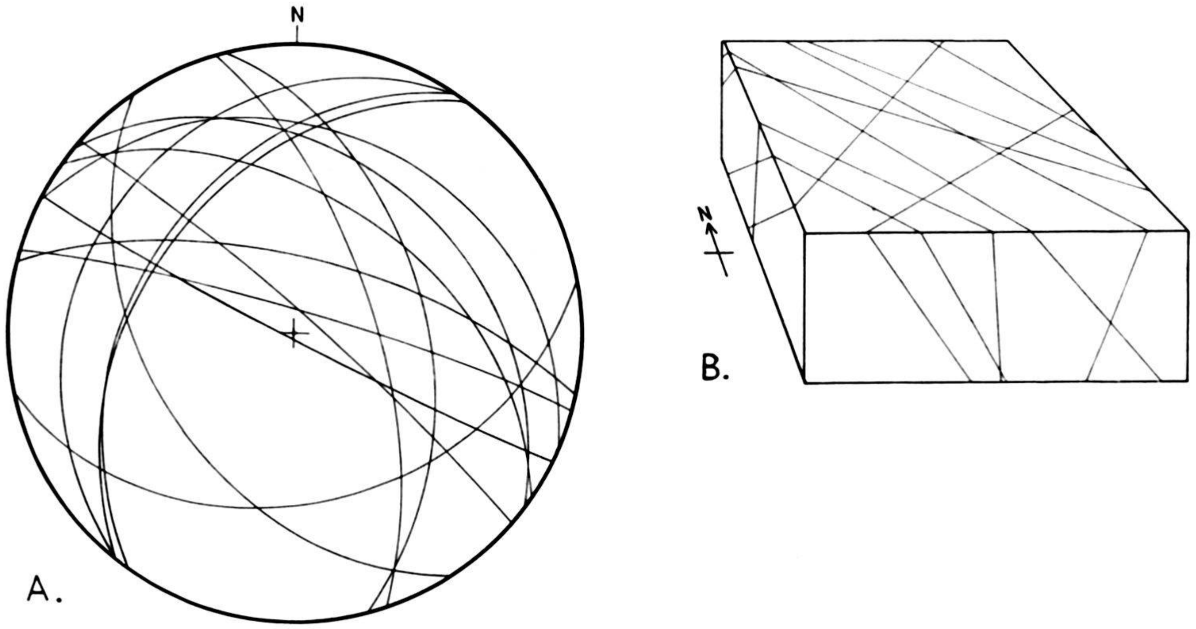

Fig. 6 *a.* Sterogram of unfolded minor faults (see text). *b.* Schematic block diagram of the fracture pattern during the volcanic episode of the NE Tödi area.

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

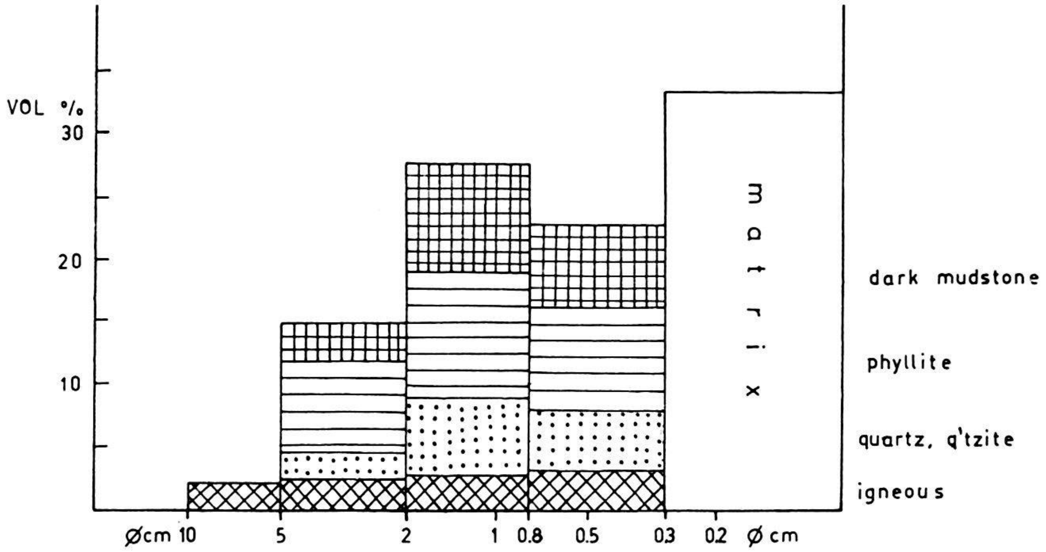

Fig. 7 Field analysis of conglomerate from Basal Conglomerates. (550 components counted on an area of 30 × 30 cm; matrix-here < 0,3 cm estimated at $^1/_3$rd total area.)

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 Biferten-grätli. 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.

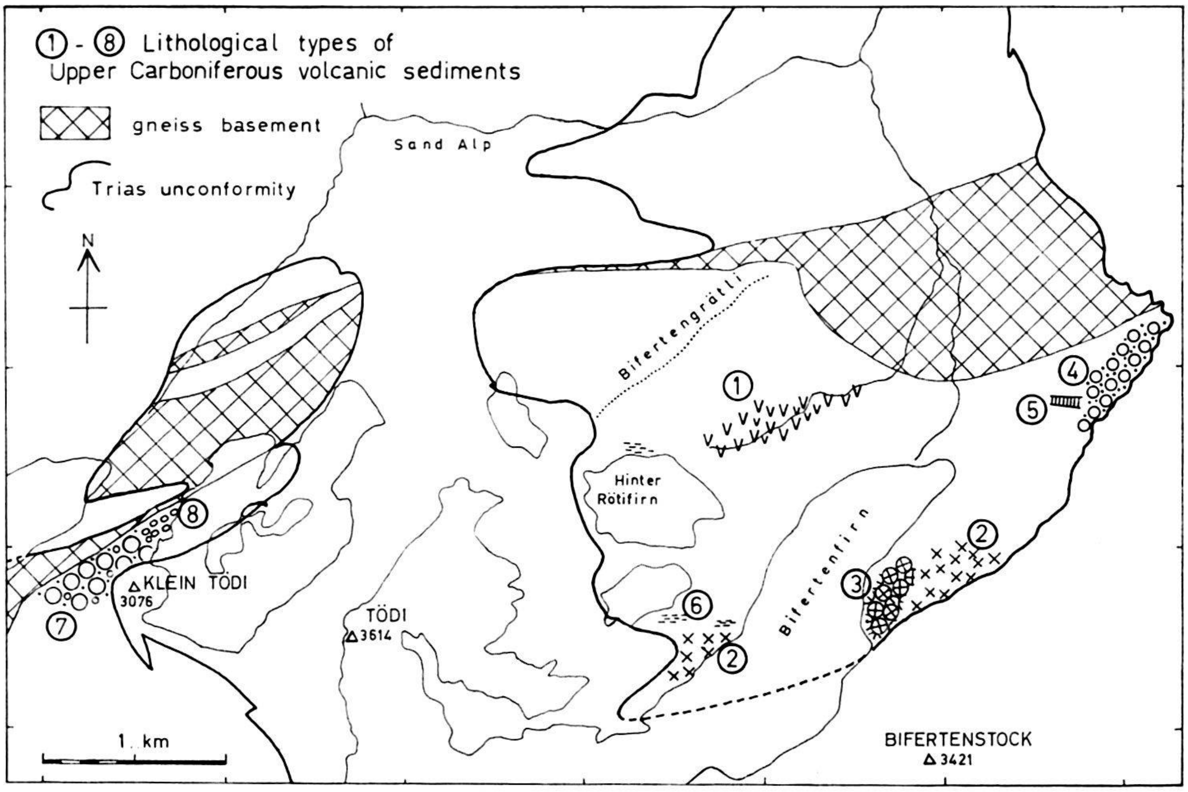

Fig. 8 Regional variations in the lithology of the Upper Carboniferous volcanics of the Biferten inlier and Klein Tödi areas (see text for descriptions of 1–8).

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.

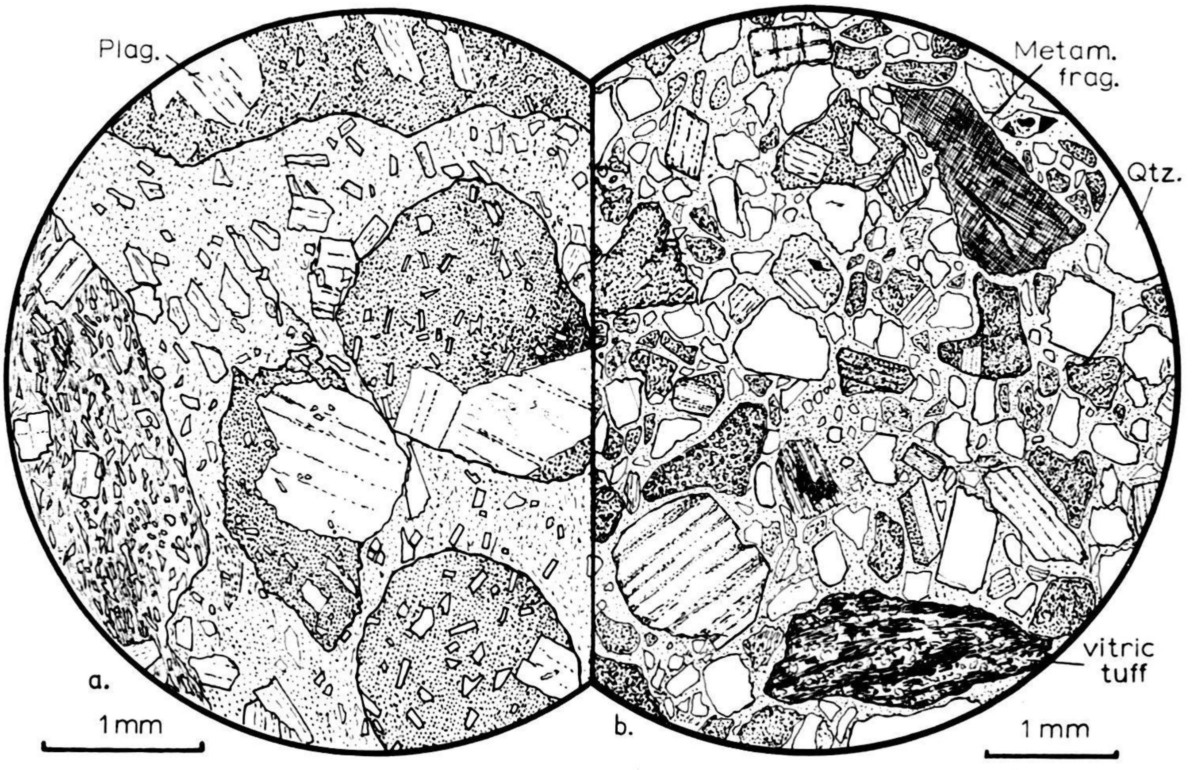

Fig. 9 *a.* Andesite breccia. Fragments of andesite and crystal tuff (left) in a tufaceous matrix. *b.* Tufaceous sandstone-breccia, with varied volcanic components.

### 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.

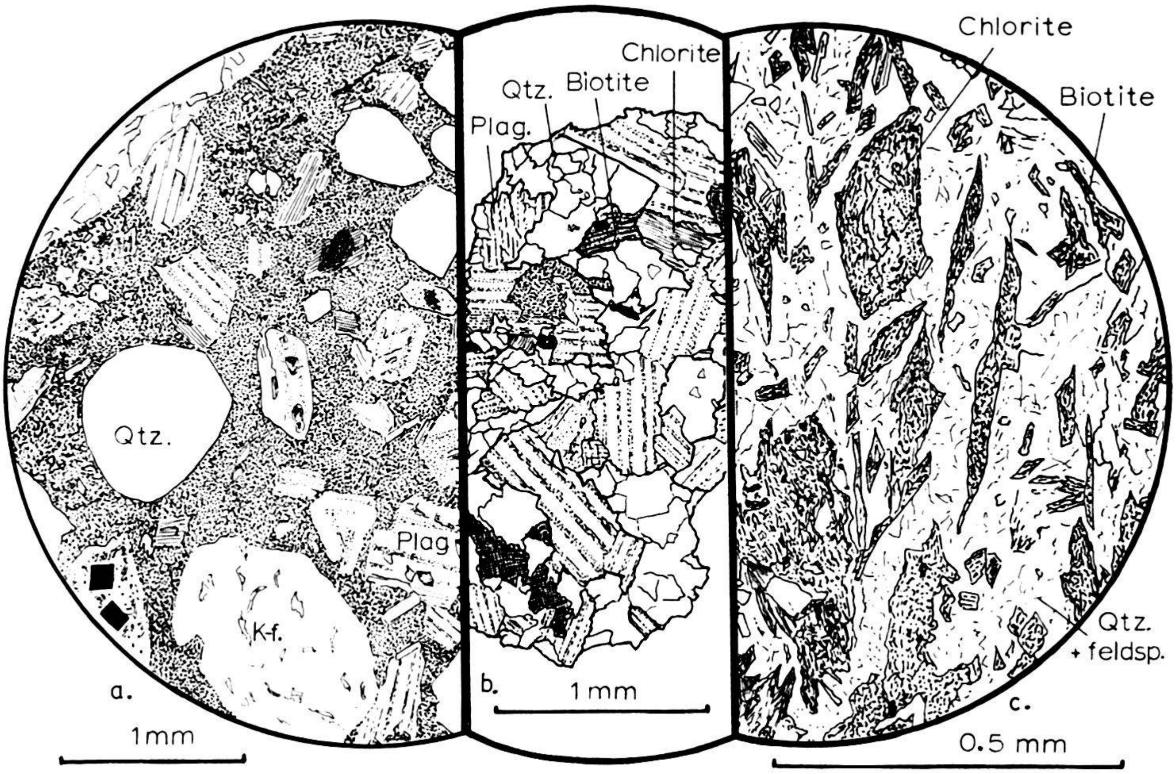

Fig. 10 Fragments in the volcanic breccias. *a.* porphyritic rhyodacite; *b.* granodiorite; *c.* altered amphibole-biotite hornfels of Val Gliems-type (chlorite pseudomorphs after accicular amphibole and biotite).

### *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 microgranodiorites* 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

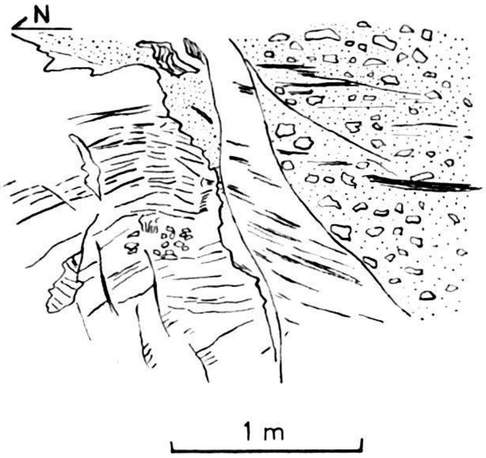

Fig. 11 Margin of vent breccias cutting banded hornfels, E. Bifertenfirn.

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.

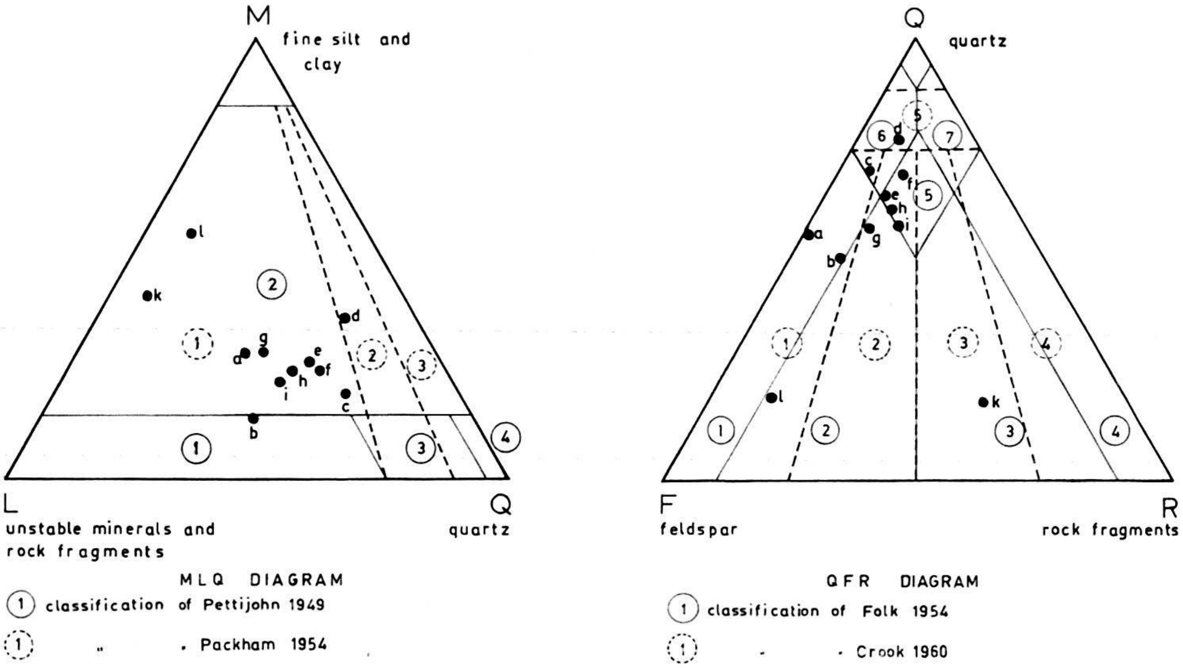

Fig. 12 Composition of the sandstones of the Bifertengrätli Formation: MLQ and QFR diagrams and a comparison of various proposed classifications.

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

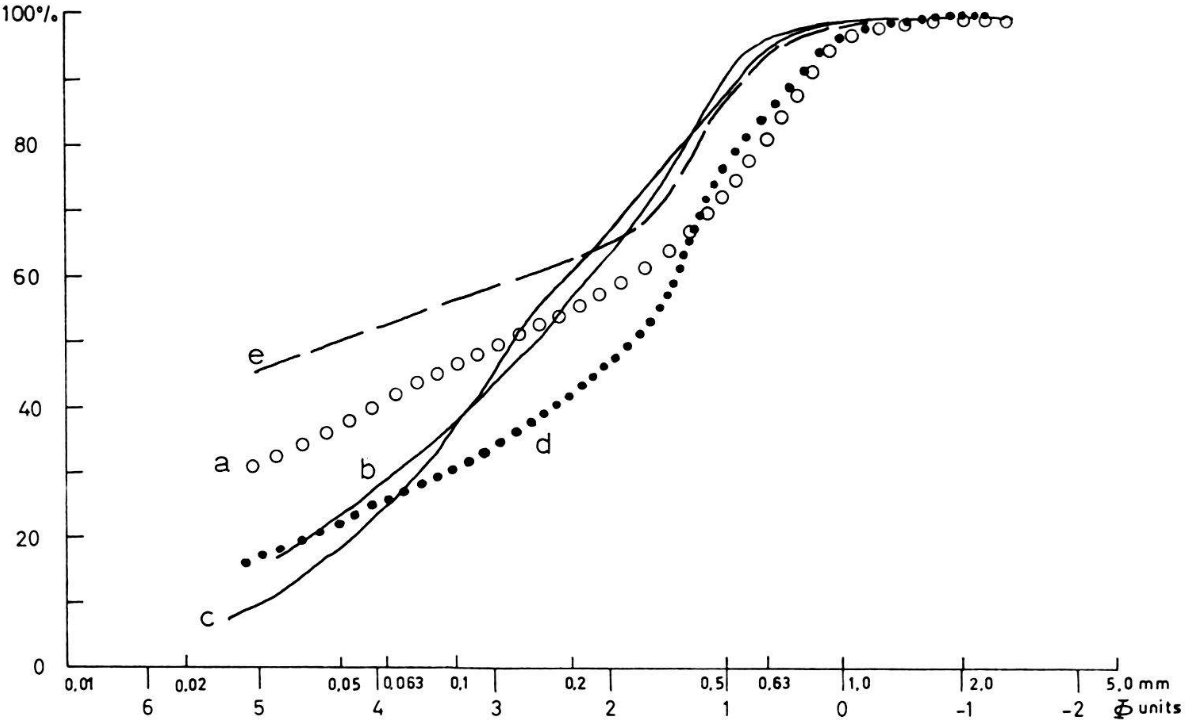

Fig. 13 Grain size distributions of sandstones of the Bifertengrätli Formation from thin section measurements. *a.* Sandstone in basal conglomerates: *b.* sandstone fragment in Schiebenruns conglomerates; *c.* sandstone fragment in Schiebenruns conglomerates; *d.* sandstone of Estuarine Member; *e.*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

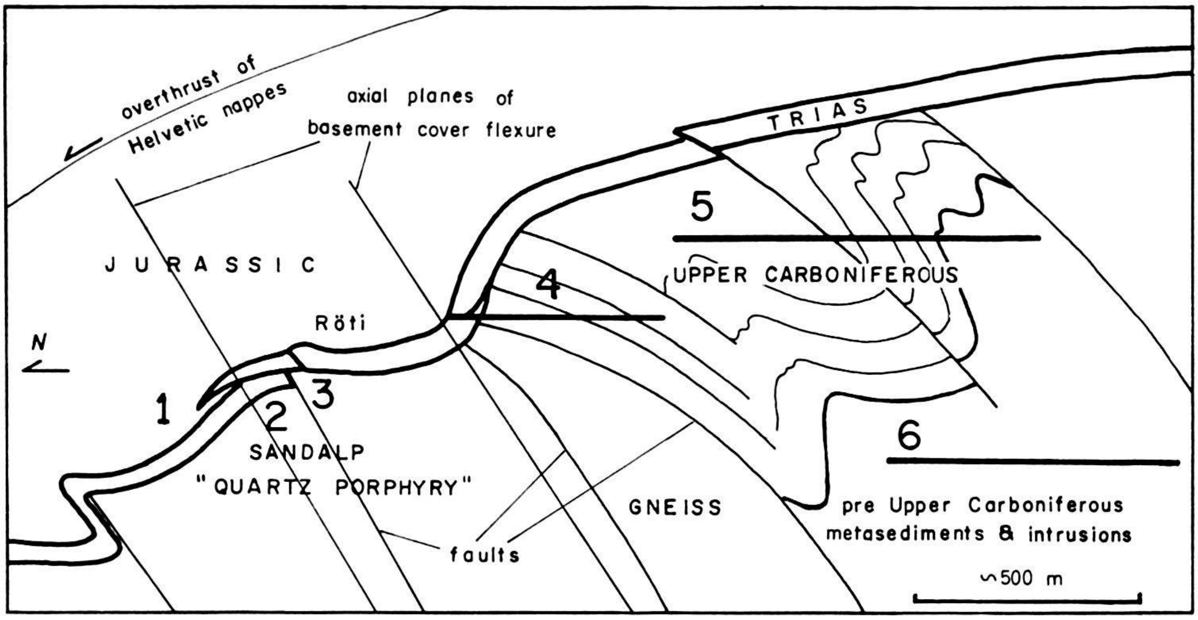

Fig. 14 Sketch section of the types of geological structures of the NE Tödi area. The numbers 1–6 refer to sections described in the text.

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 $3^1/_2$ 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 $\pi$-diagram of Bifertenfirn metasediments and Bifertengrätli Formation, 320 poles, contoured at 5, 2, 1, $^1/_2$%.

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

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

d) $\pi$-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.

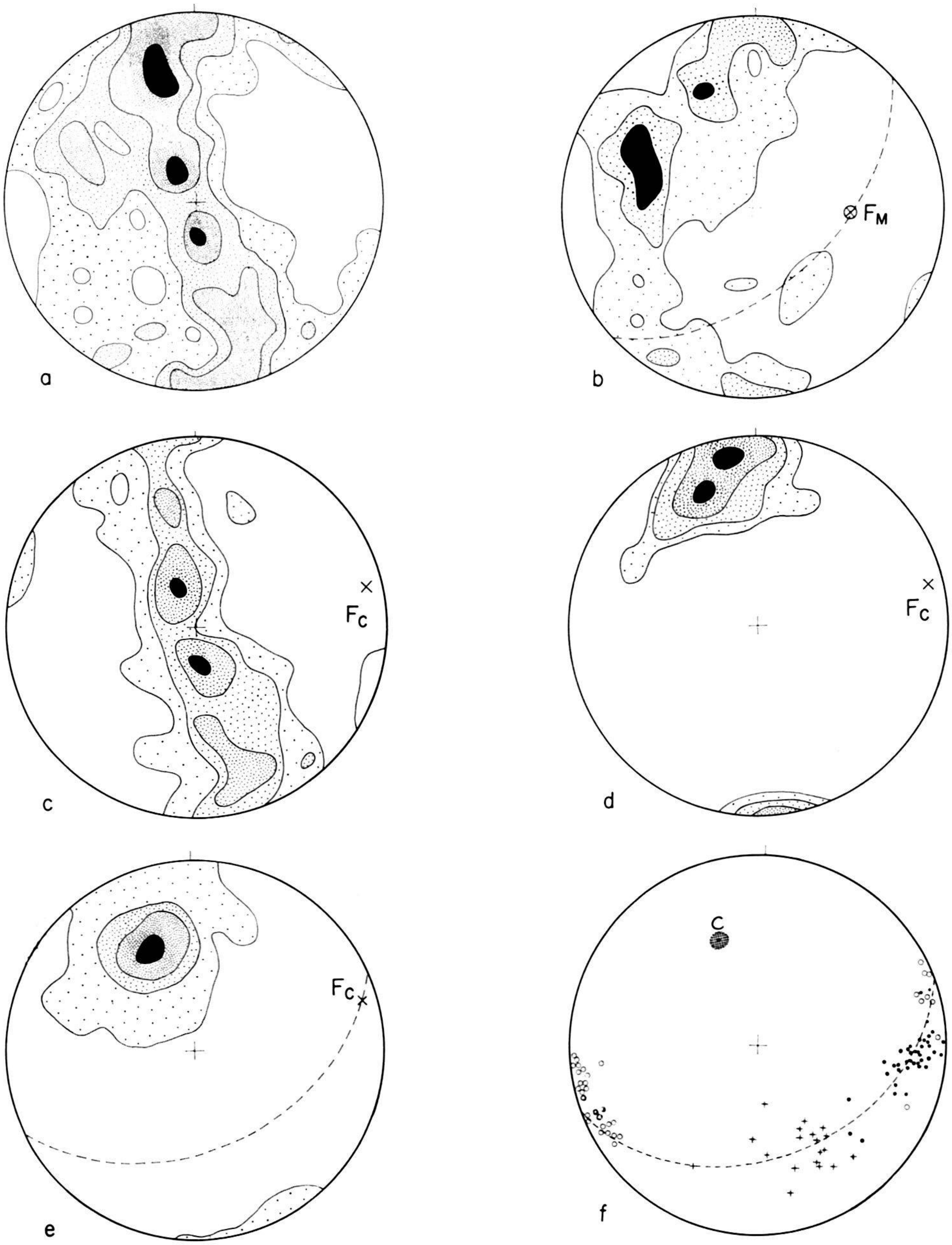

Fig. 15

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

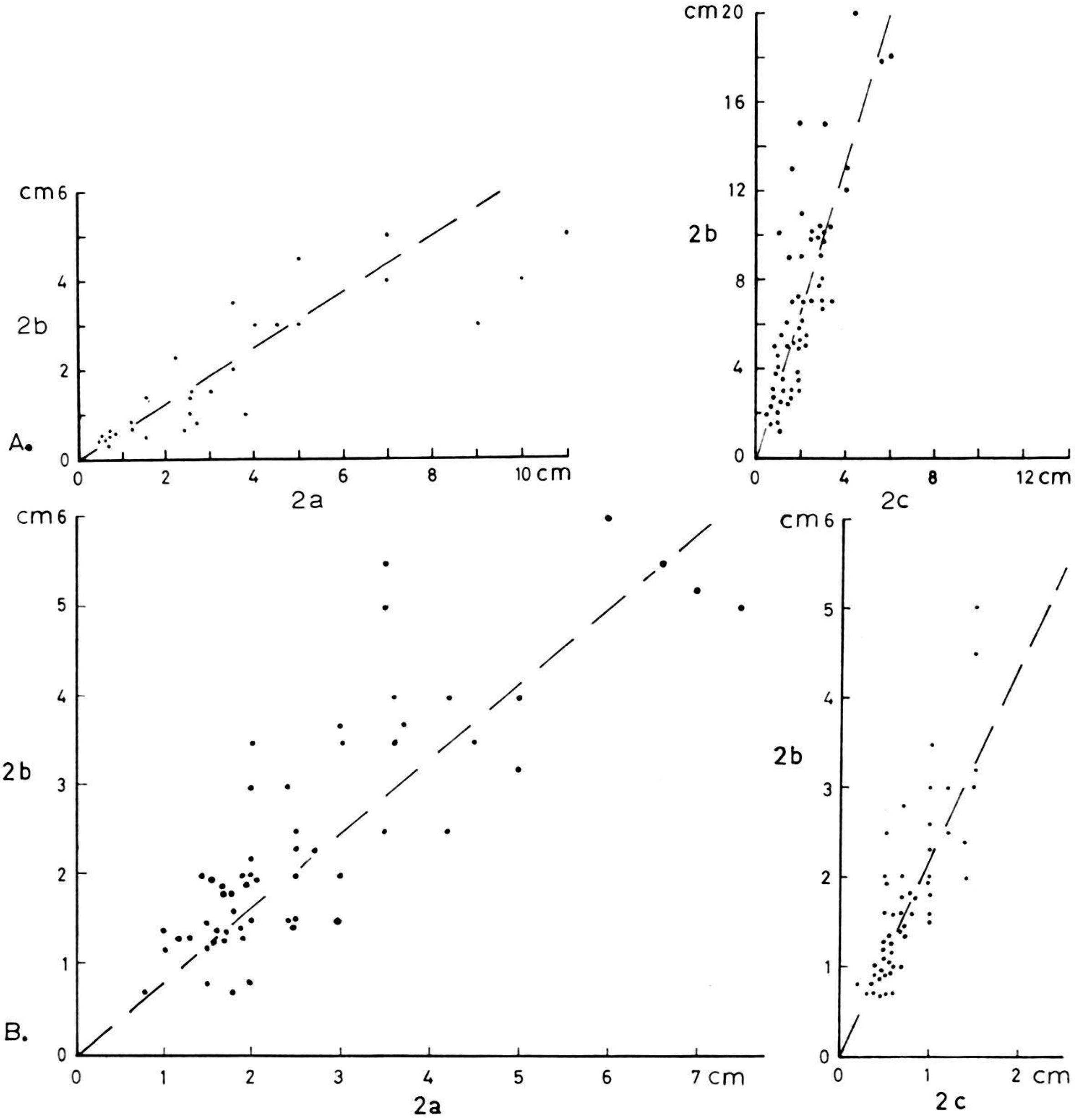

Fig. 16 Mesurements of deformed fragments of the volcanic breccias: 2a, 2b, 2c are major axes of fragments on wheathered surfaces perpendicular to the axes.
A. South Bifertengrätli, locality 1. B. Bifertengrätli, locality 2.

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.

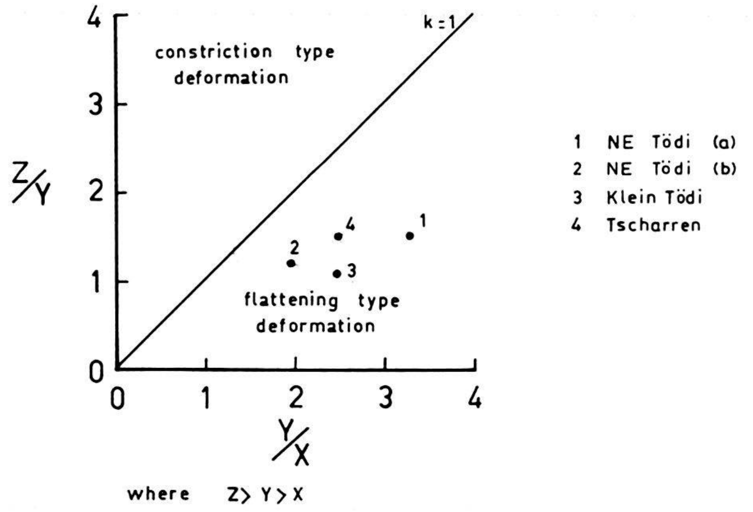

Fig. 17 Deformation plot of deformed fragments from the Upper Palaeozoic rocks of the eastern Aar Massif.

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

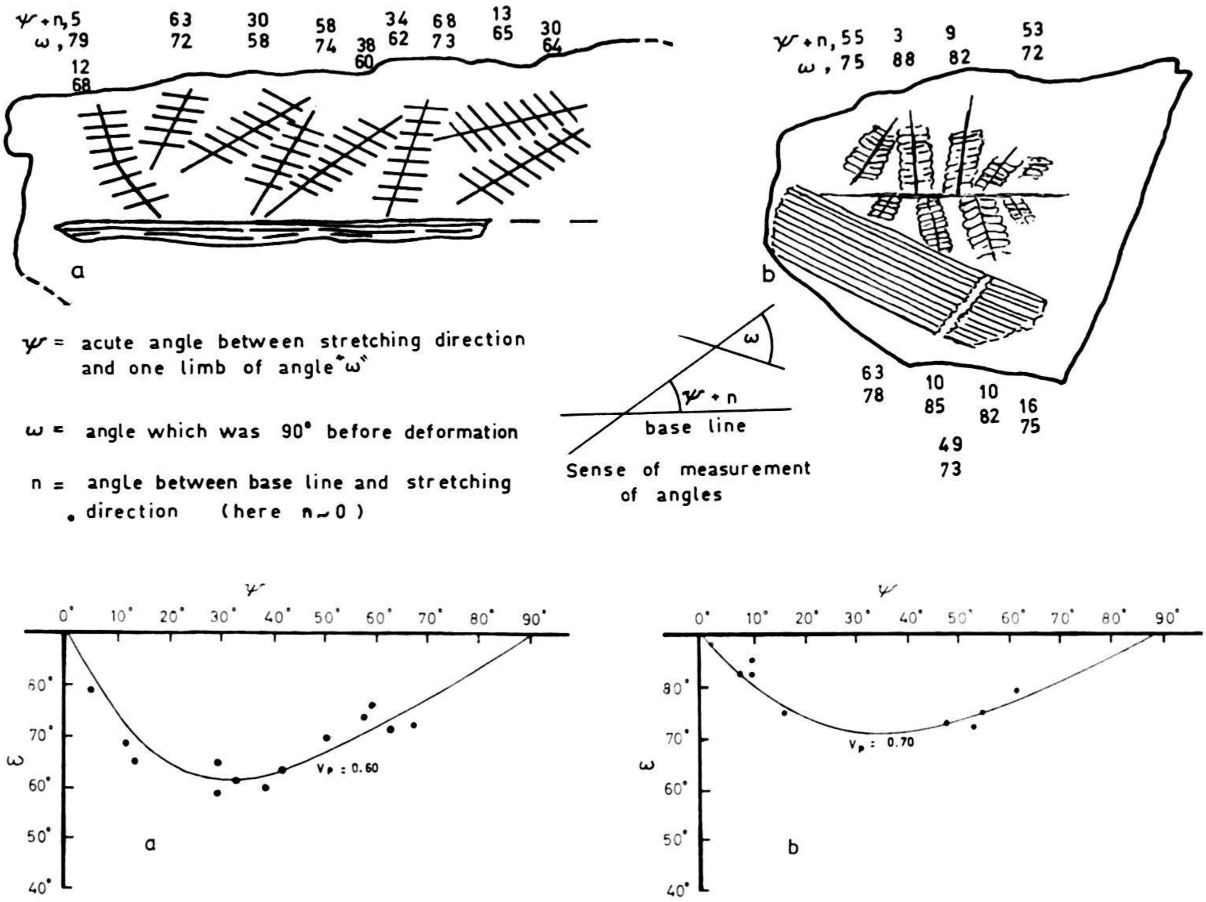

Fig. 18 Deformation of plant fragments in the Bifertengrätli Formation, showing the amount of change of an angle that was originally approximately 90% (ω), depending on its orientation to the stretching direction. The ratio of the axes of the deformation ellipse on the surface measured (Vp) are derived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