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

THE MADERANERTAL

INTRODUCTION AND SUMMARY OF PREVIOUS WORK

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

Summary of Previous Work

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

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

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

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

(2) Folding by the second Hercynian movements.

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

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

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

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

(2) Folding during the Upper Carboniferous.

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

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

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

GEOLOGY OF THE PRE-TRIASSIC FORMATIONS OF THE MADERANERTAL

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

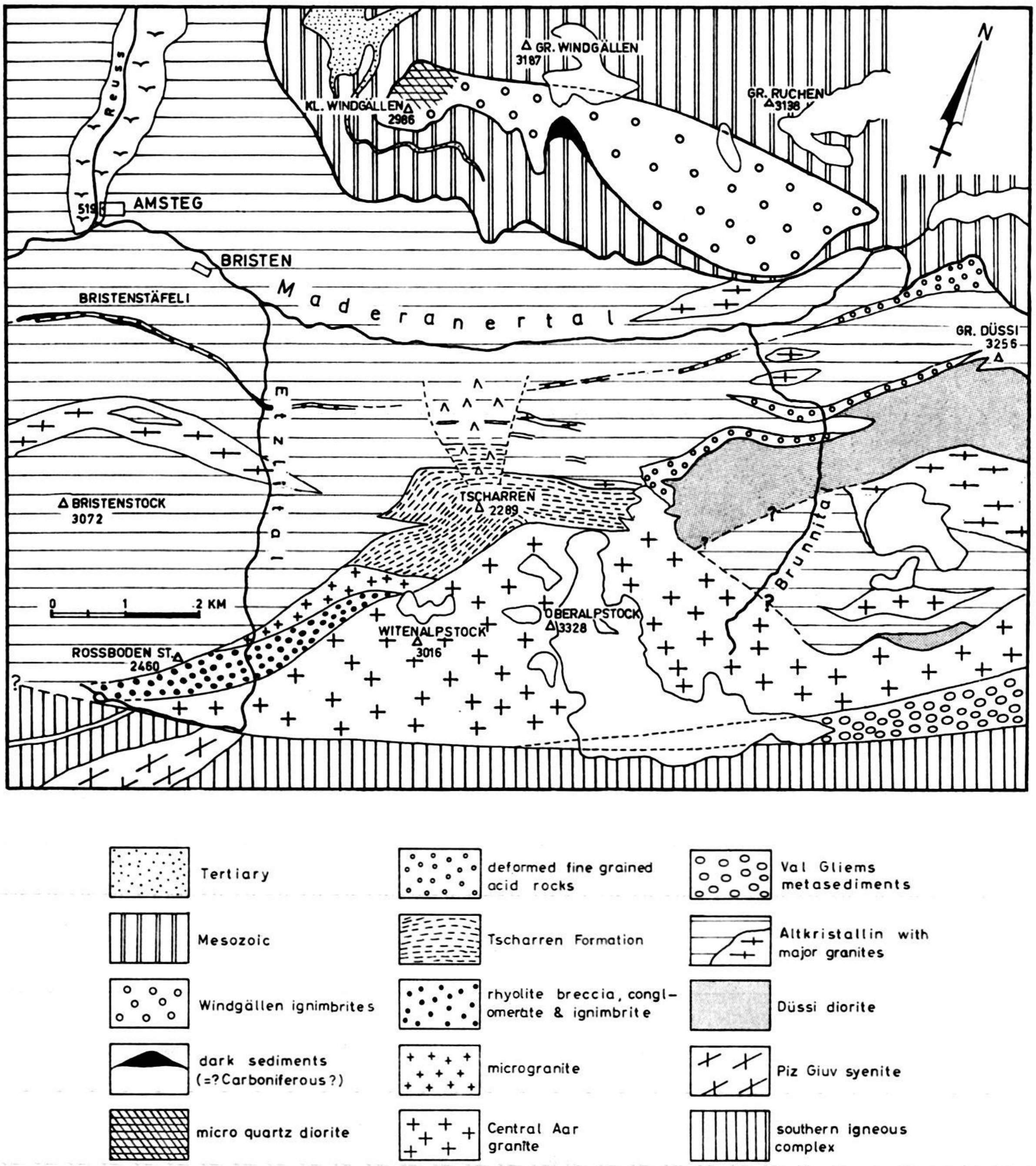

Fig. 24 Geological sketch map of the Maderanertal area.

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

THE UPPER PALEOZOIC SEDIMENTS OF TSCHARREN (THE TSCHARREN FORMATION)

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

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

The stratigraphical succession observed may be subdivided into

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

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

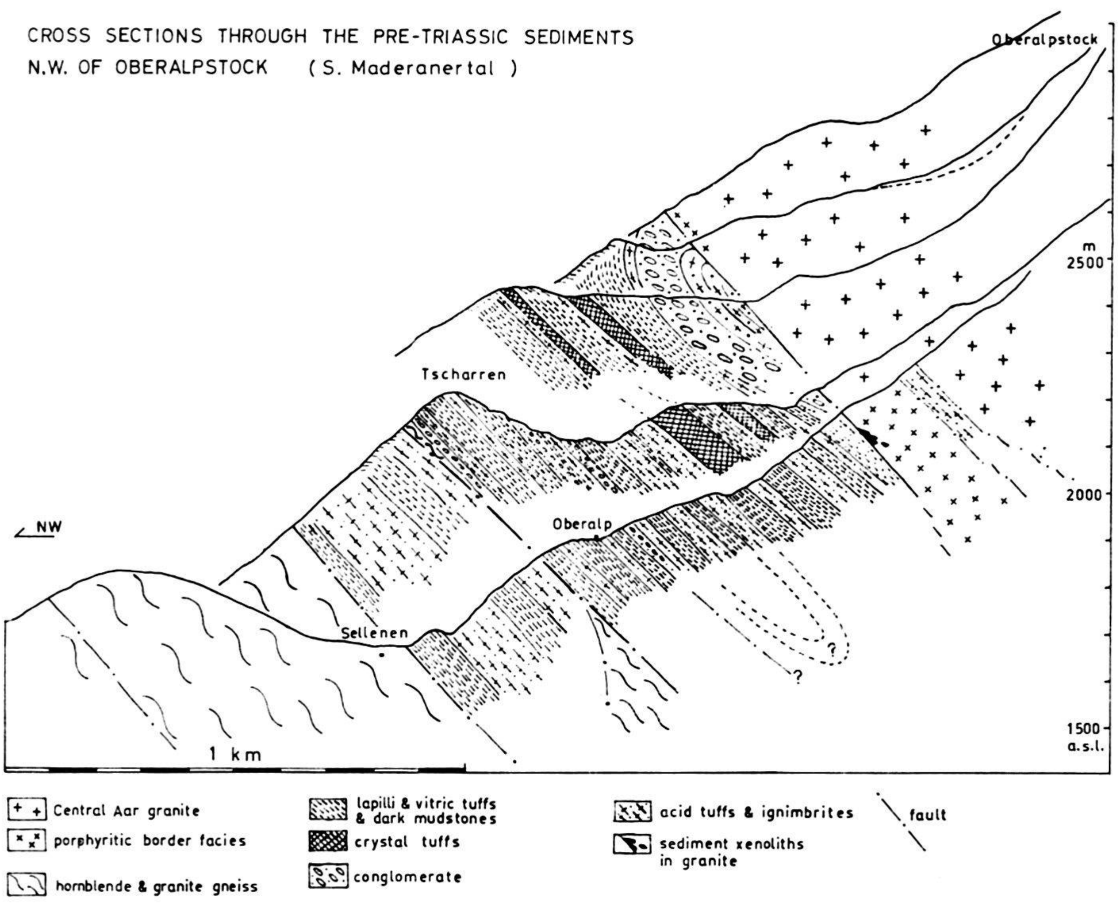

Fig. 25 Geological cross sections through the Upper Palaeozoic volcanics NW of Oberalpstock, 1:20000.

The Ignimbritic Member

Field Relations

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

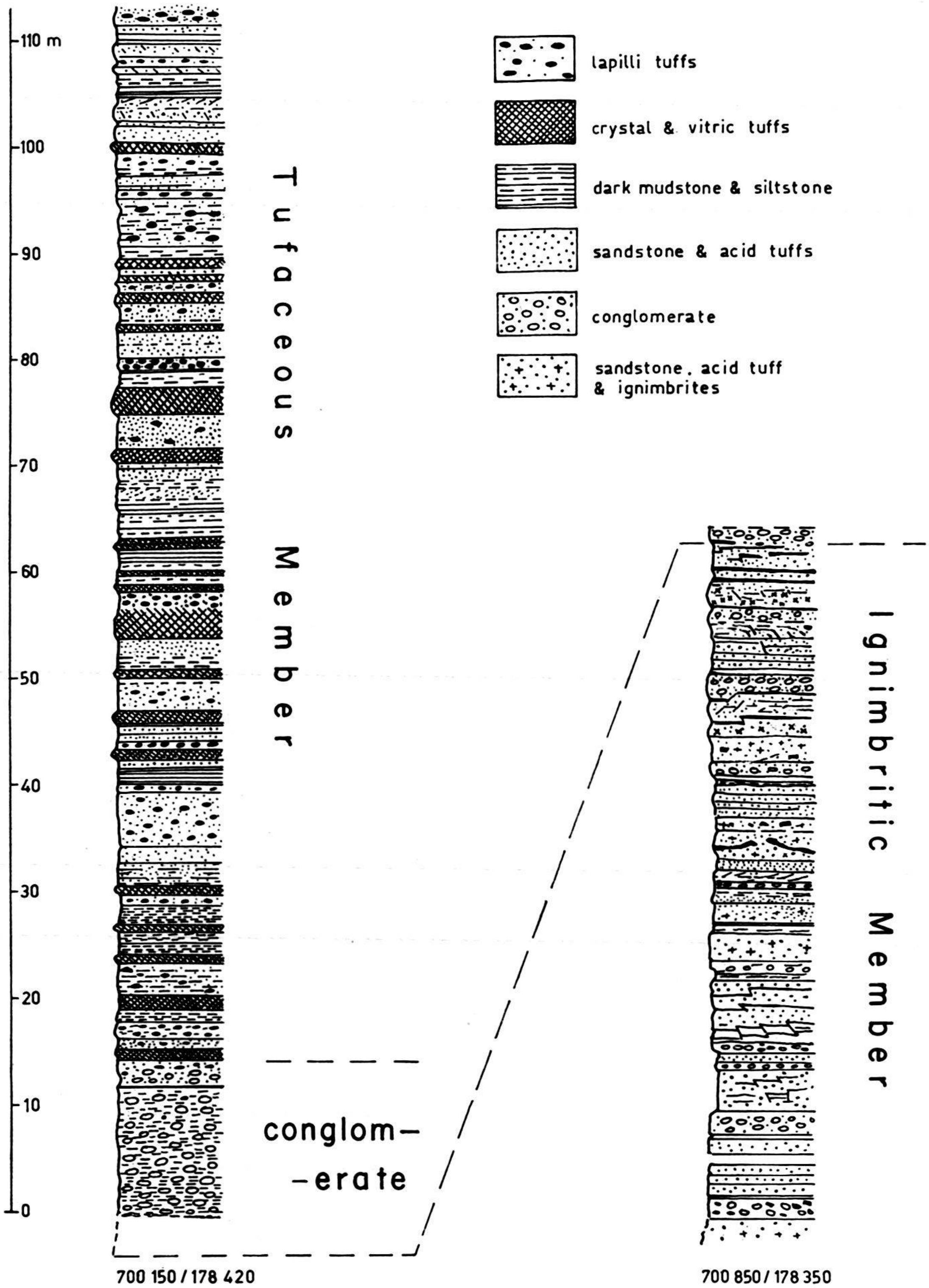

Fig. 26 Measured Section of the Tscharren Formation, southern slopes of Tscharren.

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

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

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

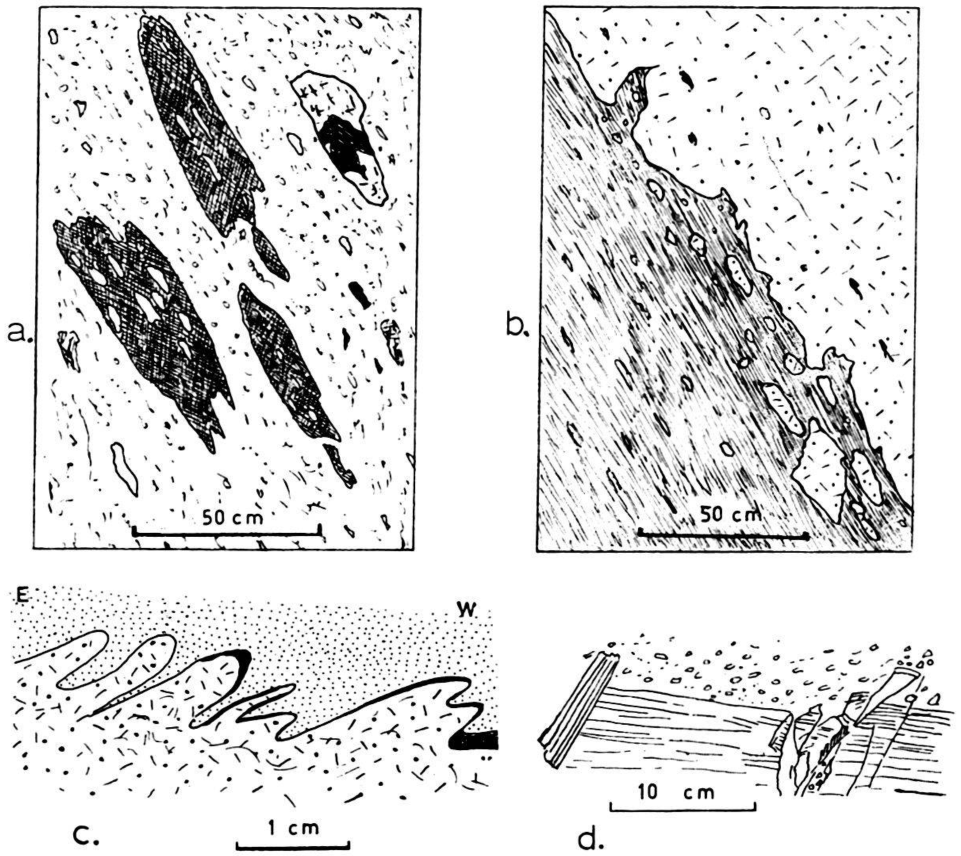

Fig. 27 Details of ignimbrite and banded rhyolite beds. a) fragments of dark-coloured lapilli tuffs and coarse-grained ignimbrites in a pyroclastic matrix. b) inverted ignimbrite bed with fragments in the younger dark-coloured tuffaceous bed. (a & b south Tscharren, 700360/178340; 2300 m). c) Sedimentary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

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

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

Petrography

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

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

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

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

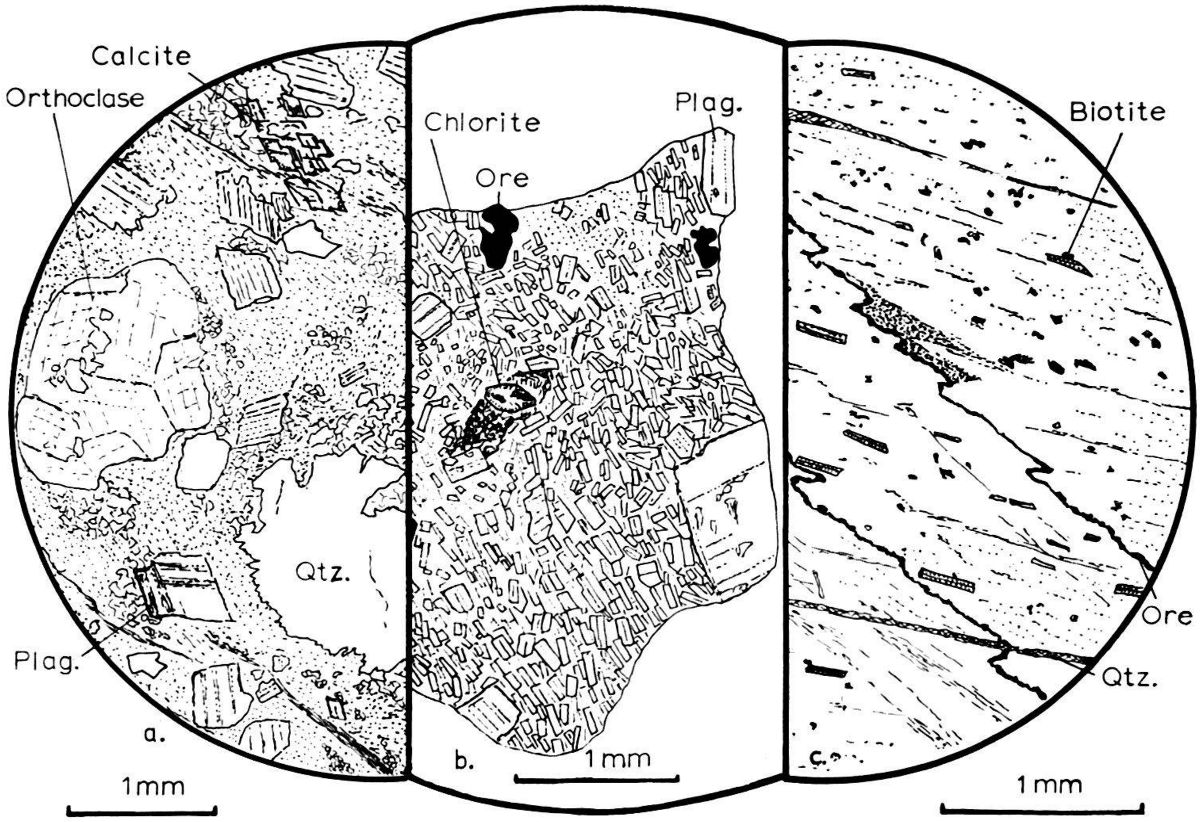

Fig. 28 a) Thin section drawing of a recrystallized acid tuff from ignimbritic member of the Tscharren Formation.

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

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

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

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

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

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

Conglomerates

Field Relations

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

Petrography of the Conglomerates

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

The Tuffaceous Member

Field Relations

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

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

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

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

Petrography of the Rocks of the Tufaceous Member

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

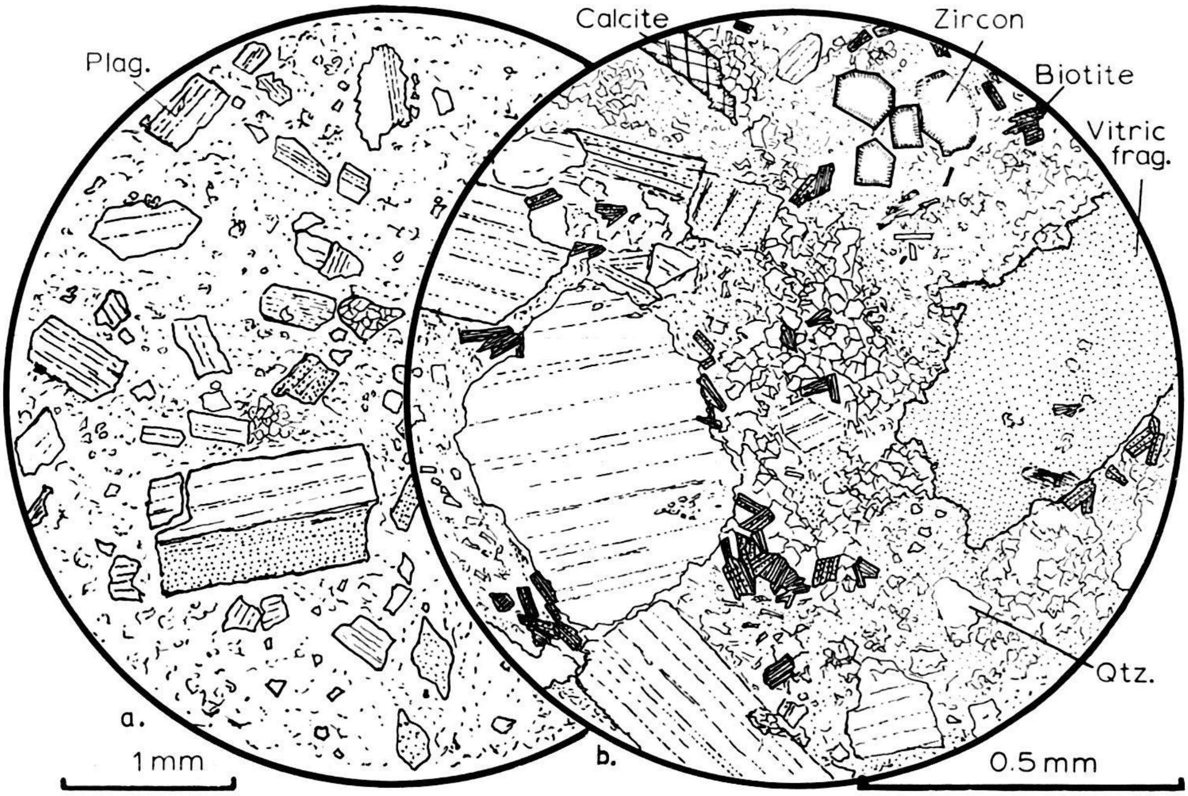

Fig. 29 Thin section of crystal tuff, Tufaceous Member of Tscharren Formation. a) showing altered plagioclase and recrystallized matrix, b) detail of recrystallized matrix with granoblastic quartz-biotite mosaic: note local patches of calcite and idiomorphic zircons.

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

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

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

Discussion of the Tscharren Formation

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

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

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

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

WITENALP

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

Ignimbrite section of Witenalp

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

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

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

Volcanic Conglomerates

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

Rhyolites and Rhyolite Breccias of Witenalp

Field Relations

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

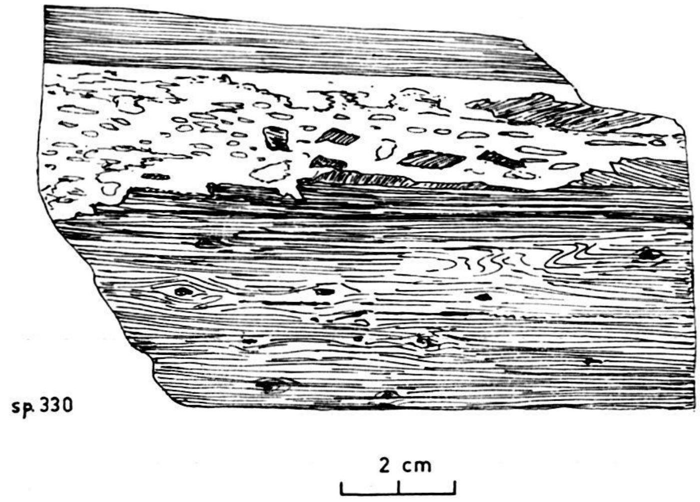

Fig. 30 Flow banded rhyolite and breccia-lapilli bed.

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

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

Fig. 31 Breccia of banded and vesicular rhyolites.

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

Petrography

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

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

ROSSBODENSTOCK AND THE WESTERN EXTENSION OF THE VOLCANICS

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

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

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

THE BASEMENT ROCKS OF THE WINDGÄLLEN

Introduction

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

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

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

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

Field Relations

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

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

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

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

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

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

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

Petrography of the Basement Rocks of the Windgällen Fold

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

(1) Acid (silicic) tuffs, ignimbrites and ignimbrite breccias and conglomerates.
(2) Rocks with a darker matrix, probably indicative of resedimentation of the acid rocks by water. Mixed sedimentary rocks.
(3) Porphyritic microquartzdiorite.

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

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

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

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

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

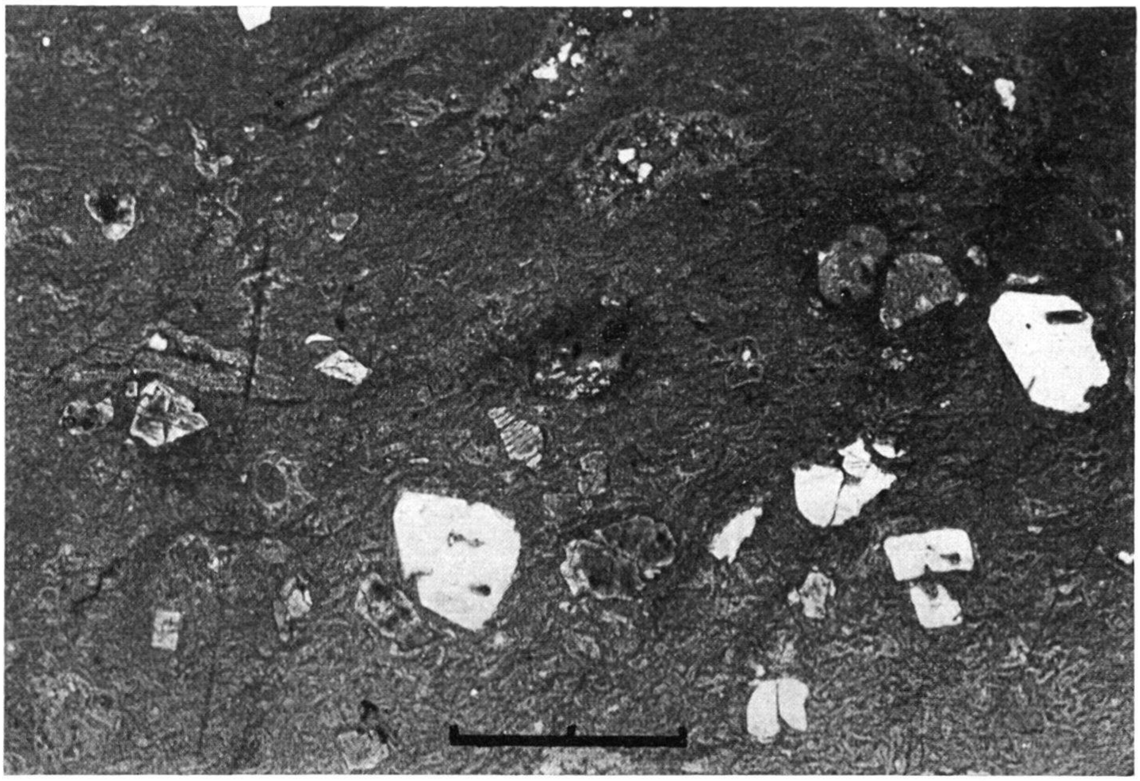

Fig. 32a Vitric acid tuff with undeformed arcuate glass shards. Note the section through the unbroken gas bubble, lower left. Scale is 2 mm.

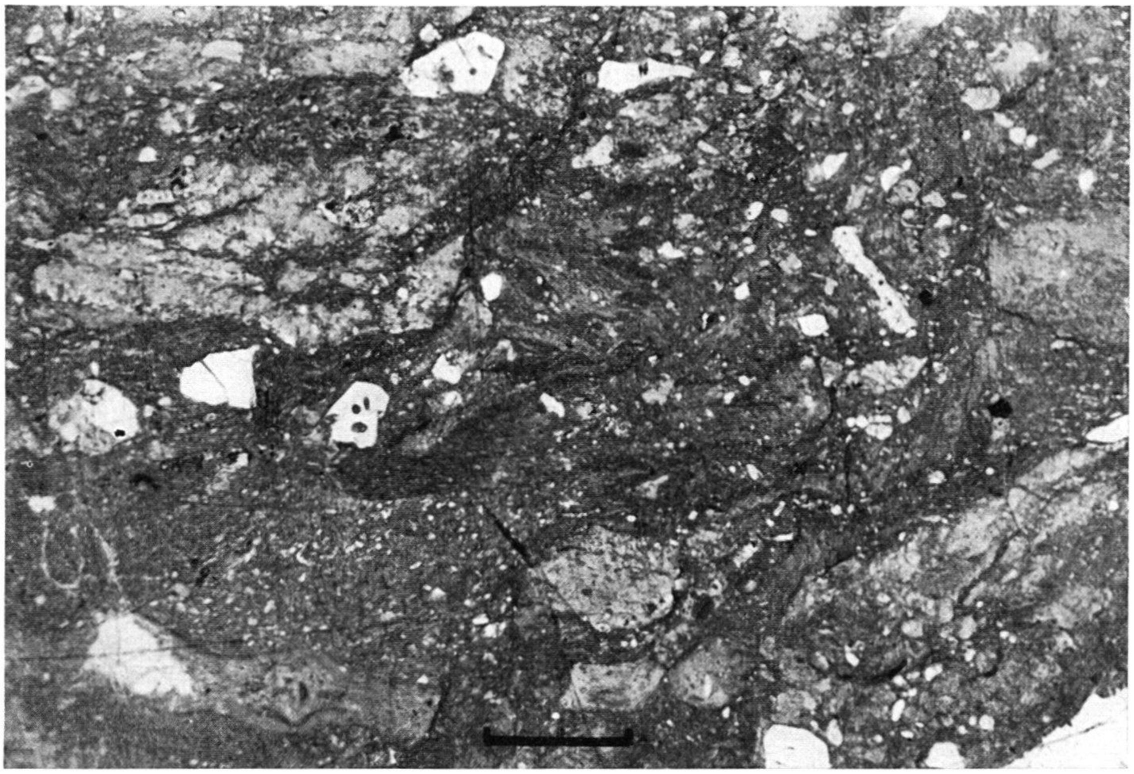

Fig. 32b Fragmentary acid tuff with ataxitic texture. Only slight deformation of the fragments. Scale is 2 mm.

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

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

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

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

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

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

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

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

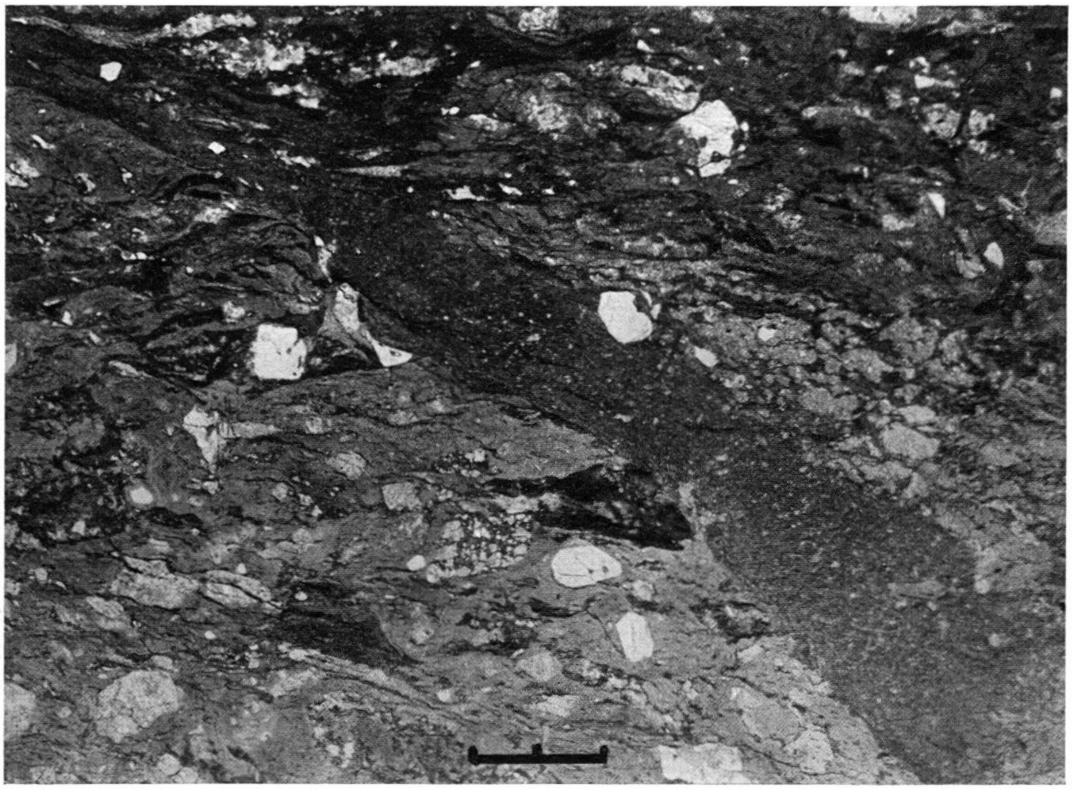

Fig. 32d Ignimbritic texture of rhyodacitic tuff: the elongated pyroclastic fragments are cut by partially remelted groundmass. Scale is 2 mm.

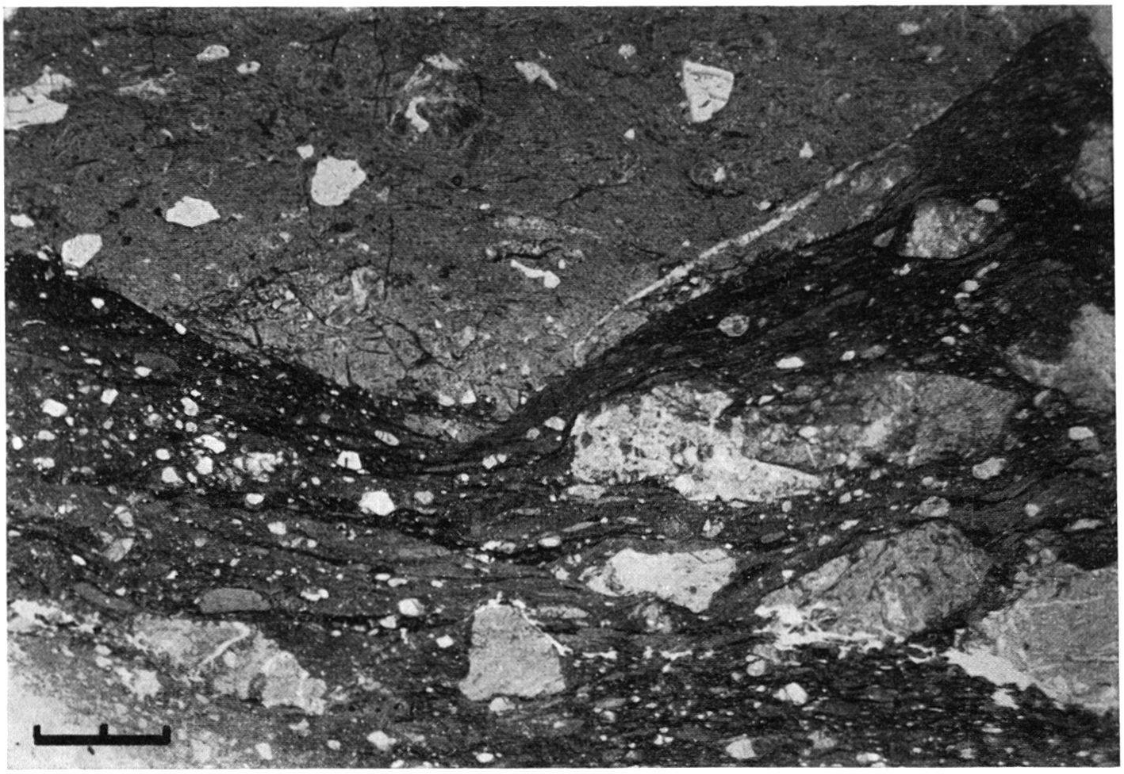

Fig. 32e Reworked pyroclastic rocks: the fragments are mainly vitric tuffs with recrystallised glass shards. Scale is 2 mm.

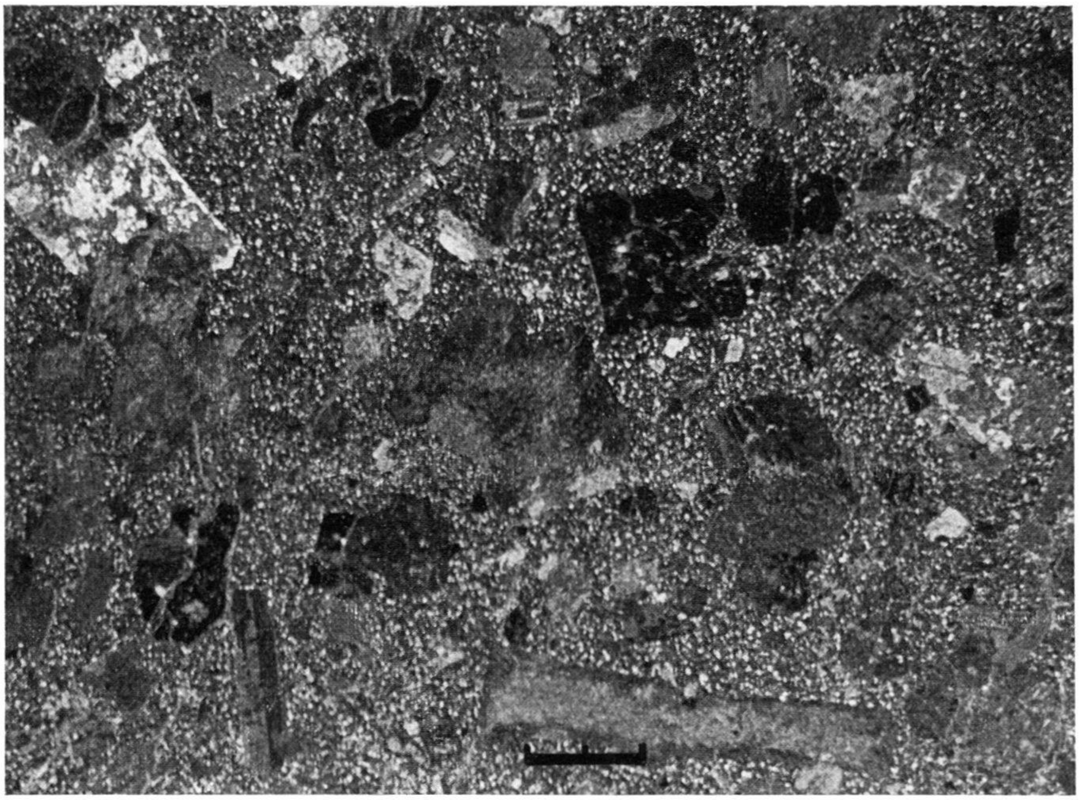

Fig. 32f Porphyritic micro-quartzdiorite from Klein Windgällen. Scale is 2 mm.

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

Mixed Sedimentary Rocks (Fig. 32e)

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

Porphyritic Microquartzdiorite (to Granodiorite)

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

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

The Metamorphism of the Windgällen Basement Rocks

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

Discussion of the Windgällen Volcanics

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

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

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

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

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

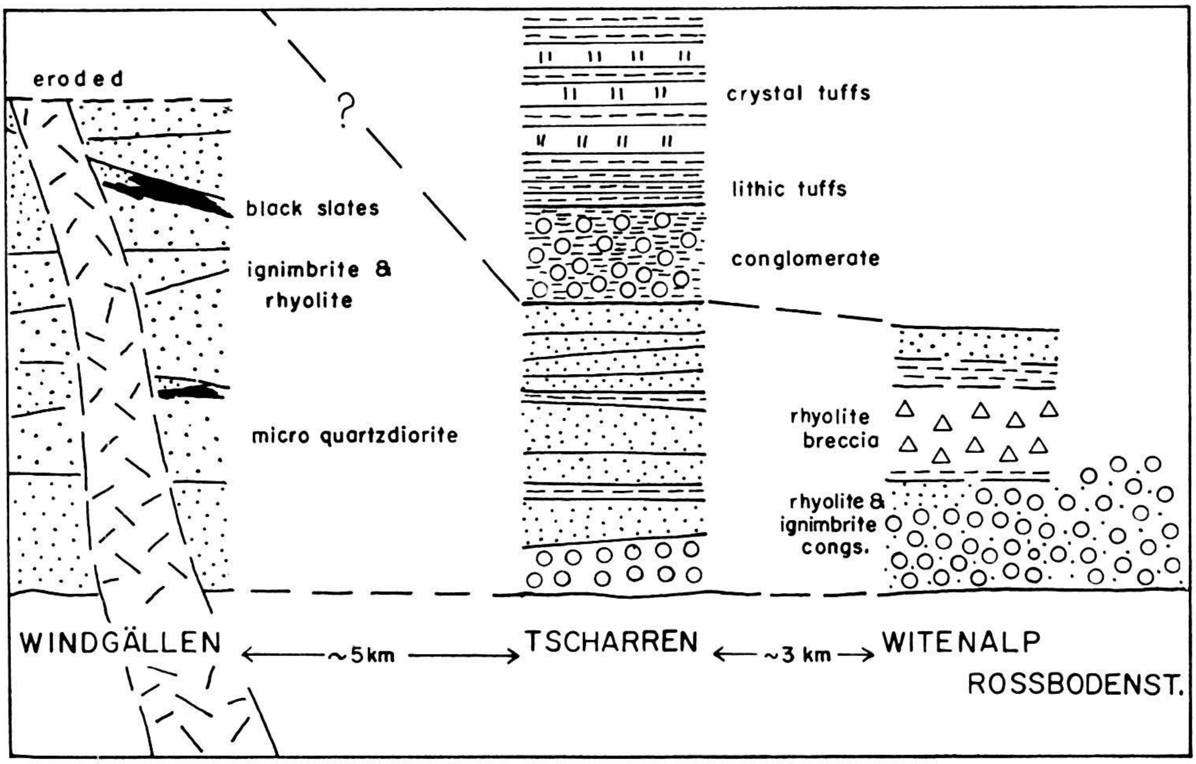

Fig. 33 Reconstruction of the volcanic sections of the Maderanertal.

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

STRUCTURES OF THE UPPER PALEOZOIC ROCKS OF THE MADERANERTAL

The Area of Volcanic Sediments South of the Maderanertal

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

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

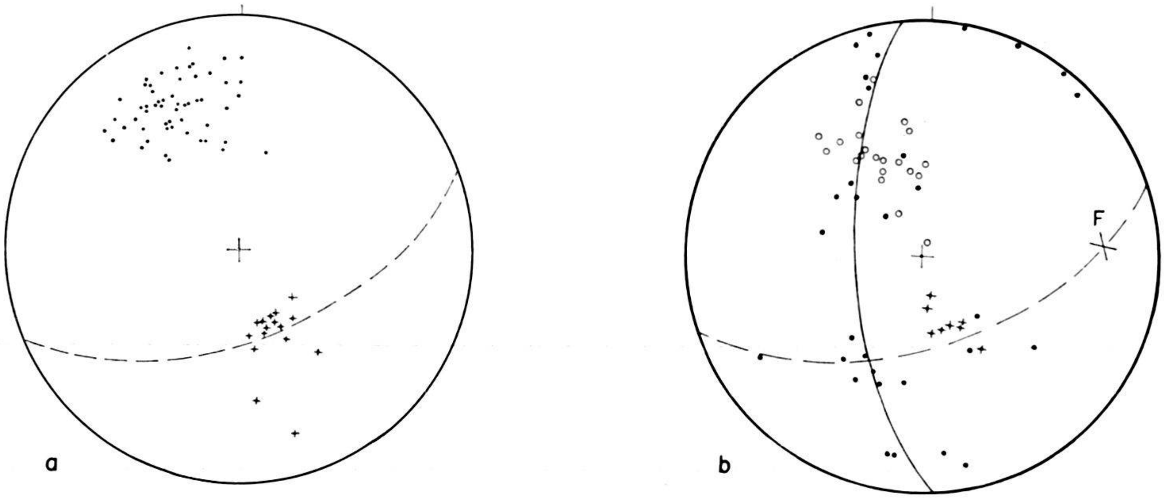

Fig. 34 Stereograms of structural measurements from the Upper Palaeozoic rocks of the Maderanertal:
a) cleavage (•) and elongation direction (+) in the Tscharren Formation: great circle is the general cleavage surface.
b) poles to first cleavage (•), poles to second cleavage (o) and elongation direction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

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

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

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

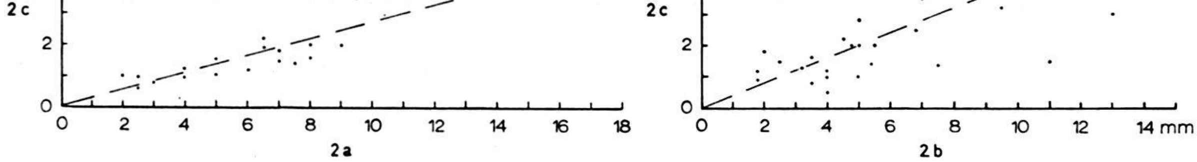

Fig. 35 Measurements of deformed fragments and lapilli of the Tscharren Formation. For explanation and deformation plot see Figs. 16 and 17.

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

The Contact of the Volcanics with the Granite

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

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

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

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

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

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

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

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

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

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

The Area of Volcanics North of the Maderanertal

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

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

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

CONCLUSIONS

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

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

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