

## Sedimentary Petrography of Glacial Deposits in the Rotach Valley, Western Allgäu, Southern West Germany

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Glaciofluvial sedimentation, Würm, lithostratigraphy, section, gravel, sand, diamicton, calcareous composition, heavy mineral analysis, pebble analysis, granulometry, paleorelief

Baden-Württemberg, Bayaria, Alpenvorland

**Abstract:** Gravel, heavy mineral, carbonate, and grain size analyses of Würmian glacial sediments, mainly till, deposited by the Rhine-Valley glacier in the Alpine Foreland, indicate that the compositional variation of till is controlled by several factors. Firstly, vertical and lateral variations are present that relate to the incorporation of variable amounts of local bedrock or pre-existing glaciofluvial deposits. Secondly, a lateral variation in the composition of the far-travelled material reflects the combined effects of variable rock types in the source areas of the glaciers constituting the composite Rhine-Valley glacier, and the shifting position of their flow paths that is likely to have taken place during the course of the glaciation.

[Sedimentpetrographie glazialer Ablagerungen  
im Rotachtal, westliches Allgäu, Südwest-Deutschland

**Kurzfassung:** Kies-, Schwermineral-, Karbonat- und Korngrößenanalysen würmzeitlicher glazialer Ablagerungen, hauptsächlich Grundmoränen, des Rheintalgletschers im Alpenvorland zeigen, daß verschiedene Faktoren ihre Zusammensetzung beeinflussen. Zum ersten gibt es laterale und vertikale Variationen, welche mit der Aufnahme wechselnder Mengen der lokalen Gesteinstypen oder prä-existierender glazifluvialer Ablagerungen zusammenhängen. Zweitens zeigt sich eine laterale Variation im erratischen Bestandteil, welche die Auswirkung der verschiedenen Gesteinstypen im Ursprungsgebiet der Teilgletscher des Rheintalgletschers und die im Verlauf der Vergletscherung wahrscheinlich wechselnde Lage der Strombahnen der Teilgletscher widerspiegeln.

### 1. Introduction

The study area is located in the northern alpine Foreland, east of Lake Constance (Bodensee), in southern West Germany and the Austrian border area (Fig. 1). The international border between Allgäu (West Germany) and Vorarlberg (Austria) lies partly along the small streams of Kesselbach and Eyenbach, which have cut deep gullies through Quaternary (mainly glacial) deposits and bedrock. Many exposures in these gullies offer good opportunities to study the complex lithostratigraphy of unconsolidated deposits in the Rotach valley. In this paper we present new results from sediment-petrographic analyses and discuss the vertical as well as cross-valley compositional variation in till.

### 2. Regional geology

The pre-Quaternary basement of the area consists of calcareous shales, sandstones, and conglomerates of the Tertiary Molasse series. For details the reader is referred to recent summaries and discussions on the Molasse geology by e. g. VOLLMAYR & ZIEGLER (1976), FUCHS (1980), and HERRMANN & SCHWERD (1983). Here we will only point out some features that are of interest to the present study.

In the Rotach Valley, the Molasse beds exhibit a tectonic dip towards northwest (25—45°) and belong to the Erected Outer Molasse in the concept developed by FUCHS (1980). Several lithostratigraphic units can be distinguished, mainly on the basis of alternating marine and terrestrial conditions of sedimentation (Fig. 2).

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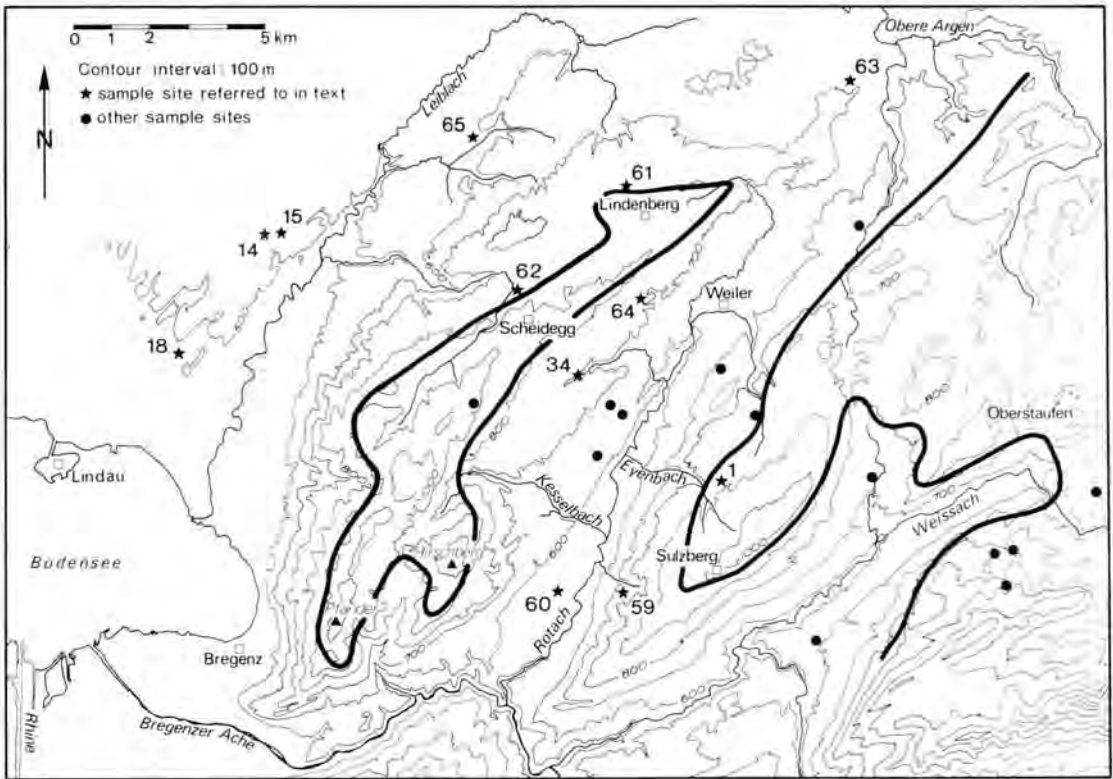


Fig. 1: Location map with position of sample sites. Heavy line represent the approximate position of the Inner Younger Endmoraine complex.

The southeastern slope of the Rotach valley (Sulzberg ridge) is built mainly in calcareous shales and sandstone interbeds of the Granitic Molasse, whereas the northeastern slope (Pfänder-Hirschberg ridge) consists mainly of conglomerates and sandstones of the Upper Freshwater Molasse (VOLLMAYR & ZIEGLER 1976). In between, the narrow zone of sandstones of the Upper Marine Molasse is present. Because the axis of the valley lies oblique to the structural zonation of the bedrock, the Upper Marine Molasse traverses the valley axis just south of Weiler (Fig. 2).

Of importance to the present study is the occurrence of an epidote-rich zone at the base of the Upper Marine Molasse ('Luzerner Schichten'); the remaining part of the Molasse in the area contains a heavy-mineral assemblage in which epidote is virtually absent and is dominated instead by garnets (WOLETZ 1958, FÜCHTBAUER 1964). The total heavy mineral content of Molasse sandstones is low: generally the weight percentage is less than 0.5% (HOFMANN 1957, FÜCHTBAUER 1964, both using the 0.06–0.4 mm fraction).

During the Pleistocene, the area was covered several times by the eastern part of the Rhine-Valley glacier,

but evidence for multiple glaciation is scarce. Multiple-till sections in the region have been described by e.g. WEINHOLD (1973), SCHREINER (1976), HERRMANN & SCHWED (1983) and DE JONG (1983). Sediment-petrographic analyses of such sections do not provide us with stratigraphic tools, and at present C-14 dating of organic beds is the only stratigraphic marker available. Dates from sub-till organic deposits, as summarized by DE JONG (1983), suggest a Middle-Würm ice-free period prior to the Late-Würmian glacial maximum of about 22,000–16,000 yr. BP. For the larger part of the area north of the Alps, it appears that there is no consensus (see e.g. WEINHOLD 1973; WELTEN 1976; SCHLÜCHTER 1978; VAN DER MEER 1982; DE JONG 1983), and nor is there really any strong evidence, concerning the age of till underlying the dated horizons. It is variously classified as being of Middle-Würmian, Early-Würmian (Turicum 2 and Turicum 1, respectively, in the concept of WELTEN, 1976) or Rissian age.

As far as we are aware, the only sub-till organic material from the Rotach valley was discovered by the second author in an exposure of the Weissebach, west

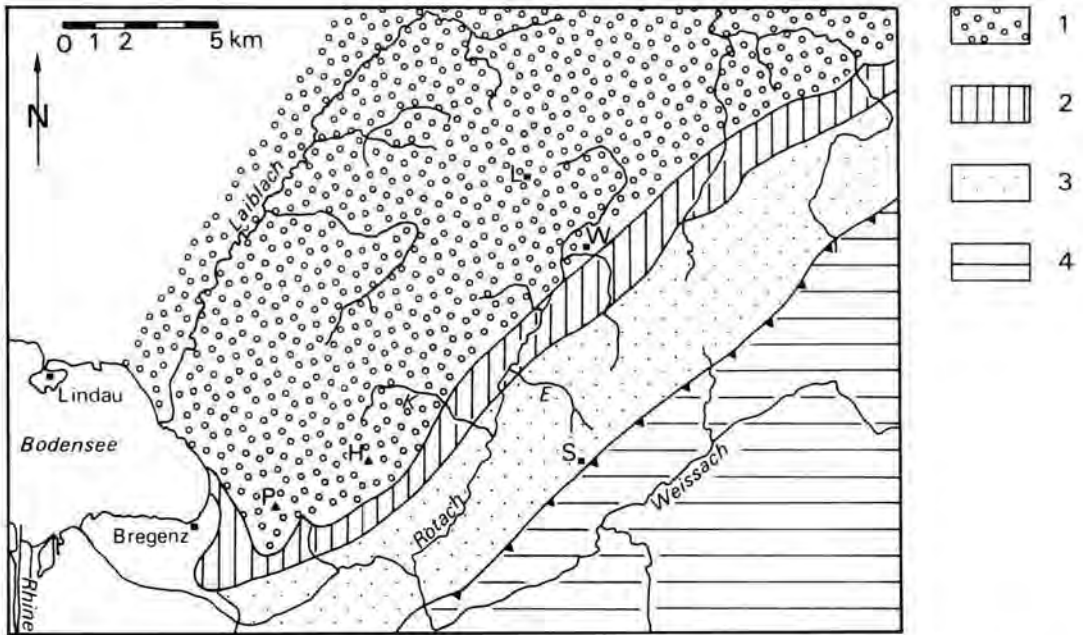


Fig. 2: Simplified bedrock geology. 1. Upper Freshwater Molasse, 2. Upper Marine Molasse, 3. Granitic Molasse, 4. Inner Younger Molasse. Letters refer to topographic names shown on Fig. 1.

of Weiler (site 64 in Fig. 1), and dated as minimal  $42.100 \pm \begin{smallmatrix} 3500 \\ 2400 \end{smallmatrix}$  yr BP (GrN 12281). The organic material occurs in a section consisting of a subglacial till on top (about 3 m thick), overlying about 8 m of gravel with some diamictons of sediment-flow genesis, overlying about 7 m of weathered gravel with a sandy layer near its base, containing the reworked organic debris. Below this are shales of the Molasse (VAN GIJSSEL 1984).

Finally, in a section of the Bösenreutin Tobel (site 18 in Fig. 1) two tills overlie an organic-bearing deposit, which is suggested to be pre-Rissian in age by HERRMANN & SCHWERD (1983).

The Quaternary cover seldom exceeds 20 m in thickness, and the contour pattern in Fig. 1 therefore approximates the bedrock relief. A number of major relief features in the bedrock surface, such as the Pfänder-Hirschberg ridge (1095 m) and Sulzberg ridge (1041 m), separated the Rhine-Valley glacier entering the Foreland into several glacier tongues occupying the major valleys. From east to west the Weissach, Rotach, Argen-Leiblach und Schussen glacier tongues can be distinguished.

Whether the Sulzberg and Pfänder-Hirschberg ridges were completely covered with ice or remained as nunataker standing above the ice during the maximum of the Late-Würmian glaciation is still a matter of dispute. According to VOLLMAYR & ZIEGLER (1976)

and HERRMANN & SCHWERD (1983), pre-Würmian moraines cover the top of these bedrock ridges, whereas e.g. SCHMID (1955) and KRAYSS & KELLER (1983) assume that these ridges were completely covered by the Rhine-Valley glacier at its maximum.

An important morphologic feature is represented by the so-called Inner Younger Endmoraine, which is analogous to the sediment complex formed during the stadial complex Würm-Stein am Rhein as defined by KELLER & KRAYSS (1980). In the study area, this ice-marginal feature has been mapped and discussed by SCHMID (1955), VOLLMAYR & ZIEGLER (1976), KELLER & KRAYSS (1980), DE JONG (1983) and VAN GIJSSEL (1985), among others. Its position is indicated in Fig. 1.

Because deglaciation of the area proceeded down the regional drainage slope, ice-marginal and proglacial lakes formed in front of the retreating glacier front (e.g. VOLLMAYR & ZIEGLER 1976; VAN GIJSSEL 1985).

The last two major tributaries feeding the Rhine-Valley glacier on its eastern flank were the Ill and Landquart glaciers. According to KRASSER (1940), the Rotach valley was covered by part of the Landquart glacier, whereas the Ill branch occupied the Weissach. The source area of these two glaciers is underlain predominantly by sedimentary rocks (mainly limestone, dolostone and calcareous shales), but in the upper reaches of their basins metamorphic rocks also occur.

Especially important is the amphibolite of the Silvretta massif as an erratic indicator in glacial deposits of the Alpine Foreland.

### 3. Methods

In the field, stratigraphic sections were measured, and sediments classified following a simple lithofacies schema (see Fig. 3).

Gravel petrography was determined for the 8–16 mm fraction, from counts of 100–300 clasts. The distinguished classes are listed in Table 1.

Heavy-mineral composition was determined for the 0.25–0.125 mm (2–3  $\phi$ ) fraction, after destruction of carbonates (and apatite) with hydrochloric acid and separation of heavy and light fractions by use of bromoform (s. g. 2.89). Opaque minerals, rock fragments, and mica-type minerals (includes in fact all platy minerals, here) were counted separately from the remaining transparent minerals and their percentages are given in the tables as percentages of the total heavy mineral fraction. Percentages of the remaining transparent minerals are given relative to each other. At least 300 grains were determined by band counting.

Carbonate content for the fraction smaller than 2 mm ( $-1 \phi$ ) was determined by measuring loss of weight after destruction of the carbonates by 1 N HCl, and is given in Table 1 as weight percentage CaCO<sub>3</sub> equivalents. The calcite/dolomite ratio was determined by measurement of peak-heights in densitometer readings from the diffraction lines of X-ray recordings of powdered sample splits. The procedure essentially follows, and produces similar results as the method proposed by TENNANT & BERGER (1957).

Grain size distribution was determined by dry sieving for the sand and gravel fractions and by pipette method for the silt and clay fractions.

## 4. Discussion of results

### 4.1. Lithostratigraphy

A number of measured sections from the Eyenbach and Kesselbach exposures are depicted in Fig. 3. The oldest deposits are strongly weathered gravel consisting mainly of local Molasse components, and occur at the base of sections at sites 4 and 30 (Fig. 3, Table 1). These gravel deposits may be correlative with the weathered gravel deposit at site 64 that contains the dated organic material (see section 2). Stream flow directions measured in these gravel deposits indicate a down-slope transport (which is normal to a supposed ice-marginal drainage); this, together

with the predominant local provenance, suggests deposition during an ice-free period, prior to the late-Würmian maximum.

Glacial deposits exposed along the Eyenbach above approximately 925 m pre-date the formation of the Inner Younger Endmoraine (IYE). Two tills are present at site 5, separated by sorted sediments. The inter-till deposit consists of laminated silts overlying a sandy-gravelly sediment-flow deposit, with slumped sand and gravel at its base (see also site 4 in Fig. 3). The gravel fraction of this deposit is very rich in far-travelled components, suggesting proximity of an ice margin. These inter-till ice-marginal deposits may be related to a minor oscillation of the glacier margin, with no regional significance. Alternatively, the lower till at site 5 might pre-date the late-Würm ice cover, but we have no indications for that.

Site 57 lies approximately at the position of IYE, and the disturbed gravel deposit at the top of this section was probably deposited during this stillstand. Also at site 57, and at site 7, a boulder pavement occurs several metres below the top of the section. Because of the large difference in altitude between the two sections, it is questionable whether the boulder pavements are correlative. This refers to a general problem in areas of alpine relief, where the large height differences over short distances create major difficulties for stratigraphic correlation.

Several two-till sections also occur on the Kesselbach side of the valley. These sections lie below the level of the IYE, and in some the upper till may therefore correlate with the formation of the IYE. This depends whether the IYE complex represents a major readvance of the glacier or whether it is a recessional complex, involving no significant advance of the glacier margin (see KELLER & KRAYSS 1980; DE JONG 1983).

The section at site 12 illustrates the complex sequences one commonly encounters in alpine environments. It must be stressed that not every intra-till sorted sediment band represents a deglaciation event. The frequency and distribution of such deposits in till suggest that in many cases they were deposited subglacially (RAPPOL 1983).

For reasons of stratigraphy, it is rather critical to be able to distinguish between subglacial till and diamictic tills formed by mass movement processes (debris-flow deposits, or "Pseudomorane" as these were called by von KLEBELSBERG 1948). The problem has been discussed by DE JONG & RAPPOL (1983) and RAPPOL (1983); criteria listed by these authors were used in this study. However, as no unequivocal criteria are available, the distinction may remain problematic especially in the case of poor exposure.





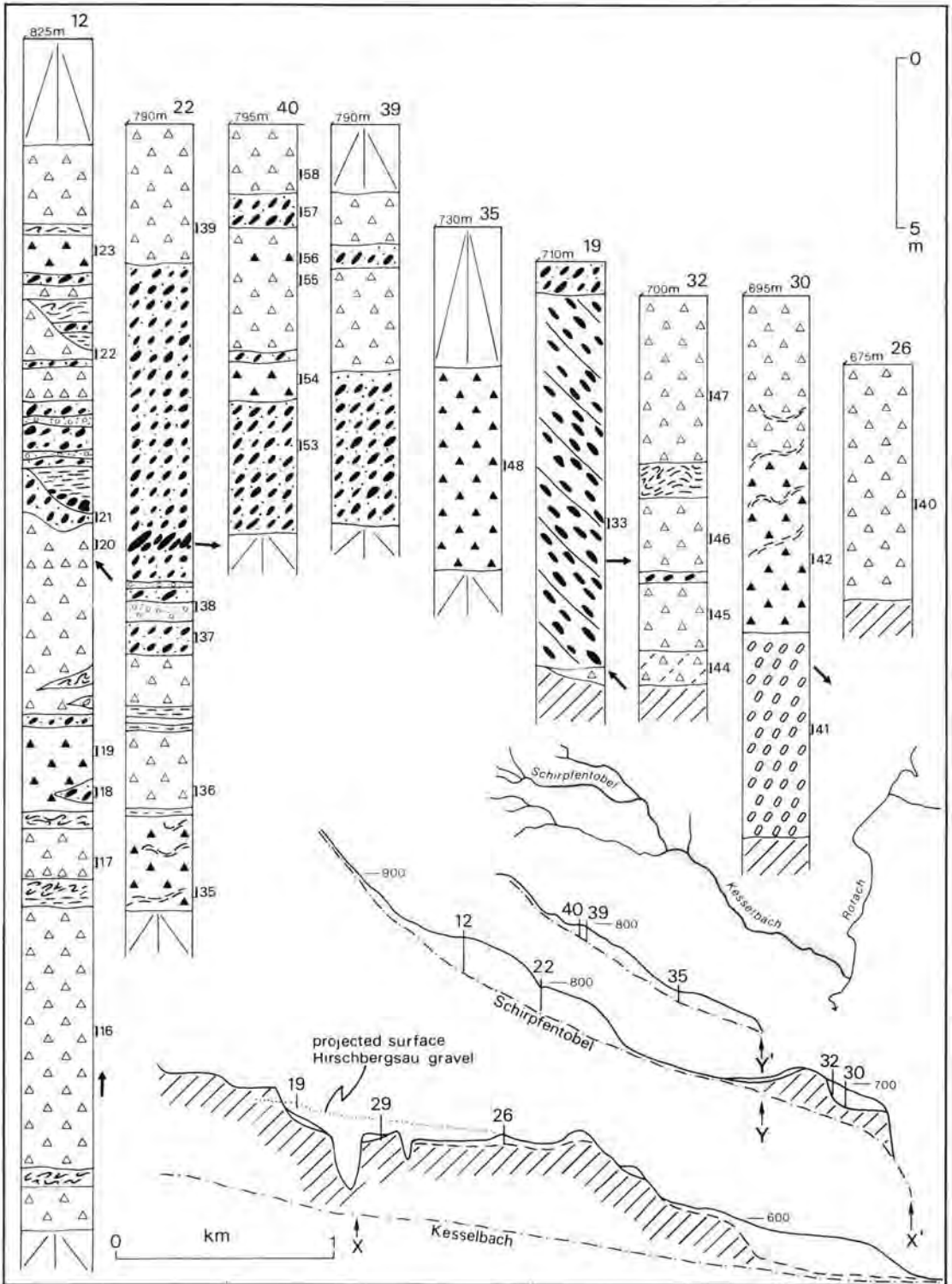
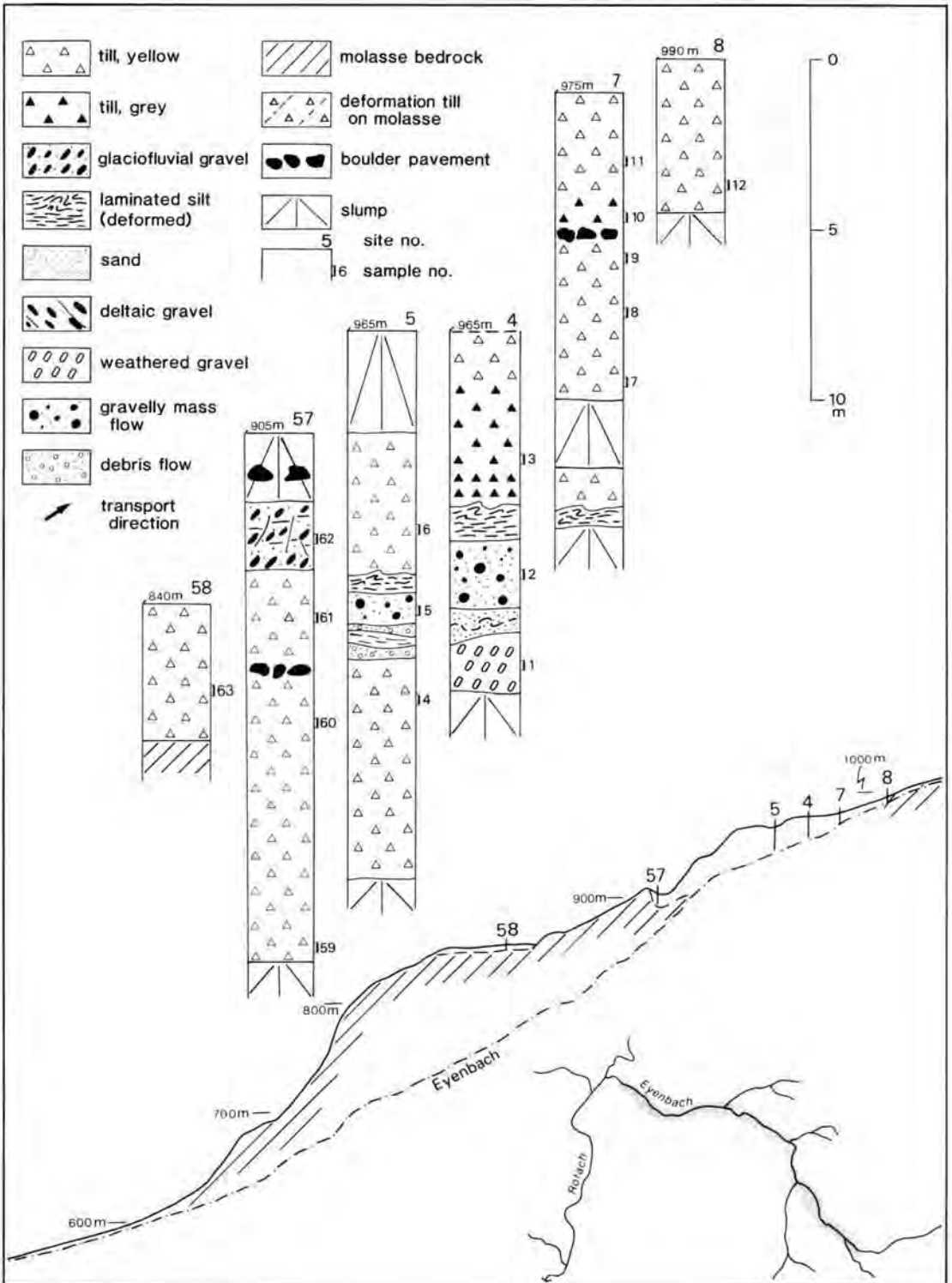


Fig. 3: Stratigraphic sections along the Kesselbach and Eyenbach gullies.





Tab. 2: Compositional data (%) from some tills deposited by the Rotach and Argen-Leiblach lobes of the Rhine-Valley glacier. The first 4 samples are from till deposited up-glacier from the outcrop area of the Upper Marine Molasse in the Rotach valley. Below these follow samples down-glacier from this zone. Down from sample 32, deposits belong to the Argen-Leiblach lobe. For samples whose numbers start with 81—, gravel petrography was determined for the fraction 5—8 mm, and without distinguishing between the different Molasse lithologies

sample no.	sample site	carbonate	calcite + dolomite	grain size				gravel petrography							heavy mineral composition								sediment type				
				gravel	sand	silt	clay	Molasse	-conglomer.	-sandstone	-siltstone	limestone + dolostone	amphibolite	rest cryst.	quartz	calcite	rest	weight %	opaque	rock fragm.	mica	amphibole		epidote	garnet	staurolite	tourmaline
15	1	71	2.1	24	26	33	17	1	4	3	86	-	-	-	2	4	0.9	42	16	18	44	24	16	5	3	2	till
65	59	55	2.3	22	33	35	10	10	30	22	32	1	1	-	1	2	0.5	46	10	14	38	9	37	6	2	2	till
8101				20	45	25	7	--	13--	--	75	1	2	-	-	8	0.9	38	5	1	16	21	54	5	2	1	till
8102				18	33	37	11	--	19--	--	69	1	3	-	2	5	0.6	24	12	2	43	27	20	2	1	1	till
8106				15	42	35	8	--	57--	--	34	1	3	-	1	4	0.7	23	9	3	17	50	27	2	-	-	till
8107				23	38	30	10	--	12--	--	70	2	8	2	2	6	1.6	14	3	1	27	42	23	2	1	1	till
8108				20	38	31	12										1.6	18	15	2	27	33	28	4	2	-	till
8109				15	39	35	12	--	8--	--	74	1	11	1	2	3	1.9	23	22	2	38	42	11	6	-	-	till
1131	63			14	27	42	18										0.1	22	2	4	12	14	52	4	-	8	till
1143	63	16.7		12	33	41	13	7	81	-	9	-	2	-	-	1	0.1	53	3	2	4	15	62	7	1	6	till
50	34			23	36	29	12	9	16	1	64	3	3	1	1	3	1.1	16	8	2	27	39	21	4	2	1	till
1150	64			18	27	39	16										1.0	33	3	5	25	25	39	1	3	4	till
32	18							8	2	-	55	6	20	2	1	6											gravel
31	18	2.4		29	34	29	9	20	7	1	49	3	14	1	-	5	4.4	7	7	3	41	44	11	2	-	-	till
30	18							9	2	-	61	4	19	2	-	4											gravel
29	18	3.3		10	31	49	10	16	7	-	51	-	14	4	-	6	2.3	9	10	5	42	37	12	1	1	-	till
26	15	5.6		16	34	40	11	5	42	13	29	-	7	1	1	2	1.0	18	7	5	34	20	32	3	3	2	till
25	14	16.7		9	28	45	19	3	46	24	15	-	3	2	2	6	0.7	24	12	2	24	29	36	3	1	1	till
24	14	100		-	-	100	-	-	-	100	-	-	-	-	-	-	0.3	60	5	5	1	2	67	6	8	13	def.till
1156	62			23	24	38	16										0.2	29	7	5	29	17	42	3	-	2	till
1151	61			18	28	37	18	1	7	2	83	-	2	1	1	3	0.8	18	12	2	35	22	31	4	1	-	till

The contact between till and Molasse is exposed in places. On sandstone and conglomerate, this contact is generally sharp and abrupt, with a polished and striated bedrock surface. On sandy siltstones however, the upper part of the bedrock is commonly brecciated and changes upwards gradually into a deformation till containing traces of far-travelled components (see Table 3, and samples 44 and 24 in Tables 1 and 2, respectively). Also where till overlies laminated, silty deposits, the latter are commonly strongly deformed in their upper part, and mixed with till. On gravel, the contact is generally sharp, but erosion is indicated by a gravel-enriched zone at the base of the till.

Till colour alternates from grey to yellow, the latter getting more brown close to the surface. According to GERMAN *et al.* (1979), till colour reflects the nature of the dominant source rock lithologies: grey results from debris rich in Alpine limestones, whereas yellow tones result from large amounts of Molasse-derived material in till. In a limited number of cases this relationship seems to hold, but more commonly another factor seems more important. Grey and yellow occur not only in till, but also alternate in glaciolacustrine silts as well as in calcareous shales of the Molasse. These colours are also found in tills deposited by cirque glaciers of the limestone region of Vorarlberg; in places till colour changes from yellowish to grey as one digs into the vertical face of a till exposure. The main factor in determining till colour is, therefore, the oxidation state of the material, which may show a relation to grain-size distribution rather than petrography

(compare for example samples 55 and 56 from site 40 in Table 1).

Sedimentation in connection with the existence of a large ice-dammed lake in the Rotach valley is represented by fine-grained lake bottom sediments and coarse-grained deltaic deposits.

Fine-grained laminated or massive deposits occur at many locations near the valley axis and may exceed a thickness of 20 m. In a small pit at Fischanger (site 60 in Fig. 1) trace fossils were observed on the coarse silty partings of the otherwise clayey and laminated deposit. However, with respect to pollen content, the deposit was virtually sterile over the entire 3 m height of its exposure (pers. comm. Dr. R. T. SLOTBOOM).

Coarse-grained delta or fan-delta deposits are found at several levels in the Rotach valley. The largest of these is found at Hirschbergsau, south of the Kesselbach. It is preserved as an undissected, eastward sloping surface at about 670–680 m a. s. l. and consists of about 10 m of subhorizontally bedded gravel overlying bedrock (HEINZ *et al.* 1984). At least two remnants of higher delta levels are present in this area, showing topsets and foresets in a gravel pit west of Hirschbergsau (site 19), and overlie striated bedrock with till pockets. These deltaic deposits represent what may be called paraglacial sedimentation (see CHURCH & RYDER 1972) by the late-glacial Kesselbach. The Hirschbergsau gravel deposit is probably time-correlative with ice-contact and deltaic deposits west of

Tab. 3: Heavy mineral composition (%) of till deposited by local cirque glaciers in the Subalpine Molasse area, south of the river Weissach, and of deformation till on sandy calcareous shales of the Molasse at site 61 (samples 1152, 1153) and site 65 (1103, 1104). See also samples 44 (Table 1) and 24 (Table 2). Sample 1131 represents Molasse-sandstone rock fragments taken from a till at Steinegaden (site 63). For site locations, see Fig. 1

sample no.	weight %	opaque	rock fragm. mica		amphibole	epidote	garnet	staurolite	tourmaline	disthene	zircon + rutile	rest	sample type
919	0.3	83	1	4	-	2	70	11	2	3	9	3	till of cirque glacier
922	0.3	68	5	7	-	3	75	8	8	-	4	1	till of cirque glacier
960	0.3	71	2	6	-	-	70	16	7	-	6	3	till of cirque glacier
1131	0.3	22	2	5	1	38	43	2	3	1	8	4	Molasse sandstone
1103	0.1	50	6	10	13	13	50	5	3	3	9	5	deformation till
1104	0.1	almost exclusively opaque minerals										deformation till	
1152	0.3	58	5	4	2	3	71	7	5	1	5	7	deformation till
1153	0.4	53	2	1	3	6	64	8	8	2	5	3	deformation till

Langen (Vorarlberg), as mentioned in DE GRAAFF (1986, and pers. comm.).

#### 4.2. Gravel petrography

Results of the gravel countings indicate the presence of a striking cross-valley variability as well as large variations in vertical profiles (Table 1).

Firstly, the nature of Molasse components in till is a direct reflection of local bedrock lithology. Till along the Kesselbach is especially rich in conglomerate and sandstone rock fragments, whereas till in the Eyenbach gully contains mainly sandstone and shale fragments. This difference reflects the main lithologies of the Upper Freshwater Molasse and the Granitic Molasse, respectively (compare with map and profiles in VOLMAYR & ZIEGLER, 1976).

Secondly, the amount of igneous and metamorphic rock fragments (I + M) is clearly higher in till of the Kesselbach sections than in that of the Eyenbach. This phenomenon seems independent of the amount of locally derived components, and therefore represents a characteristic of the far-travelled debris. There may be several factors that contribute to the explanation of this observation. In the first place it may reflect a regional trend within the area covered by the eastern part of the Rhine-Valley glacier, where we expect an increase of I + M from east towards west (see also DE JONG 1983; 67). This follows from the fact that the last two major tributaries on the eastern side of the Rhine-Valley glacier — the Landquart and Ill glaciers — drained areas that for a considerable part are underlain by sedimentary bedrock. In the Weissach valley, east of Sulzberg, the amount of I + M in till deposited by the Rhine-Valley glacier seldom amounts to 1% or more, and the majority of fragments are amphibolite (KNAACK 1985, and pers. comm.). In the Rotach valley, along the Eyenbach and along the Sulzberg ridge in general, the amount of I + M varies between 0 and 3% (it should be noted that some I + M rock fragments are present in all samples; this was noted in scanning many hundreds of particles in the 4–8 mm fraction).

Along the Kesselbach, total I + M percentages are generally well over 3%, with a tendency for more I + M -rest than amphibolite fragments. Still more to the west, the countings of DE JONG (1983) generally show a strongly subdued proportion of amphibolite compared to I + M -rest, with percentages of total I + M usually well over 10%.

In our study of the Rotach valley, another factor may be of importance. As noted before, most samples from the Eyenbach exposures are from till that pre-

dates the formation of the Inner Younger Endmoraine, while those of the Kesselbach may be younger. It is likely that the positions of the individual flow paths of the glaciers building the Rhine-Valley glacier were not stable during the full period of glaciation. During maximum glaciation, the Bregenzer Wald glacier may have pressed against the eastern part of the Rhine-Valley glacier, pushing it westwards; but there is evidence that during deglaciation, when the Rhine-Valley glacier still occupied part of the Rotach and Weissach valleys, the Bregenzer Wald glacier had retreated from the northern part of the Bregenzer Wald and made no contact with the Rhine-Valley glacier (e.g. KRASSER 1940; SIMONS 1986). For a deglaciation phase still younger than the IYE, KRASSER (1940) suggests that the Ill glacier occupied the lower reach of the Weissach valley, whereas the Rotach valley was occupied by ice originating from the Landquart valley. A shifting of the flow lines in the Rhine-Valley glacier in a southeastern direction during deglaciation may be expected to result in higher I + M percentages in till deposited at a certain spot during later stages.

There are also considerable variations within vertical profiles, as a consequence of variable amounts of local versus erratic material. In several cases, where till overlies gravel deposits that are rich in far-travelled components, the overlying till, or at least its basal part, also contains much far-travelled material (e.g. in sections 4, 5 and 40), suggesting reworking of the glaciofluvial deposits.

#### 4.3. Heavy mineral composition

Characteristics of the heavy mineral composition and its variability in till of the Rotach valley are in some respects similar to variations in gravel petrography. There are some basic differences too, however, that are mainly the result of a much higher concentration of heavy minerals in part of the far-travelled fraction. Among other things, this is demonstrated by the high concentrations of amphibole-group minerals compared to amphibolite rock fragments, both of which are not present in the Molasse and sedimentary rocks of the East-alpine and Helvetic nappes of Vorarlberg. The amphiboles and amphibolites derive primarily from the Silvretta crystalline area and are transported to the study area by the Ill glacier and, to a lesser extent by the Landquart glacier. The data given by HAHN (1969) illustrate well the importance of the Silvretta amphibolite for the heavy mineral composition of modern river sediments of the Rhine valley downstream from the Ill confluence; according to HAHN (1969: 263), heavy mineral concentrations in modern sediments of the Ill river are the highest for the entire Rhine catchment.

Table 3 summarizes some data that give an indication of the heavy mineral composition of the Molasse rocks. HOFMANN (1957) and FÜCHTBAUER (1964) indicate heavy mineral weight percentages of usually less than 0.5 % for Molasse sandstones in a large area of Switzerland and southern Germany. Even though the till contains much reworked local bedrock, and moreover a high percentage of limestone and dolomite rock fragments, its heavy mineral concentration is much higher. Given also the composition of the heavy minerals, this indicates that incorporation of Molasse material will first of all lower the heavy mineral weight percentages. Compared to other components, a relatively large proportion of the heavy minerals are thus derived from a remote source (BIK 1960; DE JONG 1983). By no means, however, does this imply that the entire till-forming debris is directly transported by the ice from a remote source. The far-travelled components are moreover probably reworked from sub-till glaciofluvial deposits, as is indicated by the vertical variation in sections in Fig. 3 and Table 1 (e.g. site 40).

Table 3 shows that, in the fraction used here, most Molasse is characterized by a heavy mineral assemblage consisting mainly of garnet and opaque mine-

erals. Two samples (sample 44 in Table 1 and sample 1131) contain less garnet and opaques, but much epidote instead; both these samples are from the Rotach-lobe deposits. The epidote-rich zone is known from the base of the Upper Marine Molasse (WOLETZ 1958) and may also occur in a thin upper zone of the Granitic Molasse (see Fig. 2).

Fig. 4 shows the effect of the presence of this zone on the heavy mineral composition of till in the Rotach valley. Down-glacier of the Upper Marine Molasse, many till samples contain an anomalously high percentage of epidote-group minerals. This can only be interpreted as being the result of erosion and incorporation of epidote-rich Molasse material. Sample 1131 (in Table 3) in fact represents Molasse sandstone fragments taken from a till at Steinegaden (site 63 in Fig. 1) deposited by the Rotach lobe. Note also that till deposited up-glacier from the Upper Marine Molasse commonly contains more garnet than till of the Argen lobe, suggesting a higher contribution of local material to the heavy mineral fraction in the Rotach valley. The same applies for till of the Weissach valley.

These results correspond well with the findings of GASSER & NABHOLZ (1969), who demonstrate a strong relationship between till and bedrock mineralogy in the Molasse zone of Switzerland.

The fact that in the Argen lobe area this relationship seems absent must be due to the following factors, 1) higher heavy mineral weight percentages in the far-travelled debris because it contains more material derived from igneous and metamorphic source rocks, and 2) more glaciofluvial deposits masking the bedrock and acting as local sources of far-travelled material.

A good example of the effect of the local glacier-bed materials on till composition is provided further by some observations in the Argen-Leiblach area. The sedimentary sequence at site 18 has been described by HERRMANN & SCHWERD (1983: e.g. their figure 2). We sampled a section at a site southwest of Tobel. At the base occur lacustrine laminated silt and sand (over 4 m thick) containing, especially in the upper part much organic material including large wood stumps. The lacustrine deposit contains a heavy mineral assemblage that is typical for the local Molasse bedrock (84 % garnet; HERRMANN & SCHWERD 1983: 11), suggesting a non-glacial origin. It is overlain by a lower till (sample 29 in Table 2), about 7 m thick. The lower till is overlain by 3.5 m of gravel with silty layers (sample 30), which in turn is overlain by 2.5 m of an upper till (sample 31), and, finally 2 m of gravel deposit (sample 32).

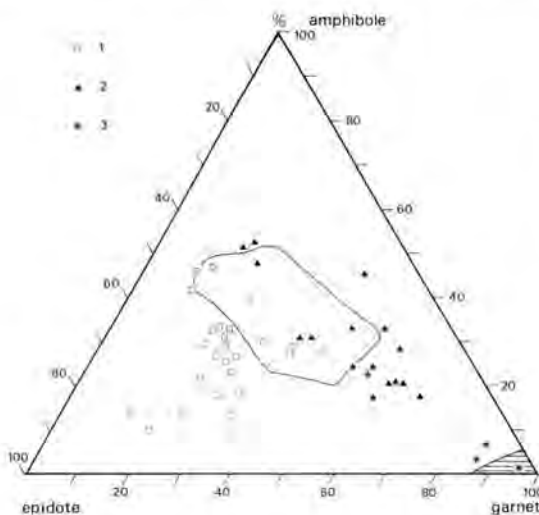


Fig. 4: Heavy mineral composition of till in the Rotach valley compared with data from adjacent areas.

1. Rotach-valley till, down-glacier from the Upper Marine Molasse outcrop.
2. Rotach-valley till, up-glacier from the Upper Marine Molasse outcrop.
3. Till from the Weissach valley.

The enveloped area represents 32 samples (of which 23 in DE JONG 1983) of the eastern part of the Argen-lobe area. The horizontally hatched area on the lower right envelopes 14 till samples from the Molasse zone covered by the western Iller glacier.

The lower till shows much evidence of reworking of a considerable amount of material from the lacustrine deposit, since it contains much dispersed organic debris and lenses of unconsolidated and deformed silty sediment. This is reflected by the high silt content, and also by a low heavy mineral weight percentage compared to the upper till (see Table 2). Incorporation of the lacustrine deposit did not affect the gravel petrography and the composition of the transparent heavy minerals, and in this respect, both upper and lower till show compositions typical for far-travelled material.

Approximately 4 km to the northeast, till overlies sandy siltstones of the Molasse. At site 14, the till (sample 25) overlies about 1 m of brecciated shales and deformation till (sample 24), with slickensided shear-planes indicating transport towards N25° E. Samples 25 and 26 indicate considerable reworking of bedrock material by their gravel composition (Table 2), and also by comparatively high concentrations of garnet and opaque minerals, and low heavy-mineral weight percentages.

#### 4.4. Carbonate content

Total carbonate content of till in the Rotach valley ranges between 40 and 60 % (Table 1) and provides no basis for till differentiation. Mean and standard deviation for 36 samples are 50.0 and 8.8 %, respectively. These values compare well with those obtained by BIK (1960) from an area in Vorarlberg, south of the Molasse zone, where till of the Rhine-Valley glacier overlies Cretaceous limestone and calcareous shale of the Helvetic series:  $50.9 \pm 8.5$  % for 36 samples. This similarity suggests that carbonate content of the local Molasse bedrock and of the erratic debris in till of the Rotach valley varies largely within the same limits. Data given by HOFMANN (1957) and FÜCHTBAUER (1964) for carbonate content of Molasse sandstone range between 30 and 70 %, showing strong local fluctuations, but from the Rotach valley little data are available.

Carbonate content of sample 15 at site 1, which was taken from a fine-grained grey till on the flank of a small moraine ridge (see Fig. 1 and Table 2), is anomalously high (71 %), corresponding with an equally extreme value of 86 % limestone and dolostone fragments in the gravel fraction. In general, however, carbonate content of the matrix and limestone/dolostone content of the gravel fraction are poorly correlated.

The calcite/dolomite ratio is higher in till along the Kesselbach, and shows a positive correlation with the amount of Molasse rock fragments in the gravel fraction. This is in accordance with a low dolomite

content, of the Upper Freshwater Molasse as reported by HERRMANN & SCHWERD (1983: 8).

The source of the erratic dolomite and dolostone should be sought in the lower reaches of the Ill valley and its tributaries. Again, the results of HAHN (1969: figure 8) demonstrate the strong effect of the Ill confluence on the carbonate, and especially dolomite content of modern Rhine sediments.

#### 4.5. Grain size distribution

Variations in the relative frequencies of the main granulometric classes in till of the Rotach valley are given in Table 1 and 2. These properties change rapidly in vertical profiles as well as laterally, which is mainly due to reworking and incorporation of variable amounts of local bedrock and/or unconsolidated materials (mainly either glaciolacustrine silt or glaciofluvial gravel). Sand-silt-clay ratios in the Rotach valley overlap almost completely with such data from the Argen-Leiblach lobe (DE JONG 1983) or Iller glacier (RAPPOL 1983). There is also not much difference from diamictons formed by mass movement processes. These data, therefore, provide little basis for the characterization of significant variations in petrography or facies.

The shape and origin of the grain size frequency distributions in till from Vorarlberg and western Allgäu was recently discussed by CAMMERAAT & RAPPOL (1987). On the basis of the  $\phi$ -scale, till of the Molasse zone is generally characterized by modes in the gravel, fine sand, and silt fractions. Most till of the Rotach valley exhibits these characteristics as illustrated in Fig. 5. Sample 1151, however, is from a grey till near Lindenberg (site 61 in Fig. 1), which overlies a yellow deformation till on Molasse shales. This sample shows a distribution more similar to tills in the area south of the Molasse, where a mode in the fine sand fraction is generally absent (RAPPOL 1983; CAMMERAAT & RAPPOL 1987). The analysis of gravel petrography indicates that it contains very little material derived from the Molasse (see Table 2).

In the Molasse area, the main difference between size distributions of locally derived Molasse debris and far-travelled material in till lies in the frequency distribution of the sand fraction. Whereas far-travelled debris is more or less evenly distributed over the various  $\phi$ -classes, Molasse components generally show a deficiency in the coarse sand fraction and a prominent mode in the 2.5–3  $\phi$  fraction. For the Rotach valley, frequency distributions within the sand fraction are shown in Fig. 6. Sample 15 clearly deviates from the general trend, in a similar way as sample 1151 in

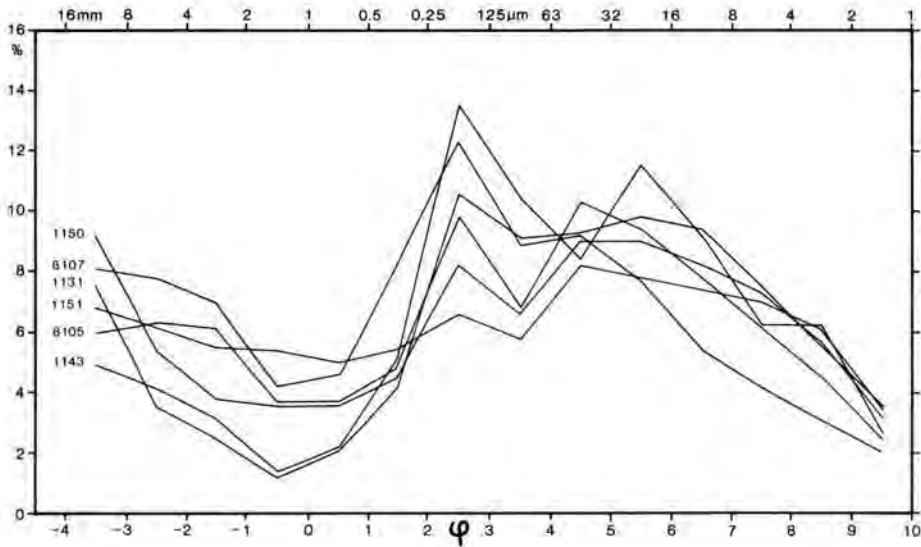


Fig. 5: Grain-size frequency distributions per  $1\phi$  interval for a number of selected till samples from the investigated area.

Fig. 5. Also, the gravel analysis of this sample indicates that it consists predominantly of far-travelled, non-Molasse components (Table 2).

Most other curves show a distribution that is strongly skewed towards the fine sand fraction, with deficiencies in the coarse sand and very fine sand fraction. There is, however, a striking difference between till from the Eyenbach gully and that from the Kesselbach. Till in the Eyenbach exposures is characterized by a prominent shoulder in the  $1-2\phi$  range; this is likely related to the grain size distribution of sandstones of the Granitic Molasse which underlies the glacial deposits on this side of the valley.

## 5. Conclusions

On the basis of their morphology, the major Pleistocene Alpine glacier systems can be subdivided into three segments: 1. the main accumulation area, with confluent cirque and small valley glaciers, 2. the main trunk valley, connecting the accumulation area with 3. the piedmont glacier where the ice mass spreads out over a large area. To attain and maintain such a system, high flow velocities and great ice thicknesses are needed in the narrow middle section (that is, the Rhine valley south of the Bodensee), and it is here that the erosional power of the ice is greatest. Many overdeepened valley sections on the north side of the Alps testify to the erosional power of these valley glaciers (e. g. BADER & JERZ 1979; SEILER 1979).

Although the piedmont area is often referred to as a predominantly depositional glacial environment, it seems clear that erosion by the ice is also an important geomorphic process. Overdeepened basins are found well into the piedmont area (e. g. GERMAN et al. 1967; SEILER 1979), and perhaps the Bodensee depression (SCHREINER 1979) should be regarded as the largest of these basins. Glacial erosion in the piedmont area is, however, also manifested by the large amount of incorporated local material, including preexisting glaciofluvial deposits, in till.

In the Rotach valley, several factors contribute to a considerable variation in till composition, and it is likely that these factors apply to a much larger area in the Alpine region than considered here.

The Rhine-Valley glacier is a large composite valley glacier, consisting of several major tributaries. Similar to compositional variations in lateral and medial moraines on active glaciers, lateral variations in composition of glacial deposits will reflect the distribution of source rocks in the areas drained by these glaciers. In the area considered here, among other things, such variations are reflected in an eastward decrease of the ratio of igneous + metamorphic rock fragments/limestone + dolostone. It is possible that the flow paths of the composite glaciers have shifted somewhat during the time of glaciation, creating differences in composition between older and younger deposits, and thus complicating the general picture.

A second source for compositional variation lies in the nature of the local bedrock, including unconsolidated

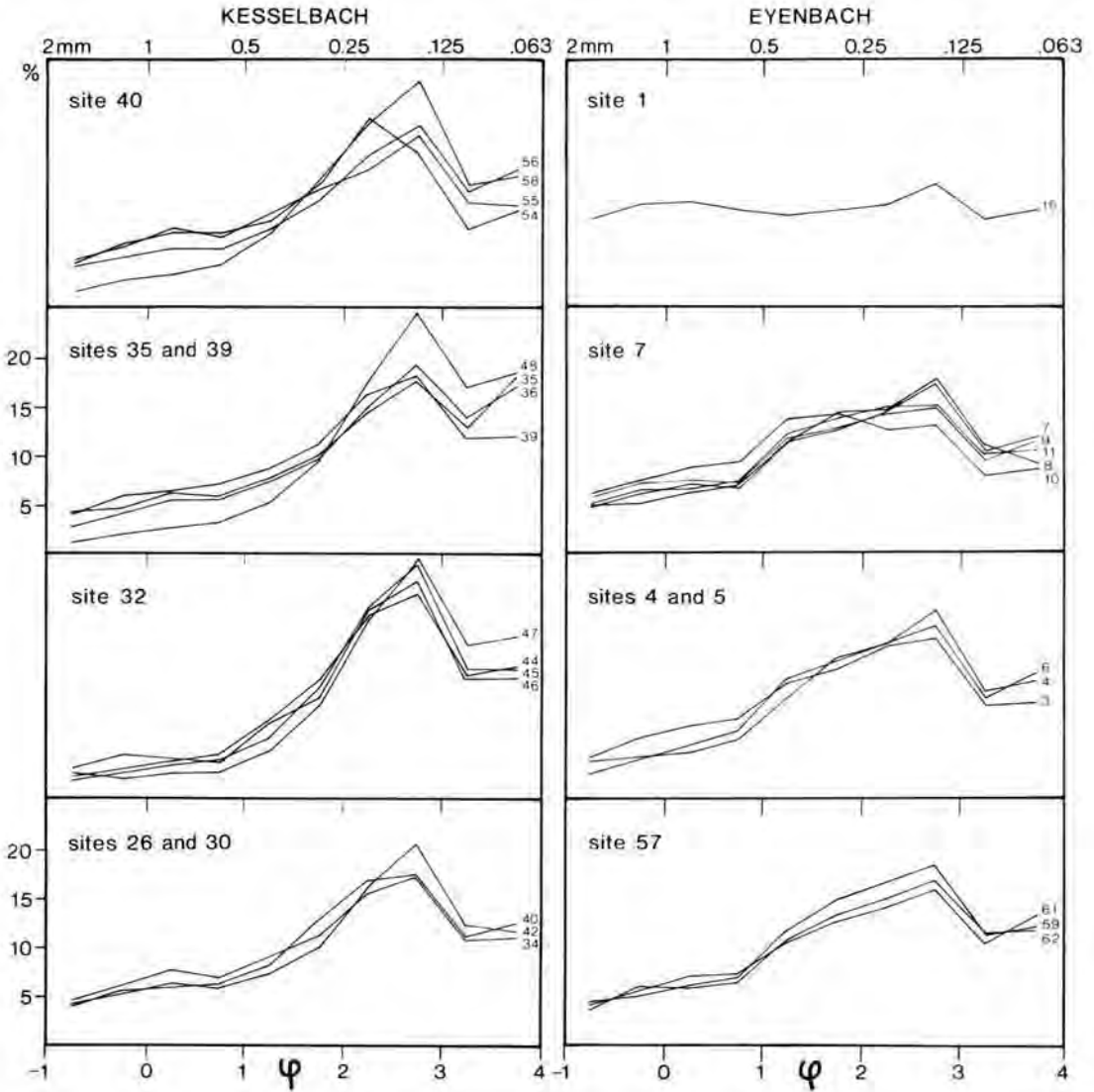


Fig. 6: Grain-size frequency distributions per 0.5  $\phi$  interval for the sand fraction (is 100 %) of till in the Rotach valley. Sites on the left are from the Kesselbach side, on the right from the Eyenbach side of the Rotach valley.

materials. As was demonstrated here, and earlier by GASSER & NABHOLZ (1969), composition of the Molasse may control many properties of the overlying till.

In many cases however, a close correspondence of Molasse and till composition may be obscured by interlayered glaciofluvial deposits.

For a correct interpretation of heavy mineral data, it is important to consider all components together with the weight percentages. For example, the amphibole content of 44 % for sample 15 (Table 2) appears much higher than the 24 % of sample 10 (Table 1); how-

ever, considering carbonate content, heavy mineral weight percentage, and amounts of opaque and platy minerals and rock fragments in the 2–3  $\phi$  fraction of the original sample material, the amphibole content in sample 10 is actually twice as high as in sample 15. Sample 15, in fact, represents material mainly derived from carbonate source rocks of Vorarlberg that are very poor in heavy minerals, and then mainly contains opaques and a type of platy mineral. A minimal contribution of material derived from crystalline bedrock (here amphibolite), completely determines the composition of the transparent heavy minerals in such a case.

Moreover, the heavy mineral concentration of Molasse rocks is low compared to that of the far-travelled material containing a significant amount of debris from crystalline source rocks, notably amphibolites.

The composition of the transparent heavy mineral fraction is therefore a poor indicator for the contribution of local material in till. Compared to material derived from limestones and dolostones, the heavy mineral concentration in the Molasse will be high. As noted by BIK (1960), most heavy minerals in till of the Rhine-Valley glacier, overlying bedrock of the Helvetic Series, are transported into the area by the ice, because the local bedrock contains hardly any heavy minerals in the analyzed fractions.

Because till composition is so strongly determined by the immediate substrate material, compositional parameters as the ones determined here, do not provide us with useful criteria for correlating tills or distinguishing tills of different age. It may help however, in distinguishing non-glacial deposits from glaciofluvial deposits, as the former tend to be relatively poor in far-travelled components. The significance of multiple tills is still difficult to evaluate, because comparative information from adjacent areas is lacking. The thin upper till in some of the Kesselbach sections may possibly represent a readvance of the ice associated with the formation of the Inner Younger Endmoraine complex. Multiple tills may be the result of several causes, however, and it is certainly not justifiable, in the absence of further evidence, to connect individual tills with separate major glacials; slight readvances, subglacial sedimentation of sorted material, and also mass-movement processes may produce separate tills or till-like diamictos belonging to one glaciation phase. Sediment-petrographic analyses as used in this study cannot be used as stratigraphic tools for tills in the area because glaciers followed much the same course during different glaciations, and local sub-till materials determine till composition to such a great extent; the data do provide however valuable information on the processes of glacial erosion and sedimentation. We strongly feel that there is much new information to be gained here, and that for further progress in our understanding of the glacial history of the Alpine foreland, detailed lithostratigraphic and sediment-petrographic analysis are needed.

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