Eiszeitalter u. Gegenwart	43	44 — 52 3 Fig., 2 Tab.	Hannover 1993

On the Relation between Subglacial Tills and the Substratum in Western Allgäu (Germany)

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Subglacial till, Molasse substratum, Quaternary deposits, granulometry, gravel petrography, heavy mineral analysis
Baden-Württemberg, Alpine foreland

Abstract: Grain-size distribution, gravel petrography, heavy mineral weight percentage and heavy mineral composition of subglacial tills from the Alpine foreland of western Allgäu (Germany) have been analysed to assess the relation between the sediments and the substratum. Except for a few well-defined local Molasse-derived deposits - the till petrography is dominated by far-travelled debris. The combination of petrographic evidence, theoretical considerations and broad-scale geomorphological observations leads to the conclusion that most till-forming debris was transported to the area during the last glaciation and that reworking of 'older' Quaternary deposits was subordinate.

[Zum Problem des Zusammenhanges zwischen Grundmoränen-Ablagerungen und dem Substrat im westlichen Allgäu (Deutschland)]

Kurzfassung: Korngrößen-, Kies- und Schwermineralanalysen würmzeitlicher Grundmoränen-Ablagerungen des Rheingletschers im baden-württembergischen Alpenvorland zeigen einen meist relativ niedrigen Einfluß des aus Molasse bestehenden Substrats auf die Zusammensetzung dieser Sedimente. Auf Grund theoretischer Überlegungen und großmorphologischer Beobachtungen wird geschlossen, daß auch die Aufnahme prä-existierender quartärer Ablagerungen untergeordnet war und daß die Petrographie der Moränen-Ablagerungen hauptsächlich bestimmt wird vom während der letzten Vorland-Vergletscherung vom Rheingletscher ins Vorland transportierten Schutt.

1 Introduction

The Quaternary deposits of the hilly and mountainous area of western Allgäu (Germany) and of the adjacent mountains of central and northern Vorarlberg (Austria) have been subject of many studies during the last decades (a.o. CAMMERAAT & RAPPOL 1987; GERMAN 1976; GERMAN & MADER & KILGER 1979; DE JONG 1983; DE JONG & RAPPOL & RUPKE 1982; RAPPOL 1983; RAPPOL & VAN GIJSSEL 1988; SIMONS 1985; WEINHOLD 1973). The study of sedimentary facies and petrography has not only resulted in a better understanding of the various glacial s.l. processes active in the past, but also enabled, through a combination with morphological studies, a detailed reconstruction of the history of deglaciation after the last major Pleistocene ice advance (DE JONG 1983; DE JONG & DE GRAAFF & RUPKE in prep.).

The present paper focusses on the origin of the subglacial tills in western Allgäu (Fig. 1), in particular on the relation between the tills and the local substratum. The topic has been discussed by several authors in the recent past. Based mainly on heavy mineral and gravel petrographic analyses, DE JONG (1983) argued that the influence of the Molasse substratum on the composition of most subglacial tills in western Allgäu was subordinate. He suggested that most till-forming debris had been transported by glaciers to the foreland, assuming little local reworking from sub-till fluvial and/or glaciofluvial deposits. Based mainly on granulometric analyses, CAMMERAAT & RAPPOL (1987; see also RAPPOL 1983) concluded that the till-forming debris in western Allgäu and Vorarlberg is for a major part of local, bedrock, origin. Sedimentary petrographic work on glacial deposits in the Rotach valley, straddling the boundary between Germany and Austria, by RAPPOL & VAN GIJSSEL (1988) showed the influence both of local bedrock and pre-existing gravels and of far-travelled debris on the composition of subglacial tills, the contribution of the first being considered predominant in most cases by these authors.

The terms 'local' and 'far-travelled' or 'remote' in the discussions refer to the compositional relationship between the tills and the substratum, not to the actual transport distance. A till is termed 'local' when (the largest part of) its sediment-petrography reflects

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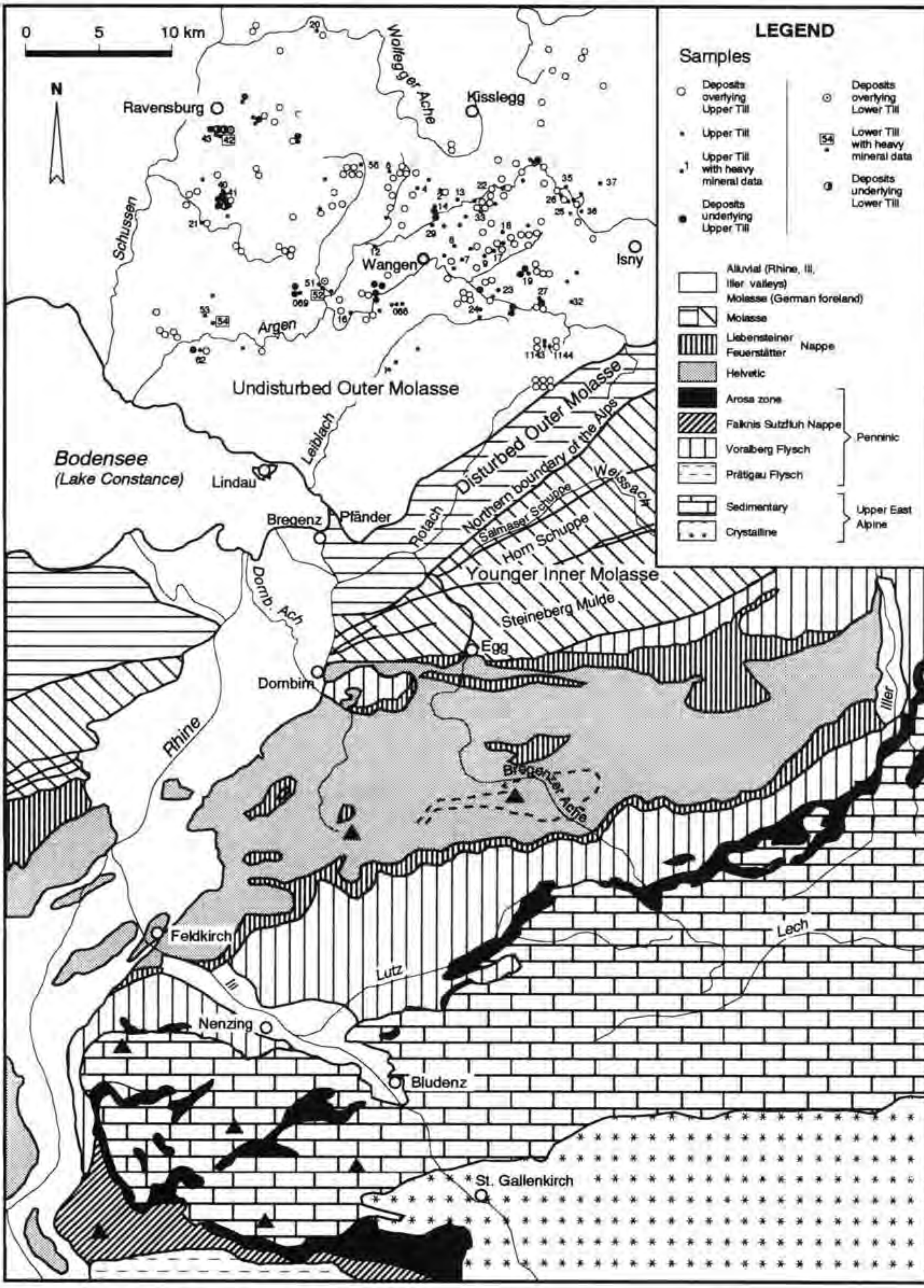

Fig. 1: Geological map of the region (after FUCHS 1980, D. RICHTER 1956, M. RICHTER 1969, and VOLLMAYR 1958). Also indicated are the sampling locations of the Quaternary deposits in the study area.

the composition of the substratum, irrespective of the actual transport distance. Conversely, the terms 'far-travelled' and 'remote' are used for tills with compositions which do not reflect the local substratum.

The emphasis on sediment-petrography bears the risk of under- or overestimating the actual transport distances and may hamper the discussions. The main glacier flow in Rhine and Ill valleys (Fig. 1) was at an angle with the SW-NE trending geological zones of the Alps and foreland. These zones show quite a variation in width (Fig. 1). It is conceivable that, for instance, Molasse debris in the Alpine foreland of Germany, which is underlain by Molasse bedrock, classifies as 'local' because of petrographic similarities with the substratum although the actual subglacial transport may have been tens of kilometers. Whereas glacial debris in the Alps after a short transport across one or more geological zones would be coined 'far-travelled' based on compositional differences with the bedrock. To avoid confusion, the terms in the present paper are used with as much specification as possible.

It is not the scope of the paper to present a comprehensive overview of the relation between tills and their substratum. Emphasis will be on a critical review of some of the aspects which have been in the centre of debate - grain-size distribution, gravel petrography, heavy mineral weight percentages and heavy mineral composition. Inspite of this limitation, a few general conclusions can be drawn.

Information on the methods of sampling and sample analysis has been presented by DE JONG (1983). The results of the analyses are tabulated in the same publication. An overview of the general glacier network in the area during the last glaciation is presented a.o. by KRASSER (1936) and KELLER & KRAYSS (1980).

2 Sub-till substratum geology

The study area is underlain by calcareous sandstones and shales of the Tertiary Upper Freshwater Molasse (Obere Süßwasser Molasse) in the so-called Undisturbed Outer Molasse tectonic unit (FUCHS 1980; HERRMANN & SCHWERD 1983; SCHMIDT 1976; SCHREINER 1978). Conglomerates are absent. Interbedded conglomerates do occur in the Disturbed Outer Molasse and Younger Inner Molasse to the S and SE, in the Pfänder-Hirschberg mountain ridge and in the Rotach and Weißach valleys (Fig. 1). Sediment-petrographically, the Molasse rocks in the study area are part of the so-called Bodensee fan ('Schüttung'), which includes the Pfänder fan, and the Hochgrat fan (FÜCHTBAUER 1954a, 1954b, 1967; HOFMANN, 1957). The Bodensee fan is characterized by a garnet-zircon-rutile-ore-staurolite heavy mineral association (Table 1). The heavy mineral weight percentage is less than 0.5%. The sediments are quartz-rich, feldspar-poor, calcareous (30-50%) and poorly to non-dolomitic. In most respects similar to the Bodensee fan, the Hochgrat fan is characterized by a garnet-staurolite-apatite heavy mineral association.

So-called older Quaternary deposits, which pre-date the subglacial tills, overlie the Molasse substratum in a number of pla-

Table 1: Heavy mineral compositions

	Hochgrat-Schuettung Molasse (Fuechtbauer 1954a)	Pfaender-Schuettung Molasse (Hofmann 1957)	Pleistocene sands E Switzerland (Gasser & Nabholz 1969)	subglacial tills western Allgaeu
garnet	48	46	20	26
zoisite	0			*
epidote	0	2	44	30
amphibole	0	0	35	36
staurolite	56	9	5	8
kyanite	2	+	1	2
zircon	1	26	2	+
rutile	2	17	1	1
sphene	0		+	1
tourmaline	4	3	1	2
apatite	34	4	8	
ore		39		abundant
rock fragments				11
troubled minerals				8
rest	1		2	2
grain size	0.06-0.4 mm	0.06-0.4 mm	0.06-0.4 mm	0.105-0.15 mm

notes: Garnet is given as percentage of total grains counted.
The other values are percentages of total grains minus number of garnet grains.
For further details refer to De Jong (1983).

ces in the study area (GERMAN 1977; DE JONG 1983; DE JONG & RAPPOL & RUPKE 1982; SCHMID 1955; SCHMIDT 1976; SCHREINER 1976, 1978; WEINHOLD 1973). The amount and distribution of these deposits is difficult to assess due to lack of exposures. Gravels, often sandy, appear to be predominant, with subordinate amounts of debris-flow deposits, fine-grained water-lain sediments, ablation tills and (older) subglacial tills. Based on a limited number of samples, DE JONG (1983) concluded that the gravel petrography of the 'older' deposits does not significantly differ from that of the subglacial tills (Table 2).

3 Petrographic analyses of subglacial tills

3.1 Grain-size distribution

The grain-size distribution of the subglacial tills (number of samples n=64) in the area of investigation has been described by DE JONG (1983) and was later discussed by CAMMERAAT & RAPPOL (1987). In a

Table 2: Gravel petrography

	Molasse Sst. (%)		Crystalline (%)	
	average	range	average	range
overlying upper till n=124	6.4	0–53.7	28.7	2.8–97.7
upper till n=79	10.5	0–81.3	24.2	5.1–61.7
underlying upper till n=23	5.1	0–10.7	22.6	1.4–44.0
overlying lower till n=2	1.7	0.7–2.7	20.6	15.7–25.5
lower till n=3	4.8	2.3–9.3	22.7	14.7–31.9
underlying lower till n=2	4.3	1.7–8.0	31.3	26.8–33.7

notes: 'Crystalline' includes granite, gneiss, ophiolite, amphibolite, epidote-rock, quartsite, etc.
For further details refer to De Jong (1983).

nutshell, the distribution is characterized by a mode in the gravel fraction and a double-peak mode in the fine sand/silt fraction, with a deficiency in the coarse sand fraction.

CAMMERAAT & RAPPOL (1987: Fig. 2) showed the similarity in the grain-size distribution for samples from the present study area and samples from the Molasse area to the S and SE, and concluded that the till-forming debris in both areas is for a major part of local (bedrock) origin. As mentioned before, the Molasse substratum in the latter area is composed not only of sandstones and shales, but also of conglomerates.

The mode in the gravel fraction of the samples from the area of investigation cannot be attributed to the incorporation of erosion products from the Molasse bedrock. The Molasse sandstones and shales in the study area are only moderately lithified and quite friable, hence do not weather or erode to pebble- and boulder-size debris. Large Molasse sandstone and shale clasts are notably absent in the deposits of the study area, and the Molasse sandstone percentage of the size grade 5-8mm is generally subordinate (Tab. 2). No evidence exists for the present or former occurrence of Molasse conglomerates in the area. These factors have been somewhat underexposed in previous discussions on the relation between tills and substratum. They imply that the gravel fraction has either been transported to the area from southerly sources or incorporated from locally present 'older' Quaternary deposits.

3.2 Gravel petrography

The gravel petrography of the fraction 5-8mm has been analysed for 79 samples from the so-called upper till (DE JONG 1983). The percentage of Molasse sandstone pebbles is considered the best gravel-petrographic measure for contribution by the local Molasse substratum. Molasse shale pebbles are notably absent. The sandstone percentage is generally low (Tab. 2; Fig. 3), even if one takes a bias to low percentages into account due to the destruction of friable sandstone pebbles during sampling and sample preparation. The composition of most samples is dominated by non-Molasse debris. This is different from the observations of RAPPOL & VAN GIJSSEL (1988) in the Rotach valley, who found in many samples from the Eyenbach and Kesselbach stream incisions large percentages of local Molasse debris - conglomerates, sandstones and siltstones - and concluded to an important contribution by the local Molasse substratum. The work by RAPPOL & VAN GIJSSEL suggests that, when important, a contribution by the local Molasse bedrock will be reflected in high percentages of Molasse components in the gravel petrography. Conversely, the low percentages in most samples of the present study area may be seen as an indication for a relatively low influence of the local Molasse substratum.

Reworking of glaciofluvial deposits into (the basal part of) an overlying till has been concluded by

RAPPOL & VAN GIJSSEL (1988) for some deposits in the Rotach valley, based on corresponding, relatively high percentages of erratic material. The well-rounded nature of some pebbles in the tills of the Argen lobe area of the Rhine glacier suggests reworking of fluvial and/or glaciofluvial sediments. A 25 cm thick sheared layer at the base of a till mantle was reported by DE JONG & RAPPOL & RUPKE (1982) for a drumlin in west Allgäu consisting largely of sorted drift. This evidence shows that debris from 'older' Quaternary deposits has been incorporated into the tills. Below, it will be argued, however, that the degree of glacial erosion of pre-existing deposits was limited.

3.3 Heavy mineral weight percentages

Data of heavy mineral weight percentages is available for 39 so-called upper till and 3 so-called lower till samples (Fig. 1 and 2). The weight percentages of the heavy mineral fraction (size grade 0.06-0.4 mm) of the Bodensee fan Molasse sandstones are less than 0.5% (HOFMANN 1957).

Samples 1143 and 1144, collected in pits near Steinegaden in the eastern part of the study area (Fig. 1), show heavy mineral weight percentages of 0.3% (in the decalcified size grade 0.105-0.15mm), which is in good agreement with the fore-mentioned percen-

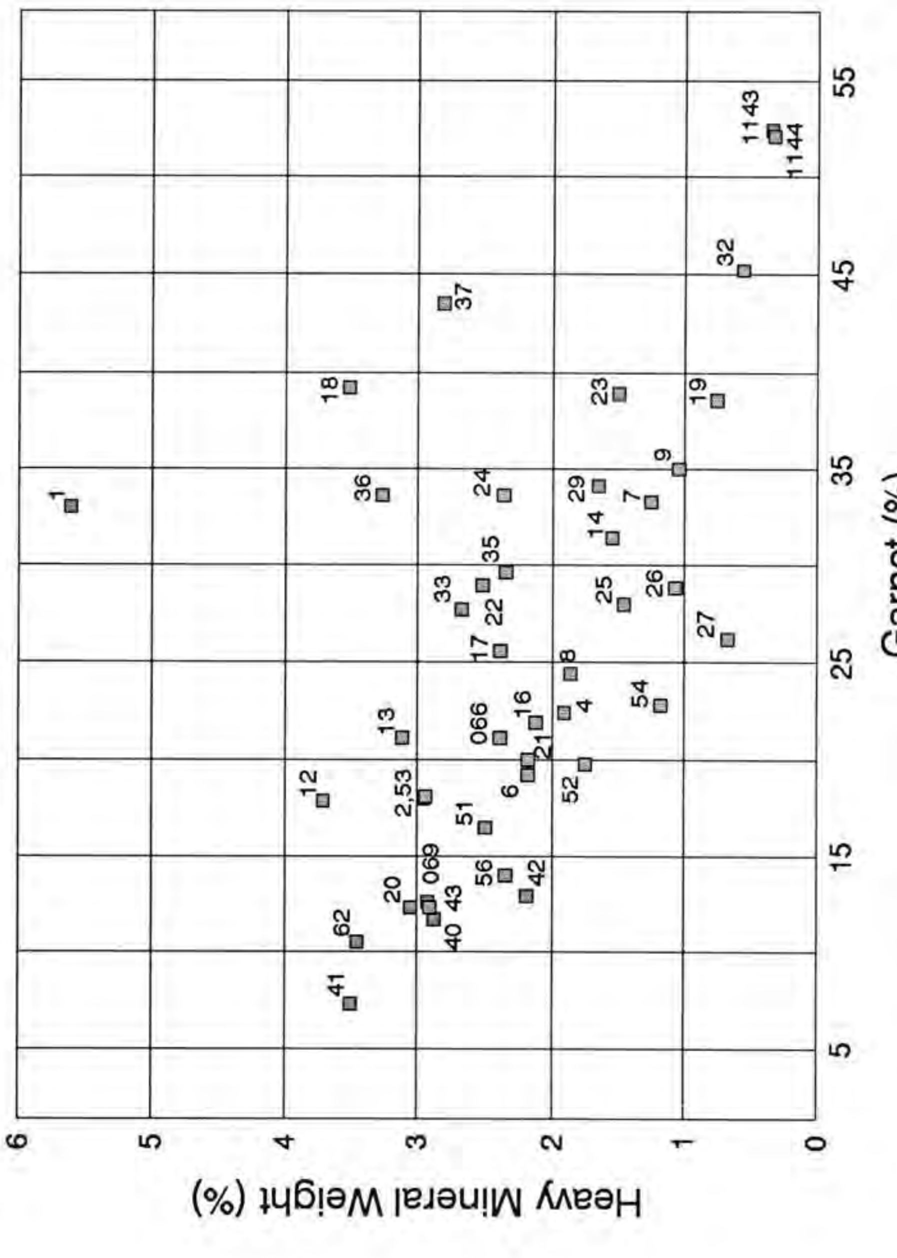

Fig. 2: Cross-plot of the garnet percentage and the heavy mineral weight percentage for 39 upper till and 3 lower till (numbers 42, 52 and 54) samples.

tage from HOFMANN (1957) for the Molasse bedrock. These samples also show garnet-dominated heavy mineral compositions and high Molasse sandstone percentages in the fraction 5-8mm (Fig. 2 and 3) and, hence, are considered typical representatives of local, predominantly Molasse-sourced subglacial tills.

Non-Molasse till-forming debris could conceivably have been derived completely from the non-sedimentary rocks of the Silvretta mountains (Fig. 1) - with high heavy mineral weight percentages (HAHN 1969) - as well as completely from the calcareous rocks of Vorarlberg - with very low percentages (e.g.

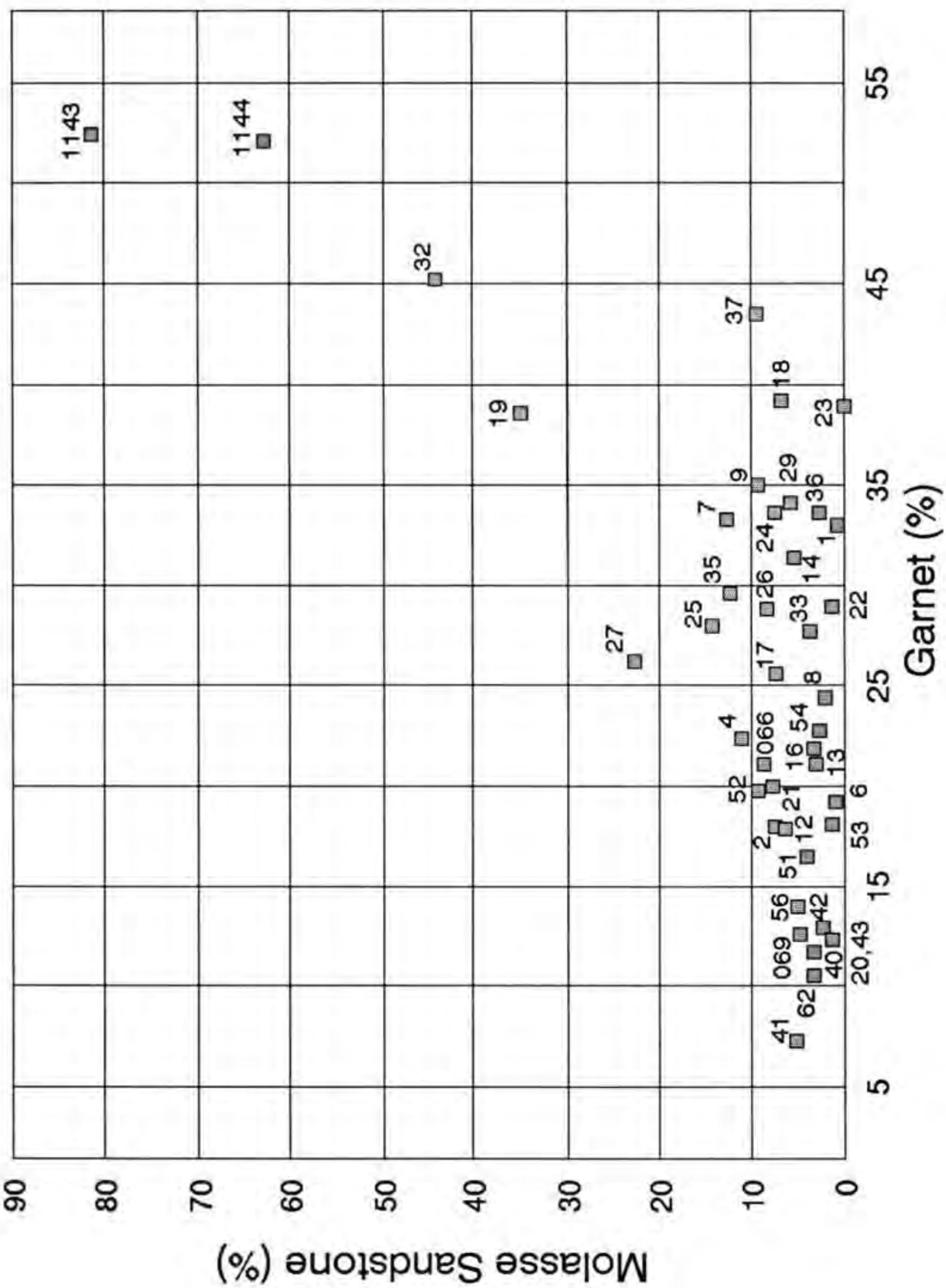

Fig. 3: Cross-plot of the garnet percentage and the Molasse sandstone percentage for 39 upper till and 3 lower till (numbers 42, 52 and 54) samples.

BIK 1960; SMIT SIBINGA-LOKKER 1965). Such 'extremes' then are likely to have undergone changes during transport due to admixing of new lithologies. It is, hence, difficult if not impossible to characterize the heavy mineral weight fraction of the far-travelled debris with one figure. Using the analog of recent fluvial sediments of the river Rhine downstream from the confluence with the river Ill (HAHN 1969), a figure or range of several percents might be a reasonable approximation.

The heavy mineral concentrations of most subglacial till samples in the study area are considerably larger than those of the Molasse substratum and the Molasse-derived tills (Fig. 2) and are interpreted to result from a large if not predominant contribution from non-Molasse debris. A predominant influence of the Molasse substratum would have been reflected in substantially lower heavy mineral concentrations.

Little to no information is available for the heavy mineral fraction of the 'older' Quaternary deposits (see also HERRMANN & SCHWERD 1983; RAPPOL & VAN GIJSSEL 1988). Based on the similarity in gravel petrography with the subglacial tills (Tab. 2) and on an analogy with the fluvial sediments of the Rhine (see above), the weight fractions may be estimated at several percents. This, then, means that reworking of older deposits into the tills is hard to distinguish from direct sourcing on the basis of weight percentages only. As will be argued below, however, the glacial erosion of the pre-existing deposits was probably not very large and, consequently, the contribution of such erosive products to the till petrography limited.

3.4 Heavy mineral composition

The heavy mineral composition of the Molasse bedrock is dominated by garnet (Tab. 1). The subglacial tills on average show a garnet-amphibole-epidote association. The cross-plot of the garnet percentage versus the heavy mineral weight percentage for 39 so-called upper and 3 so-called lower tills in the study area (Fig. 2) shows a decrease of garnet with an increase in heavy mineral weight percentage, reflecting the waning influence of the Molasse debris. For example, the samples 1143 and 1144 and, to a lesser degree, 19 and 32 show relatively high garnet percentages and low heavy mineral concentrations. The concentrations of Molasse sandstone pebbles are very high and high respectively (Fig. 3), as one would expect for samples derived from the local Molasse substratum.

As mentioned before, little to no information is available for the heavy mineral fraction of the 'older' Quaternary deposits. Based on the similarity in gravel petrography with the subglacial tills (Tab. 2) and on an analogy with the fluvial sediments of the Rhine (see above), the heavy mineral compositions may be quite similar to those of the tills. This, then, means that local sourcing from the older deposits cannot be differentiated from sourcing by far-travelled debris on the basis of composition only. See also below.

4 Discussion and conclusions

The results of the petrographic analyses show that, with a few notable exceptions, the subglacial tills are composed largely of non-Molasse debris. The tills consist to a large degree of debris which was either transported directly to the study area from southerly sources or reworked from locally present older Quaternary deposits. Or, from a combination of these.

Theoretically, substantial erosion and deformation of (unconsolidated) porous gravels is likely to occur only at low effective normal pressures at the ice/bed interface (BOULTON 1975; SMALLEY & UNWIN 1968). Conditions of impeded internal drainage through porous 'older' Quaternary deposits resulting in low effective normal pressures could conceivably have existed in the Allgäu, due to the presence of impermeable layers or topographic obstructions. The presence, however, of drumlins partly or completely composed of pre-existing gravels (DE JONG & RAPPOL & RUPKE 1982) and the preservation of sheet-like layers of gravels below the tills (DE JONG 1983) suggest that subglacial erosion of this type of substratum was probably of limited extent only.

As mentioned before, the full extent of the 'older' Quaternary deposits in the study area cannot be determined due to lack of exposures. Full terrain covering geomorphological mapping of large parts of the west Allgäu at scale 1:25,000 (DEN BESTEN 1984; CASTEL 1982; GILLEBERT 1985; DE JONG 1983; WOLFERT 1984), however, has shown that in wide areas subglacial till is not underlain by pre-existing deposits. One could argue that this demonstrates that older deposits have been completely eroded to form the subglacial tills. This scenario, however, is considered less likely. The interpretation of a predominant direct sourcing from southerly areas is preferred by the present author.

The cirques, the wide glacial valleys - which are often overdeepened, e. g. the Upper Rhine, Ill and Großwalser valleys in Vorarlberg - and the overall glacial erosive character of the Alpine relief witness the importance of glacial erosion in creating the present morphology. Glaciers have eroded the cirques and valleys and have swept freshly eroded and older glacial drift as well as the interglacial and interstadial fluvial and mass movement debris to the foreland. The result has been a net transport of debris from the

Alps to the foreland (and beyond). A sizeable part of this material forms the subglacial tills in the view of the present author.

RAPPOL & VAN GIJSSEL (1988) argue that glacial erosion is also an important geomorphic process in the piedmont area. The topography of highs ('Riedel') and lows ('Senke') in the foreland, with differences in elevation up to 100m, probably reflects the relief of the Molasse surface (DE JONG 1983; see also GERMAN et al., 1967, MADER 1971, and WEINHOLD 1973). Alternating fluvial and glacial erosion, as described by SCHREINER (1979) for the Bodensee basin, is held responsible for the formation of this morphological framework. The degree of the (glacial) erosion, however, is clearly of a lower order than that in the Alps.

In summary, the petrography of the subglacial tills in the area, except for a few well-defined local tills, is dominated by far-travelled debris. The combination of petrographic evidence, theoretical considerations and broad-scale geomorphological observations leads to the conclusions that most till-forming debris was transported to the area during the last glaciation and that reworking of 'older' Quaternary deposits was subordinate.

These conclusions differ from those of RAPPOL (1983), CAMMERAAT & RAPPOL (1987) and RAPPOL & VAN GIJSSEL (1988), who concluded on average to a predominant influence of the local substratum (see also GASSER & NABHOLZ 1969). It is stressed that the present conclusions do not invalidate their work as far as the area outside the present area of investigation is concerned. All studies show that the petrography of subglacial tills can reflect any source from the wide range between remote and local. It is beyond the scope of this paper to analyse the causes for the variations. It is noted, however, that the core of the study areas of RAPPOL, CAMMERAAT & RAPPOL and RAPPOL & VAN GIJSSEL is situated in mountainous relief, whereas the present study area lies completely in the hilly Alpine foreland. In addition, the distribution of the samples throughout the present area of investigation shows some interesting features. The Molasse-derived samples (19, 32, 1143 and 1144) are from the eastern part of the area - the foot of the Pfänder mountain - where the glacier flow probably was confined by the bedrock relief and morphology. The samples from the western part of the area, where glacier flow was less constrained, do not show a strong Molasse influence. 'Older' Quaternary deposits occur in the latter area, but as argued before it remains questionable if they should be considered an important source rock for the tills.

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