Medial moraines of Alpine glaciers as supra-glacial transporters of debris

And a new interpretation of certain 'drumlins'

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ABSTRACT. Certain Quaternary landscape structures in the northern Swiss and South-German Alpine Foreland are until now summarily called drumlins and considered to be of sub-glacial origin. Instead, from studies of recent Alpine valley glaciers we relate many of them to supra-glacial transport of rock debris in medial moraines. We suggest that also Quaternary valley glaciers moved larger amounts of material on their surface, often over large distances, than previously believed. We propose to divide the so-called drumlins into genuine, sub-glacial forms and supra-glacial structures for which the medial moraines essentially provided the material. As non-European example of re-interpretation serves the large Livingstone Lake drumlin field in Saskatchewan, Canada. Its structures are typical for former medial moraines. Similarly, other features hitherto considered of sub-glacial origin, such as flutings and megaflutings, as well as some unexplained singular structures might have been provided by medial moraines.

1. INTRODUCTION

Our starting point is the question about the mechanisms of long-distance transport of rock debris by alpine glaciers. For continental Arctic and Antarctic ice sheets not overtopped by mountains, debris transport, of course, occurs only at the bed. Penck and Brückner (1901-1909, Vol.1, p. 6.) postulated that the principal debris transport by Quaternary alpine valley glaciers likewise took place at the bottom of the ice. In consequence, the ground moraine was regarded as the archetype of glacial sediments also for the alpine surroundings. The claim has often been criticized, but appears to be the canon. This view is contradicted, however, by the great amounts of surface debris at several alpine glaciers of today, largely as medial moraines (Figs. 1, 2). The medial moraines can coalesce into broad debris bands and in some cases cover all of the ice in the region of the glacier snout ("debris-mantled glacier", Benn and Evans*, p. 226). Examples from the Alps are the Glacier de Miage[c], the Zmuttgletscher[d], and the Oberaletschgletscher[e]. (The indices refer to the Appendix where the geographic co-ordinates are given.)

Fig. 1. Yentna[a] Glacier, Alaska Range (Denali), as example for a recent ice stream of the alpine type. Differences among the medial moraines in respect to width and rock materials are obious. Some medail moraines join into broad cords. Photo: C. Willi and P. Burkhardt, Buochs (Switzerland), 1983.

Fig. 2. The complex of the Gorner[b] Glacier (Wallis, Switzerland) seen from the North as example for a recent system consisting of glaciers of varying size and medial moraines. Only the two largest parts of the complex, the Grenz Glacier (Gr) and Zwillings Glacier (Zw) form the terminal tongue. The medial moraine between the Lower Theodul Glacier (Th) and the Triftji Glacier (Tr), as well as one medial moraine each **on** them are visible from start to end. The

medial moraine between the Breithorn Glacier (Br) and the Schwärze Glacier (Sch) turns into a secondary lateral moraine and moves from the right-hand side of the Breithorn Glacier to the left-hand side of the Schwärze Glacier. The Gorner Glacier (Go) itself ends within the picture, while the medial moraine between it and the Grenz Glacier (Gr) turns into a secondary lateral moraine of the latter. The signum Y refers to two Y-formed stumps at the origines of medial moraines of the ‘Little Ice Age’. Photo: J. Alean, Eglisau (Switzerland), 1983.

[*]Because of the enormous number of publications particularly about drumlins, for brevitys sake we will often cite summaries from textbooks, especially from the monumental work of Benn and Evans (1998), abbreviated henceforth as B&E.

The supra-glacial debris transport had so far only rarely been considered as a geomorphological agens. For the Alpine Region, that view was already discussed by Baltzer (1896) and hinted at *by* Heim (1919). After Penck and Brückner (1901-1909), however, the subject became almost taboo in Europe, whereas B&E (e.g., p. 212) ascribed a large role to the supra-glacial transport. Among the later athors, Boulton and Eyles (1979) described the sedimentation by valley glaciers and the resulting sediment forms at the respective ice margins for recent glaciers. Quite recently, Wagner (2001, 2003) and Hantke (2003) took up the issue of supra-glacial transport especially in Switzerland.

What is the source of this rocky material? “*The majority of the debris transported by valley glaciers is derived from mass wasting of valley walls*“ (B&E, p. 610) with whom we agree. Eyles and Rogerson (1978), however, remarked about Norwegian and Canadian glaciers that debris may rise from the bed into the medial moraine by upward-directed ice flow along the septum between the two coalescing glaciers (B&E 1998, p. 221 et sequ.). Studies of that process in the Alps did not yield a positive result (Röthlisberger, 1967, p. 24). Quite to the contrary: The debris cover of the medial moraine often is only a few centimeters or decimeters thick, but rarely more than one meter. Below is sheer ice, which toward the glacier snout rises together with its cover above the surface of the other ice because of reduced ablation, analogous to glacier tables.

The question now is whether and to which degree the glaciers of the Alps carried surface debris also during the Quaternary glaciations. We answer affirmatively: Even at the climax of the largest glaciation, mountain chains clearly overtopped the feeding areas of the glaciers, so that the conditions for generating surface debris were always fulfilled. The same is apt to hold for valley glaciers in alpine settings of other continents.

At the junction of any two valley glaciers, a medial moraine is formed by the two inner lateral moraines (cf. Fig. 2). Thus, an ice-complex composed by *n* initial glaciers produces *n-1* medial moraines. The junctions may occur below or above the equilibrium line of the ice stream. If the junction happens to be above the equilibrium line, the medial moraine disappears under the firn until the glacier reaches the ablation zone where the characteristic longitudinal band appears.

Unless disturbed, medial moraines retain their identity over any length of ice flow and the debris moves with the speed of the ice. During the transport from the site of origin to that of deposition, which for Quaternary alpine glaciers in many cases must have lasted millennia, the debris is exposed to aggressive external factors like large temperature fluctuations, water, and wind, so that its character may be altered. The originally sharp edges of stones may be blunted or even rounded. Every medial moraine, however, will somewhere reach the margin of the ice, be that by lateral stranding or terminally at the glacier snout, where the debris is deposited. During still-stands or oscillations of the ice tongues, characteristic structures are generated (Figs. 3, 4). For visualizing the size of such structures, assume a medial moraine of 30 m width with an average thickness of only 10 cm and an ice velocity of 100 m per year. In 500 years, the debris volume would attain 100 m in length, 30 m in width and 50 m in height. The moraine material may partially be converted by water into gravel of all kinds at any elevation reached by the ice.

Fig. 3. The two hills Säuhoger[f] near Kehrsatz (Bern, Switzerland) as example for a bipartite structure formed out of a medial moraine of the Aare glacier stranded laterally on the left slope of the Aare-valley in two standstills. The ice flowed from the right. Photo: G. Wagner. 2009.

Fig. 4. The Eichlihubel[g] Hill near Allmendingen (Bern, Switzerland) as example for a low, drumlinoid hill with a drop-like plan view on level ground (glacier flow from the right). In contrast to a genuine drumlin its broad end is not proximal but distal. Photo: G. Wagner, 2009.

These observations made us to suggest that the supra-glacial debris transport has to be considered for understanding several puzzling glacial structures of the Alpine Foreland, especially of a large fraction of the hills regarded as ‘drumlins. Concerning the understanding of drumlins and ‘drumlinoid’ structures in Switzerland, the dean of Swiss geology, Albert Heim (1919, p. 262), recognized already early in the last century the necessity of a differentiation. From the genuine sub-glacially formed drumlins he separated a group called “upper moraine drumlins” *(Obermoränendrumlins),* which he explained as formed out of supraglacial material, especially medial moraines or transported avalanches. The term “upper moraine drumlin”, really is a contradiction in itself, but reflects the confusion of theories. Indeed, the origin of drumlins has been an extremely controversial subject until today. Menzies (1996: p.75) called it *“this most definitive of all glacial questions.“* And B&E wrote (p. 431): *“There are almost as many theories of drumlin formation as there are drumlins.”* They posited (p. 448): “*… the consideration of all possibilities for their explanation.”*

In the following, we first discuss previous views (section 2), before we present our new hypothesis (section 3).

2. THE STRUCTURES UNDER DISCUSSION

2.1. Subglacial associations

B&E starts the chapter ‘Subglacial Associations’ as follows: “*Subglacial associations are among the most enigmatic products of glaciation, and a reasonable understanding has begun to emerge only in recent years*.” (p. 422). We note that the term “ground moraines” is not used in the chapter and is also elsewhere rarely employed. Among the “subglacial bedforms” B&E distinguish “*longitudinal und transverse accumulations of sediment formed below active ice.”* (p.

425). *"Longitudinal forms are streamlined features aligned parallel to ice flow and can be divided into drumlins, flutings, and megaflutings. The distinction . . . is based upon the length and elongation ratio of the bed form."*(p. 425). The three types *"form a continuum and any lines drawn between them can only ever be arbitrary."* (p. 426).

"Flutings … are elongate streamlined ridges of sediment aligned parallel to former glacier flow. They are generally a few tens of centimetres to a few metres high and wide, and occur in groupings of sub-parallel ridges." (p. 426).

*"Drumlin: long axes are oriented parallel to the direction of ice flow**, with higher and wider stoss*** **(upstream)** ***ends which taper down to a pointed lee end*** (emphasis by us) …. *Long, narrow drumlins have been termed spindle forms, and broader, often asymmetrical drumlins are known as **parabolic forms**. More complex forms also exist .… With increasing elongation ratios, drumlins grade into megaflutings or megaflutes."* (p. 431, Fig. 11.11, also Fig 11.15 and 11.16. pp. 436-437).

Megaflutings often are arranged linearily behind each other. *"The lengths of mega-scale glacial lineations range from 8 – 70 km, widths from 200 – 1300 m and spacings from 300 m to 5 km."* (p. 431).

2.2. Supraglacial associations

Among the Supraglacial Associations B&E (pp. 481-493) include *inter alia* medial moraines und hummocky moraines. *"Medial moraines are among the most striking features of valley glaciers"* (p. 224, section 6.4.4.1). The term hummocky moraines is applied by B&E *"to moraines deposited during the melt-out of debris-mantled glacier"*. (p. 483). Because debris-mantled glaciers originate from joining of all medial moraines of an ice flow, we note that hummocky moraines can also be considered as formed by medial moraines.

Regarding the morphogenetic importance of supra-glacial moraines, B&E (p. 212) make the general remark that " *….processes of debris movement and sorting on glacier surfaces exert a strong influence on landform evolution in many glacial environments."* Further down (p. 481) they write: *"Large medial moraines are referred in literature as "interlobate moraines…."*. Further: *"The interesting corollary is that such overridden interlobate features may well lie at the core of some megaflutings."* B&E (pp. 482-483) mention a medial moraine of 3.5 km length on Jura Isle[h] in Scotland and "interlobate moraines" of almost gigantic size in Canada: *"The Burntwoodknife interlobate moraine, formerly separating the Hudson Bay and Keewatin sectors of the receding Laurentide ice sheet, covers a distance in excess of 500 km on the west side of Hudson Bay and is composed of broad ridges of glacifluvial* *sediment and till. Individual segments are up to 12 km long, 4 km wide and 60 m high (Dredge et al., 1986; Klassen, 1986; Dyke and Dredge, 1989). The large quantities of sands and gravels comprising these moraines were deposited in proglacial lacustrine environments .., attesting to the large scale reworking of medial moraine debris during glacier recession. In fact these features are regarded more as glacifluvial than supraglacial in origin (Dredge and Cowan, 1989; Vincent, 1989). Similarly, continuous esker systems may demarcate the former position of medial moraines in glaciers or ice sheets. The deposition of a continuous esker ridge is clearly related to sediment supply, and this may be assured wherever en-glacial meltwater streams coincide with medial moraine positions."*

3. MEDIAL MORAINES AND DRUMLINS: CRITERIA AND NEW INTERPRETATIONS

From the citations and on other pages it appears that B&E considered a genetic connection between medial moraines and drumlinoid large features (flutings and megaflutings), as well as esker ridges, as a possibility. We therefore do not introduce a fundamentally new idea when regarding many drumlin fields as due to medial moraines. We, however, attempt to think through all the consequences of this idea.

By which criteria may we distinguish between products of medial moraines and genuine, subglacially formed drumlins? Sedimentology is of little help, because both drumlins and medial moraines can show all imaginable variations of sediments in the vicinity of the ice edge. We therefore are almost exclusively dependent on morphological and topographical criteria.

3.1. Wedge or drop form, but in which orientation?

Terminal depositions of medial moraines on level surfaces **show a drop- or wedge-shaped plan view that widens in the downstream direction** and often **becomes parabolic with one or two prolonged arms** (cf. Wagner, 2003, Figs. 4-6). In contrast, genuine drumlins as described by B&E (p. 431) are in plan view typically drop-like with higher and wider stoss (upstream) ends which taper down to pointed lee ends. (Fig. 5). In this context the drumlin field of Livingstone Lake[i] in northern Saskatchewan, as described by B&E (p. 440) deserves particular attention. We note that the features depicted in B&E Fig. 11.17 (cf. our Fig. 6) do not show drop-like outlines with their pointed end downstream, but the opposite. Morover, the typical form is parabolic with pairs of more or less prolonged downstream arms. It is no wonder, that Shaw (1989) cited the drumlin field of Livingstone Lake "*as evidence for a completely different theory of drumlin formation*" (B&E, p. 437). As the actor, we propose a large medial moraine cord, 900 km long out of the Mackenzie and Selwyn Mountains, in a glacial oscillation period.

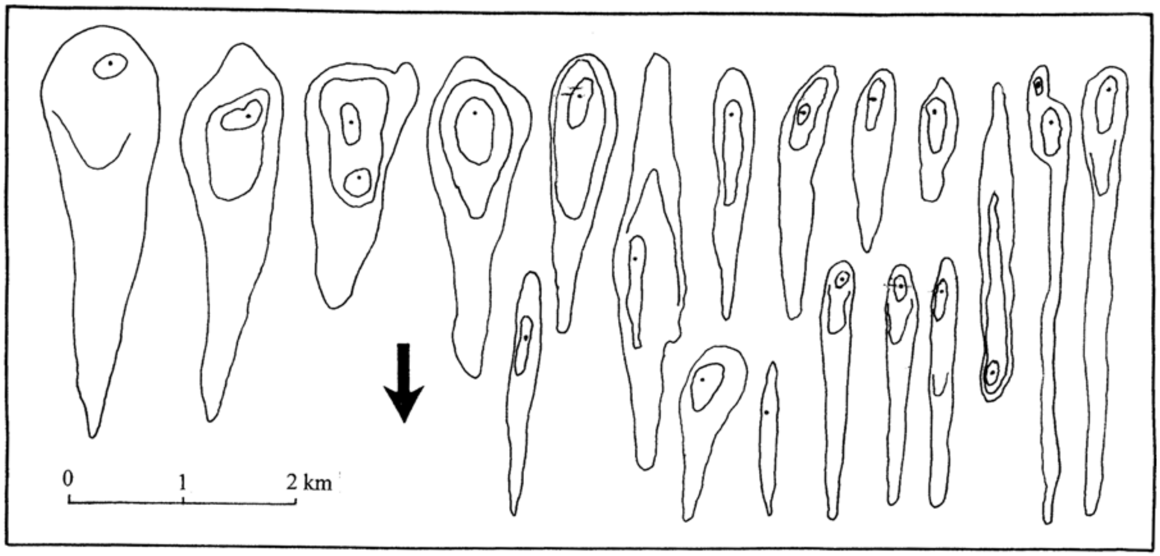

Fig. 5. Typical forms of genuine drumlins in plan view: Drop forms with pointed ends downstream. The arrow shows the direction of the ice flow. – Modified from Benn and Evans, 1998, Fig. 11.11.

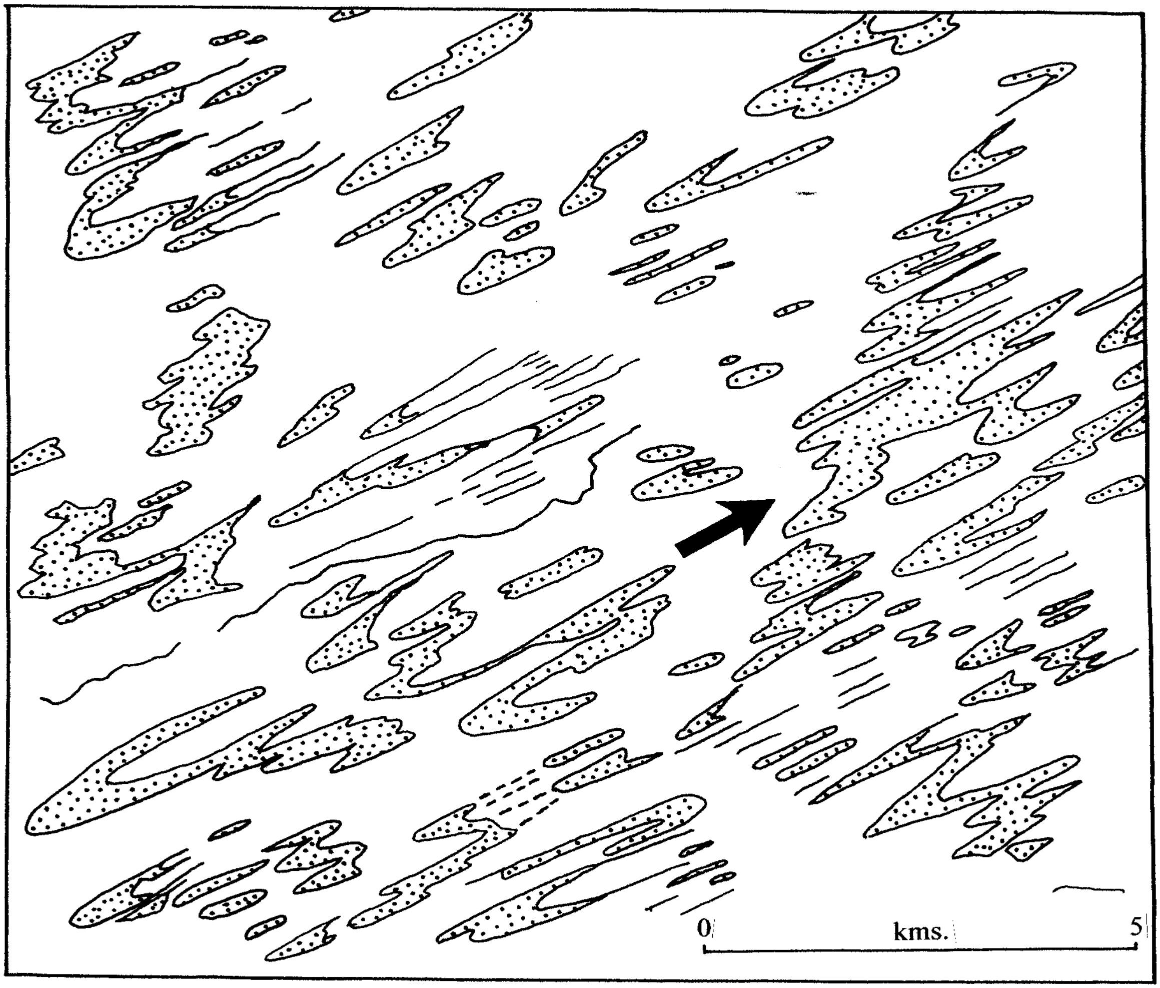

Fig. 6. Drumlin field at Livingstone Lake[i] (northern Saskatchewan, Canada). The numerous paraboloid structures with arms in the ice flow direction (arrow) are typical for mounds at the ends of medial moraines but not for sub-glacial drumlins. Modified from Benn and Evans 1998, Fig. 11.17.

3.2. High points and slope angles. Medial moraines deposited on level ground rise from proximal to distal. There will be an abrupt, often concave terminal slope and there may also be steep lateral slopes, all often having inclinations of 25-30^{o} . In contrast, genuine drumlins created by ground moraine are hills with low slope angles and often of so low a height that they do not show in detailed topographical maps. According to Klebelsberg (1948) the distal slope is 1-10 degrees, while that at the steeper proximal end may reach up to about 20^{o}. They have normally one culmination, whereas hills of medial moraine origin show very often two or more high points, either side by side or one behind the other.

3.3. Dimensions. The deposited medial moraine may be a single hill or be of any length, often with transverse cuts, depending on whether the moraine was formed by a standstill or an oscillating or a slowly back-melting glacier. The largest structures, called interlobate moraines, extend with interruptions over dozens, or even hundreds of kilometers, while individual segments according to the cited BB (section 2.2) may be 12 km long, 4 km wide, and 60 m high. In our region, a single feature of that order is the Reichenau[k] Isle (Fig. 7) in the Untersee (southern Germany). Even the largest structures, however do rarely reach 100 m in height. These enormous differences in dimensions are easily compatible with the medial moraine hypothesis.

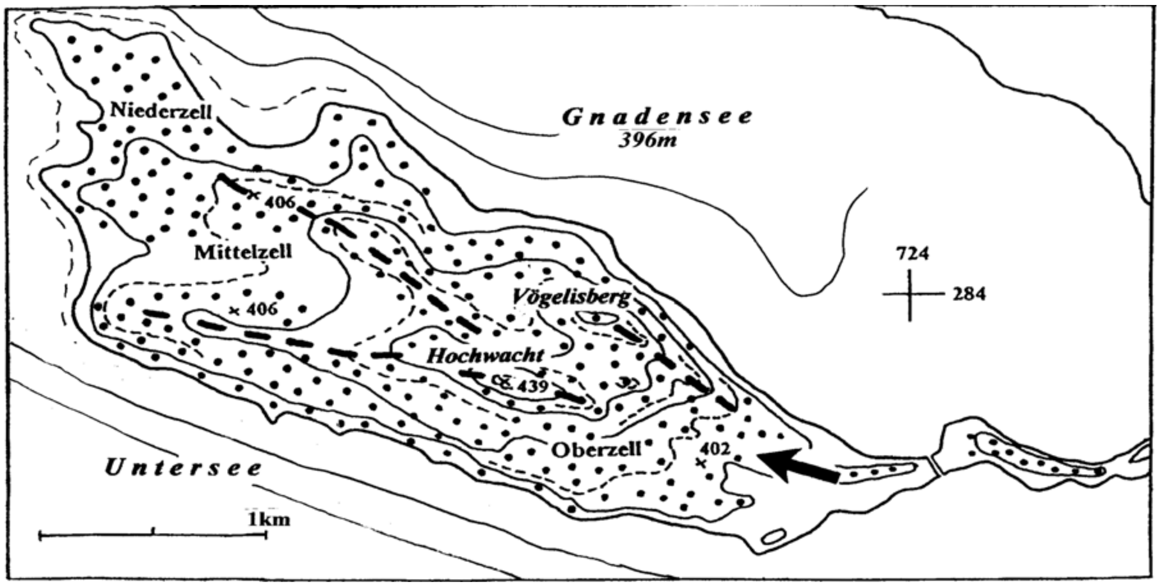

Fig. 7. The Reichenau[k] Isle in the Untersee (southern Germany) as example for a large structure created by a medial moraine. With its rise in the flow direction of the Rhine Glacier (from the right), its two peaks, and the outstretched “fingers“ the isle demonstrates typical features of a sedimentary complex at the end of a large medial moraine cord. If the topography below the lake surface (at 396 m above sea level) is taken into account, the isle is 6 km long and 2 km wide, with a total height of 60 m. The Reichenau Isle contains the sediments of at least two glacial cycles, those of the last one [‘Würm’] overlying older gravels from near an ice margin. It is plausible that the medial moraine took the same route with each ice advance.

3.4. Arrangement. Deposited medial moraines may be single or arranged linearly or sub-linearly, or occur in swarms, depending on whether the origin was only one, perhaps narrow medial moraine, or a broad cord, or even a debris-mantled glacier.

3.5. Overriding. Wherever a glacier overrides its own terminal deposits, be it during an advance within the same or during a new glacial cycle, the original hills will be structurally modified and / or covered by new ground moraine. This latter process explains that many drumlins possess a gravel core covered by ground moraine. Possible subsequent overrides should always be kept in mind in discussing glacial structures.

3.6. Topographic situation. At the height of Alpine glaciations, the ice in valley glaciers was several hundred meters thick. Accordingly, stranded medial moraines may occur high above today's valley floors as moraines or gravels (cf. 'Cover Gravels'!) and testify to the hight of the ice.

In contrast, at late stages of the last glaciation medial moraine deposits were produced by only short transport distances, so that the relation of their terminal deposits to the origin is apparent. This appears to be the case at the drumlin field at Lampolding[l] in the German/Austrian Alpine Foreland near Salzburg. According to a personal communication of 24 April 2001 by the late Prof K. A. Habbe (Erlangen, Bavaria), the field is situated just outside of the confluence of the former Saalach and Salzach glaciers:*"It seems fairly certain that it has been moulded out of the medial moraine between the Saalach and Salzach branches of the Salzach Vorland-glacier."* Habbe considered – but we differ – the provision of material by the medial moraine and the drumlin creation as two separate processes, yet in this last letter of his he called the issue *"a matter under discussion"* (Habbe died in 2002).

3.7. Stumps of medial moraines. During a standstill a medial moraine leaves sediments with typical structures not only at its terminal end, but also at its origin, the junction of two valleys: Parts of the lateral moraines debris of the two coalescing glaciers remain at the junction point and form a stump of a medial moraine. Such features can be found in many places in alpine valleys (Y-shaped structures in Fig. 2).

4. CONCLUSIONS

A great deal of the structures in the Alpine Foreland, which so far were regarded as drumlins, actually exhibit morphological features atypical for genuine drumlins, but typical for products of medial moraines as described in section 3. In our opinion, this fact requires a change of paradigms. If debris delivery by medial moraines is accepted as the principal mechanism of transport of material by valley glaciers, then glacial landforms besides drumlins and drumlinoid features may also be discussed. Many small or large singularities, until now considered as results of erosion, may be understood instead as primary sedimentary forms by medial moraines. Further, parts of structures listed among the sub-glacial associations in section 2.1, like flutings and megaflutings and the ‚Deckenschotter' (Cover Gravels, section 3.6) in the northern Alpine Foreland should be reconsidered.

There is a wide scope for more field work, but also, it may be time to investigate the dynamic of alpine glacier systems, and especially of the debris transport by medial moraines, through computer simulations.

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APPENDIX

Geographic coordinates for sites designated in the text

(in parenthesis number and coordinates of the Swiss Landeskarte LK)
a Yentna Glacier 62.5 N / 152 W, Alaska
b Gorner Glacier 45.9 N / 7.75 E, Switzerland (LK No. 1348 Zermatt, 091/627)
c Glacier de Miage 45.8 N / 6.9 E, Italy (LK No. 292 Courmayeur, 070 / 556)
d Zmuttgletscher 46.0 N / 7.6 E, Switzerland (LK No. 1347 Matterhorn, 094 / 616)
e Oberaletschgletscher 46.4 N / 8.1 E, Switzerland (LK No. 1269 Aletschgletscher, 144 / 646)
f Säuhoger 46.9 N / 7.5 E, Switzerland (LK No. 1167 Worb, 194 / 602)
g Eichlihubel 46.9 N / 7.6 E, Switzerland (LK No. 1167 Worb, 195 / 606)
h Jura Isle 56.0 N / 6.0 W, Scotland
i Livingstone Lake 58.5 N /107.0 W, Saskatchewan, Canada
k Reichenau Isle 47.7 N / 9.0 E, Germany (LK No. 1033 Steckborn, 284 / 722)
l Lampolding 47.9 N / 13.0 E, Germany/Austria
m Zweilütschinen 46.6 N / 7.9 E, Switzerland (LK No. 1228 Lauterbrunnen, 164 / 635)

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