Geografiska Annaler: Series A, Physical Geography

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tgaa20

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To cite this article: Jürg Alean , Lea Schwendener & Michael Zemp (2020): Migrating boulders on the surface of Alpine valley glaciers, Geografiska Annaler: Series A, Physical Geography, DOI: 10.1080/04353676.2020.1850064

To link to this article: https://doi.org/10.1080/04353676.2020.1850064

GEOGRAFISKA ANNALER: SERIES A, PHYSICAL GEOGRAPHY
https://doi.org/10.1080/04353676.2020.1850064

Migrating boulders on the surface of Alpine valley glaciers

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ABSTRACT
Boulders in the ablation areas of Alpine valley glaciers were found to not travel along with the ice in a passive manner only. Many show an additional but smaller component of movement towards the south. We investigate this phenomenon and its governing processes using field observations and measurements from terrestrial and aerial photographs of glaciers in the Swiss Alps. We found that large boulders can migrate from their medial moraine due to cyclic formation of classical glacier tables and also a similar process that produces ice tails. The main driving factors behind boulder migration are the size (and shape) of the boulder, ablation, radiation, and surface slope. On glaciers roughly oriented to the east or west, these processes result in a sorting of boulders from the supraglacial moraine towards the southern side, i.e. towards the sun. Future studies complementing our approach using a differential global positioning system should be able to better distinguish between the velocity components of ice flow and boulder migration, determine the precise azimuth of the latter, and investigate the potential influence on photogrammetric feature tracking.

KEYWORDS
Glacier; Alpine glacier; glacier table; supraglacial debris cover; supraglacial moraines; supraglacial boulder migration

1. Introduction

Amongst the most prominent surface features of many Alpine valley glaciers are medial moraines and individual boulders of surface debris, many of which form glacier tables. Boulders on glaciers, and in particular those forming glacier tables, were already described in the nineteenth century (e.g. Hugi 1842; Zschokke 1842; Ludwig 1853) and illustrated in paintings and drawings. Figure 1 provides an example of glacier tables in a graphic reproduction by Lory and Hürlimann (1822). Sometimes artists purposely drew the figures of the staffage too small in order to deliberately emphasize the effect of the phenomenon, in this case the glacier table, which caused as much awe and amazement at the time as it does today (Zumbühl 2009). In fact, glacier tables, impressive ice fronts, waterfalls etc., overtopped by high summits and with tiny figures (e.g. bold alpinists or hunters) in their vicinity, were typical Alpine landscape motifs at the time of the Romantic period (Zumbühl 1980). Glacier tables are often associated with medial moraines. Various types of medial moraine formation, and changes along the longitudinal profile of glaciers have been proposed by various authors. An excellent overview of early relevant literature is given by Eyles and Rogerson (1978a).

Surface debris, and larger boulders in particular, have been routinely used for determining the horizontal component of ice velocity using high-resolution images from remote sensing and feature-tracking (e.g. Kirkbride 1995; Kääb 2005; Immerzeel et al. 2014). Modern literature (e.g. Sugden and John 1976; Bachmann 1983; Cuffey and Paterson 2010; Cogley et al. 2011; Hambrey and Alean 2017) provides definitions of glacier tables, mainly following historical descriptions.

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Figure 1. Historic representation of glacier tables on Unteraargletscher, Bernese Alps, Switzerland. The hunter in the centre foreground has been drawn much too small to create an unrealistic impression of the size of the glacier table. Source: Lory and Hürlimann (1822).

However, despite considerable recent interest in the debris cover of glaciers (e.g. Kirkbride 1995; Benn et al. 2012; Racoviteanu and Williams 2012; Immerzeel et al. 2014; Scherler et al. 2018; Mölg et al. 2020), the phenomenon of glacier tables and its driving factors (e.g. boulder size, surface topography, ablation rates) has not – to our knowledge – been further investigated.

On various glaciers in the Alps, we have observed several remarkable phenomena that, we began to suspect, are related to glacier table formation and destruction (Figure 2). We give here a first brief overview of these observations, since they provided the original reason for starting this research. More details will be given in the results section of the paper.

(1) We saw evidence of a sorting process near the south side of medial moraines: large boulders had clearly separated away from the medial moraine, whereas smaller debris had not (cf. Figure 3). However, we did not find evidence for a similar sorting process on the north side of medial moraines.
(2) We also found many individual boulders located at the south end of an ice ridge, up to a few metres high and sometimes dozens of metres long (cf. Figures 4, 5 and 6). From here onwards we call this feature 'tail'. Typically, these tails were reminiscent of ice pedestals left behind after the capping boulder of a glacier table had fallen off, but the tails are so long that they cannot have formed by one single fall of the boulder.
(3) We also saw that many more capping boulders of glacier tables were tilted towards the south (cf. Figure 2) than towards the north. The southerly-tilting tendency of capping boulders is even evident in various historical representations such as in Figure 1.

Medial moraines typically emerge at the upper end of the ablation area. Their development and sometimes even waning further downglacier has been described in several studies e.g. by Small and Clark (1974), by Small et al. (1979) and by Gomez and Small (1985) on Glacier de Tsidjoire Nouve,

Figure 2. Classical glacier table on Vadret Pers, Grisons, Switzerland (2007). The view is upglacier towards southeast. Despite temporary support by the person in the photo, it will soon fall off towards the south.

Bas Glacier d'Arolla and Haut Glacier d'Arolla, Valais, Switzerland respectively, and by Eyles and Rogerson (1978a, 1978b) on Austerdalsbreen, Norway, and Berendon Glacier, British Columbia, Canada. However, none of these studies indicated the asymmetrical sorting of boulders which we have observed.

Eyles and Rogerson (1978a) coined the phrase 'ablation dominant moraine', describing the most common type of medial moraine considered in our study. Such medial moraines are a result of continuous accumulation of debris from within the glacier, as more and more ice is lost due to ablation. 'Ice stream interaction' and 'avalanche type' moraines are much less common in our study area. Ablation dominant moraines have a tendency to grow in height as they move downglacier, sometimes reaching a relative elevation of up to 20 metres. This is because the thickening debris cover reduces ablation more and more. Small and Clark (1974) call this the 'waxing stage' of a medial moraine. After the lateral slope of the medial moraine has reached a certain steepness, debris begins to slide off, thus increasing the moraine's width. Eventually the medial moraine may even undergo a decline in height because the laterally scattered debris becomes less effective in reducing ablation. The effect of increasing height and debris sliding off the centre explains well why boulders are often found in great quantities at the margins of medial moraines. However, these studies offer no immediate reason why these boulders should further separate from the moraine's edge and 'migrate' further on to the relatively flat, debris-free glacier surface.

Therefore, we propose that processes associated with direct incoming solar radiation must be involved. Our first hypothesis is that boulders capable of glacier table formation, or those lying at the end of the tails described above, are not moving along with the ice in a passive way only; they are also moving towards the south (in the northern hemisphere). As a second hypothesis, we interpret boulder movement relative to the glacier surface by two different, but related, processes. (a) Large boulders tend to form glacier tables due to shading and reduced ablation of the ice underneath the boulders. However, at temperate latitudes in the northern hemisphere, direct incoming solar radiation is strongest on the south side, as is ablation of the ice pedestal (cf. Figure 4a). Therefore, the boulder is most likely to fall off its pedestal towards the south. After the fall, it may even slide away from the ice pedestal for a certain distance. In its new position,

Figure 3. (a) (top): Boulder sorting on the south side of a medial moraine on Vadret Pers, Grisons, Switzerland. View against the direction of glacier flow; viewing direction in the centre of the photo is ESE. Only on the right, i.e. south side of the moraine, can isolated boulders be seen on the side of the moraine, some having built glacier tables. (b) (bottom): View along the same medial moraine but further downglacier and now in the direction of glacier flow which here is west. On the left, i.e. the south side, isolated boulders appear even further away from the medial moraine compared to Fig. 3a. In both views, very few isolated boulders can be found on the north side of the medial moraine.

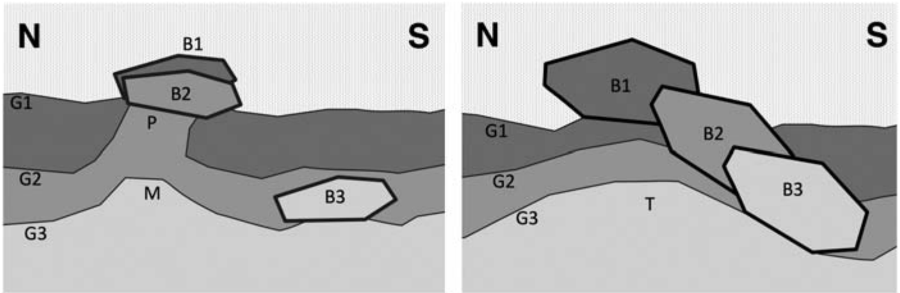

Figure 4. (a) (left): Cycle of glacier table formation and boulder migration: A boulder is at first lying at position B1 on the glacier surface G1. Ablation lowers the ice surface around the boulder, which remains standing on an ice pedestal P. The boulder has changed its position only slightly (B2), but is now tilting towards the south (situation in the northern hemisphere, temperate latitudes). The pedestal ablates more on its south side causing the boulder to eventually to fall off towards the south, where it could slide for a certain distance until it comes to rest. Ablation lowers the glacier surface further (G3), and the boulder (at B3) will begin forming another glacier table. A trace of the former pedestal remains as a mound (M) on the glacier surface. (b) (right): Cycle of ice tail formation and boulder migration. Similar process as in (a); however, instead of dropping off an ice pedestal, the boulder gradually slides off a mound of ice produced by reduced ablation under the boulder. At position B2 the boulder continues to cast a shadow on the mound, so the boulder remains tilted towards the south. As ablation continues, the boulder slides further southwards, i.e. to position B3. The mound has grown longer and now forms an elongated tail (T) on the north side of the boulder.

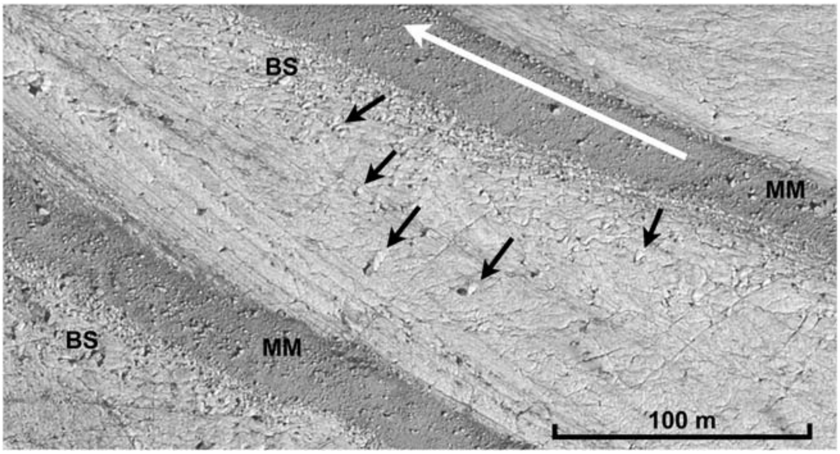

Figure 5. Aerial photograph of a small section of Persgletscher, Grisons, Switzerland, centred around 46°24′27″N, 9°57′11″E; north is up. Glacier flow is towards the upper left (i.e. north west), as indicated by the long white arrow. Visible are two medial moraines (MM), boulder sorting and migration of boulders away from the medial moraines (BS) and ice tails left behind by individual migrating boulders, the latter indicated by black arrows pointing to the tail, and in the direction of boulder migration relative to the underlying ice. Image reproduced by permission of swisstopo (BA20037).

the boulder may then form a new glacier table. Repeated cycles of glacier table formation by the same boulder will cause it to move in a roughly southerly direction relative to the glacier ice. (b) A boulder may also form an 'incomplete' glacier table by tilting towards the south before a proper ice pedestal has formed. On its north side it remains propped up by a mound of ice which also is shaded and, therefore, ablates less than the surrounding glacier ice (cf. Figure 4b). On the other hand, ablation is particularly strong on the south side, where the boulder rests on the flat glacier surface, absorbs short-wave solar radiation and re-emits infrared radiation towards the ice. Contrary to process (a) explained above, such a boulder may continue to move southwards, relative to the underlying ice, in a gradual manner, without pronounced cycles of glacier-table building

Figure 6. Two large boulders and related ice tails on Persgletscher, Grisons, Switzerland (2006). The boulders appear to have migrated away from a nearby medial moraine (marked MM) visible on the right, each leaving behind a tail of ice highlighted by dotted lines. The medial moraine is much closer than the tall lateral moraine going back to the Little Ice Age (marked LM). Both boulders seem to be migrating more or less continuously towards the south (left in the photo) as explained in Figure 4b, rather than producing classical glacier tables and dropping off their ice pedestals. The view is downglacier, towards the west.

and dropping off. On its north side, it leaves behind a more or less continuous ridge of ice, the tail. Such a tail would show a tendency for self-preservation; having been protected from deposition of dust for some time by the boulder, the ice tends to have a higher albedo than that of its surroundings and, therefore, ablates more slowly.

In order to verify our hypotheses, we conducted qualitative and quantitative analysis of aerial photographs of several Alpine valley glaciers and field experiments on Oberaargletscher in the Central Alps of Switzerland.

2. Data & methods

2.1. Field observations, measurements, and statistical analysis at selected boulders

Our field observations and measurements can be grouped into three parts: (a) a photo-documentation of the related phenomena, (b) in situ measurements at selected boulders using ablation stakes, and (c) a statistical analysis of boulder sizes and ice pedestals within a medial moraine.

(a) Photo-documentation of related phenomena

In order to illustrate many glacier tables, the tendency of capping boulders to fall towards the south and the existence of tails we collected terrestrial imagery from various glaciers in the Swiss Alps and present them at Glaciers online (https://www.swisseduc.ch/glaciers/migrating_boulders/). We found many excellent examples of migrating boulders on Gornergletscher, Oberaargletscher, Oberaletschgletscher, Vadret Pers and Unteraargletscher.

(b) Measurements at selected boulders

After preliminary experiments on Vadret Pers and Oberaargletscher late in the field season 2016, we conducted field measurements on Oberaargletscher in Juli and August 2017 on three selected boulders: OA1 at 660300 (E_m_CH1903LV03), 154201 (N_m_CH1903LV03), 2390 m a.s.l. (Z_masl; boulder length 2.5 m, boulder width 2.0 m), OA2 at 659854, 154048, 2435 m a.s.l. (3.4 m x 1.9 m) and OA3 659841, 154129, 2440 m a.s.l. (2.2. x 1.7 m). All boulders had a more or less tabular shape, i.e. were less thick than wide. Near OA3 a smaller boulder, OA4, could be tracked simultaneously. Ablation stakes were drilled in roughly the four cardinal directions from each boulder. During repeated field visits, we determined the changing positions of each boulder relative to the stakes. This was done by tape measurements and by taking photographs from all sides. These photographs were then assembled in Agisoft PhotoScan (https://www.agisoft.com/; cf. Li et al. 2016) to generate 3D-models and vertical views which were then aligned using the stakes as reference points (cf. Figures 8 and 9). As the stakes were drilled into the moving glacier ice surface, we were actually measuring horizontal boulder migration relative to the moving ice. Ablation was also measured at the stakes.

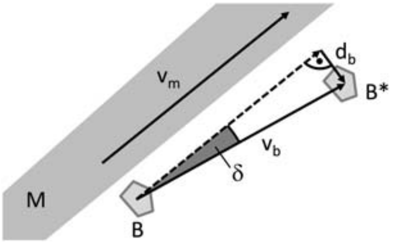

Figure 7. Velocities relevant to migrating boulders. Boulder B has moved within one year to position B*. The glacier ice on which it rests is assumed to have moved parallel to the nearest medial moraine (M, vector v_m), in this case towards the upper right (NE). The boulder's displacement (vector v_b) is at an acute deflection angle δ against v_m. Since the length of v_m (i.e. the ice flow velocity) is less well known as its direction (azimuth), the deflection angle δ is considered to be known with higher accuracy than the deflection length of d_b. We hence use the deflection angle as an indicator of the efficiency of boulder migration due to the formation of glacier tables and ice tails.

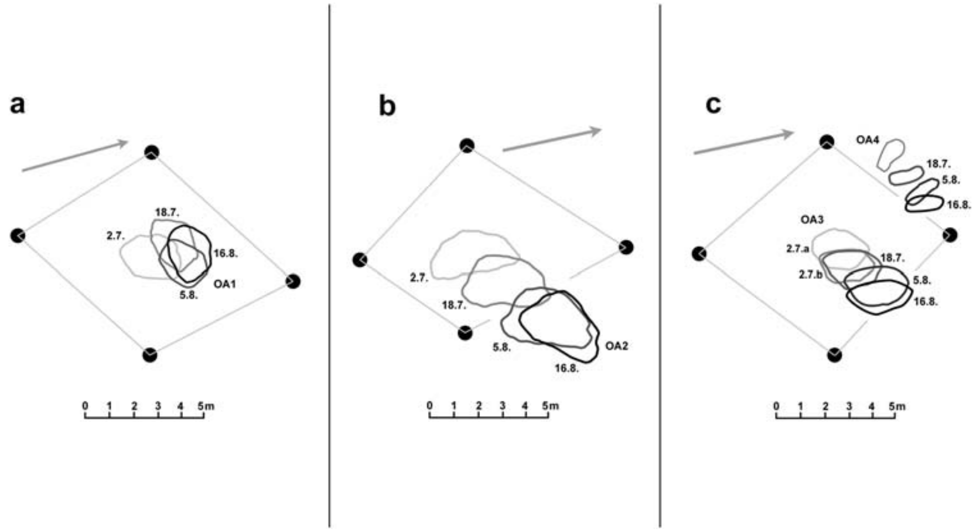

Figure 8. (a-c): Boulder migration during summer season on Oberaargletscher, Bernese Alps, Switzerland. In situ measurements of boulders OA1 to OA4, vertical view, north is up. (a), (b), and (c) have the same scale but are at different locations on the glacier. Boulder OA3 fell off its ice pedestal during the field visit on July 2nd and is shown at two positions, before and after the fall. Black dots show the location of ablation stakes, grey arrows the direction of glacier flow as determined from the orientation of the nearby medial moraine. As each view moves along with the glacier, boulder movement is shown relative to the glacier ice. Dates are given in the format DD/M.

(c) Statistical analysis of glacier table sizes

In a sample area 90 metres long and 35 metres wide on Oberaargletscher (in the vicinity of OA3) we measured the size of boulders on glacier tables during one field visit. The purpose of these measurements was to find out which size of boulders most likely leads to the formation of a glacier table. In addition, we wanted to confirm that medial moraines are indeed a good indicator of the direction of glacier flow. This would be the case if such a medial moraine mostly contains small debris unable to form glacier tables. In total, 36 boulders of various sizes ranging from 0.1 × 0.2 m to 1.2 × 1.7 m were selected, their size measured and, if present, the height of the glacier table. For simplicity, we defined boulder size as the sum of length and width, and the height of glacier table as the height of the ice pedestal excluding the overlying boulder.

2.2. Qualitative analysis of aerial photographs

Since field observations were practical on a few glaciers only, we included more glaciers by using the aerial photographs available for the whole of Switzerland. This was done using the online viewer of the Swiss Federal Office of Topography (swisstopo; https://map.geo.admin.ch/).

Glaciers were considered if they fulfilled the following conditions: (1) they have at least one clearly defined medial moraine, (2) one medial moraine is at least one kilometre long so that boulders riding along on the ice surface have enough time to undergo several cycles of glacier table building and falling off, and (3) at least one medial moraine has a clearly defined margin against debris-free ice. Glaciers included in this analysis are listed in Table 1.

On the aerial photographs we looked for (a) signs of boulder sorting, i.e. larger boulders on debris-free ice at increasing distance from the medial moraine, (b) tails leading away from isolated boulders indicating recent migration of the boulder (cf. Figure 5). If tails were present, their average direction was estimated. In addition, the direction of normal ice flow was estimated based on the general direction of the medial moraine. This was necessary as we had no independent measurements of the ice motion (cf. also section 2.3).

Figure 9. (a-e): Photo series documenting the cycle of glacier table formation and boulder migration on Oberaargletscher in summer 2017, Bernese Alps, Switzerland. Boulder OA3 seen from the east, i.e. against the glacier's flow direction on July 2nd before (a) and after the fall (b), on July 18th (c), August 5th (d) and August 16th (e). South is to the left. Boulder OA4 is partly visible on the lower right in frames (a), (b), and (e). Other boulders, some on ice pedestals and leaning towards the south can be seen in the background. Note that these photos correspond to the situation as shown in Figure 8c. Similar photo series for boulders OA1 and OA2 are available in the external photo-documentation.

Table 1. Overview of glaciers for which aerial photographs and field measurements were performed (*Vadret Pers was formerly part of Vadret da Morteratsch, but has recently separated from it as a result of glacier recession; length and width are given as measured on a 1:25,000 map of 2015).

Glacier name	Geographical coordinates of relevant section of the glacier	Exposition of relevant section (N=0°, E=90°, S=180°, W=270°)	Length (2009, km)	Surface area (2009, km^2)	Quantitative aerial photograph analysis (DD/MM/YYYY)	Field measurements (DD/MM/YYYY)
Gornergletscher	45°58′04"N 7°46′56"E	280°	13.4	51.6	14/09/2012 20/08/2013 27/08/2014 05/08/2015	none
Oberaargletscher	46°32′08"N 8°13′09"E	70°	4.8	4.1	27/08/2012 21/08/2013 27/09/2014 26/08/2015	16/08/2016 10/09/2016 07/10/2016 02/07/2017 18/07/2017 05/08/2017 16/08/2017
Unteraargletscher	46°33′28"N 8°10′35.57"E	50°	11.8	22.5	27/08/2012 21/08/2013 27/09/2014 05/08/2015	none
Vadret Pers*	46°24′25"N 9°57′39"E	220°	5.4 (2015)	6.9 (2015)		23/08/2016 20/09/2016

2.3. Quantitative analysis of aerial photographs

On three glaciers (Gornergletscher, Oberaargletscher, Unteraargletscher), we tracked 23–26 boulders each using aerial photographs from four consecutive years, i.e. over a three-year period from 2012 to 2015 (cf. Table 1). To compare the motion of these boulders with the ice movement presented us with a problem. In practice, displacement of boulders is used to measure glacier motion on aerial photographs, but our study basically requires an independent method for measurement; we do not expect the boulders to be strictly travelling along passively with the ice. Ideally, we would compare boulder movement with ice movement determined from stakes drilled into the ice. This, however, was impossible within the constraints of the study. Therefore, in order to solve our problem, we assumed that medial moraines give a good indication of the direction of glacier flow. Most debris of a medial moraine is too small to form glacier tables and, therefore, indeed rides along passively with the ice (cf. section 3.1). In other situations, debris cover is so complete that no glacier tables can form on the moraine as no bare ice is exposed. At the same time, aerial photographs shows us boulder displacement, however not necessarily parallel to the medial moraine (cf. Figure 7). The angle between the direction of glacier flow (as reconstructed from the medial moraine) and the direction of boulder movement (as measured in aerial photographs) indicates the migration of boulders towards the south.

3. Results

3.1. Field observations and measurements at selected boulders

Our photo-documentation shows many glacier tables with boulders either tipping towards the sun or having fallen off their pedestal towards the south, many tails to the north of the boulder hinting at earlier positions of the boulder, and sometimes remarkable sorting of larger boulders near the southern margin of a medial moraine, but absent on the northern margin. We interpret the multitude of these phenomena as a good indication for the fact that migrating boulders are common on glaciers with medial moraines trending roughly east or west. Boulders on glaciers flowing north or south would also migrate, but roughly parallel to the direction of glacier flow. Therefore, they would not appear to move away from the medial moraine and, as a consequence, boulder sorting would not occur.

The in situ measurements of boulder migration on Oberaargletscher yielded the following results (cf. Figures 8 and 9). Between July 2nd and August 16th boulder OA1 moved only 1.5 metres, i.e. less than its own length, towards the east. At the same time it rotated clockwise by nearly 90°. Cumulative ablation during this time was 2.69 m ice equivalent. Boulder OA2 moved much further, namely 4.8 m in total, approximately towards SE, thereby rotating approximately 45° clockwise. Cumulative ablation here was 2.56. Boulders OA3 and OA4 moved 2.8 and 2.7 m respectively, both approximately towards SE. Boulder OA3 rotated slightly, boulder OA4 oscillated between clockwise and anti-clockwise rotations. Cumulative ablation at this location was 2.73 m.

Figure 10 shows the statistical analysis of boulder sizes and ice pedestal heights on Oberaargletscher. Boulders smaller than 0.5 m (length plus width) had no ice pedestals at all or the pedestals were lower than 0.1 m. Larger boulders tended to be perched on higher pedestals, the highest (within the investigated boulder field) reaching 0.6 m. Since boulders were encountered at an arbitrary time within their cycle of pedestal formation and destruction, many ice pedestals are well below the maximum possible height that they might reach. It needs to be noted that some boulders on Oberaargletscher consist of a rather flat plate of gneiss or schist, whereas others are granitic and are less flat. The shapes may affect the ability of a boulder to produce a glacier table.

An important result of these measurements is the following: medial moraines consisting mostly of smaller debris will indeed travel passively along with the underlying ice, i.e. most of the debris will not form glacier tables and would, therefore, not migrate. Such a medial moraine is consequently a good indicator of the direction of glacier flow.

3.2. Qualitative analysis of aerial photographs

Figure 11 summarizes the results of the qualitative study using aerial photographs. On most glaciers with a roughly western or eastern exposure, we found either boulder sorting (for example Otemma, Brenay) or tails (Adler, Oberaletsch) or both (Findelen, Pers B). Boulder sorting always occurred towards the south. Where tails were present, they always indicated boulder movement towards the south relative to the moraine. However, the azimuth of the tails was usually not exactly south, but rather southwest for glaciers with westerly exposition and southeast for glaciers with easterly exposition. This seems to indicate that boulders fall from their ice pedestal not simply towards the south, but also with a tendency towards the line of greatest slope. Among glaciers

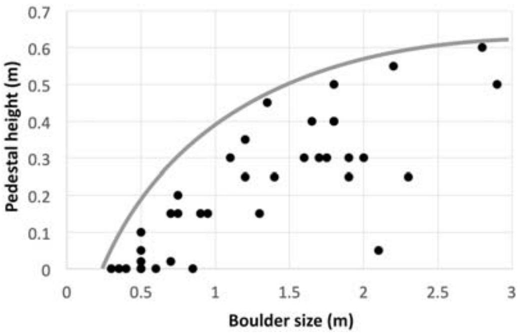

Figure 10. Relationship of boulder size and height of the ice pedestal. As glacier tables were encountered at an arbitrary time during cycles of pedestal formation and destruction, some of the pedestals have not yet reached their maximum size. The grey line indicates to which maximum size pedestals grow in this sample area. Boulder size was defined and measured as boulder length plus boulder width.

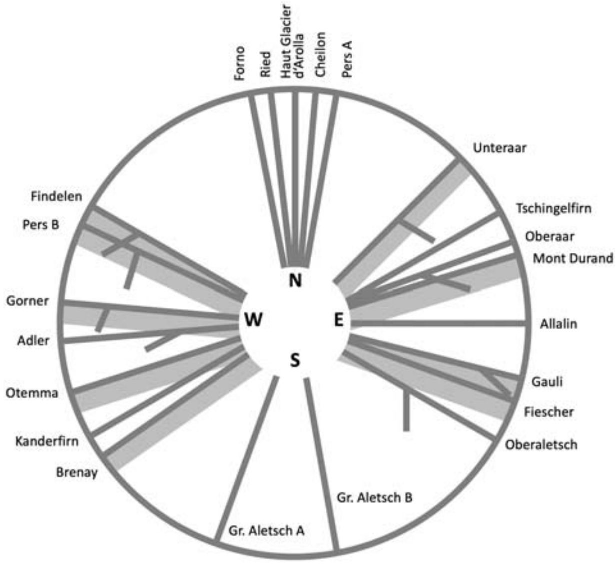

Figure 11. Boulder migration in relation to glacier orientation in the Swiss Alps. Glaciers considered in the aerial photo survey are represented by lines radiating from the centre of the drawing. Their orientation represents the direction of glacier flow in the relevant section of the glacier. Grosser Aletschgletscher and Persgletscher are represented by two sections (A, B) with different flow directions. Short lines branching off represent evidence of at least several tails and the average azimuth of the tails. Lines with wide, light shadows indicate glaciers where a sorting effect on the margin of the moraine was observed. In all cases, the sorting indicates boulders had migrated southwards from the moraine. For example, the relevant section of Gornergletscher is flowing approximately to the west, shows tails indicating boulder migration towards SSW and also boulder sorting at the south side of the moraine. Adler Glacier is also flowing roughly towards W, has tails indicating boulder migration towards WSW, but no boulder sorting was evident. Observations at Oberaargletscher and Oberaletschgletscher are from field observations rather than aerial photographs.

flowing east or west, Allalingletscher and Kanderfirn lacked evidence of sorting and had no tails. In these two cases, the aerial photographs seem to indicate a lack of large boulders to provide evidence of clearly visible sorting. On glaciers with roughly northern or southern exposure we found neither evidence for boulder sorting nor tails (for example, Grosser Aletsch, Pers A and Glacier de Cheilon).

3.3. Quantitative analysis of aerial photographs

The boulders tracked on Gornergletscher (23 boulders), Oberaargletscher (26) and Unteraargletscher (25) show, on average, the expected effect of migrating slowly away from the nearest medial moraine. This can be seen in Figure 12, representing Gornergletscher. From one year to the next, boulder movement is sometimes somewhat erratic, as the boulder may or may not have fallen off its ice pedestal just before the aerial photo was taken. This effect, however, is smoothed out considerably over a three-year period. For the statistical analysis of boulder movements, we therefore considered only the total of the three-year displacement from 2012 to 2015.

Figure 13 shows a summary of the distribution of measured boulder deflection angle δ (cf. Figure 7) from the direction of glacier flow. On Unteraargletscher, which in the relevant section is flowing towards the NE (azimuths of medial moraine sections between 30° and 70°), the average deflection angle of boulders in relation to the medial moraine is +6°. The plus sign means that the migration is primarily towards the south, as expected. Note that the boulder, in fact, does not travel south as the normal glacier flow is in a generally northeasterly direction and much faster than the boulder migration due to glacier table cycles. The net effect is a deflection of only +6°, on average, towards the right (south). A few boulders were displaced the 'wrong' way, i.e. towards the north. Extreme values are −9° and +27° compared to the direction of ice movement as inferred from the direction

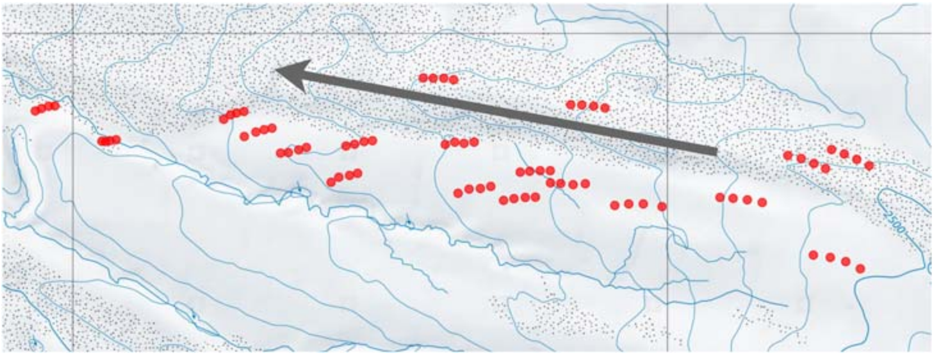

Figure 12. Multi-year boulder migration on Gornergletscher, Valaisan Alps, Switzerland. Recorded positions of boulders, in bundles of four, on the glacier tongue as recorded on aerial images in the years 2012 (position furthest right), 2013, 2014 and 2015 (position furthest left). The area is centred at 45°58′06″N, 7°46′54″E; the distance between the two vertical lines is 1 km, north is up. The grey arrow indicates the direction of glacier flow as estimated from the orientation of the medial moraine (dotted area) in the background map of 2016. Map reproduced by permission of swisstopo (BA20037).

of the nearest medial moraine. On average, the boulders moved 20.9 m/a (normal glacier flow plus migration). On Oberaargletscher, which is also flowing roughly eastward, the average deflection angle is +12° towards the south. The variation of deflection angles is much bigger than on Unteraargletscher, possibly related to a much smaller ice velocity. On Gornergletscher we found an average deflection angle of −15° at an average velocity of 16.7 m/a. As expected, the deflection angle is negative which, again, is towards south as this glacier flows in a westerly direction. The variation of deflection angles is more similar to that on Unteraargletscher.

4. Discussion

Our hypothesis was that boulders travelling on the surface of Alpine glacier tongues often do not only travel along with the ice passively, but also move somewhat towards the south. Indeed, our observations and measurements have clearly confirmed that boulders capable of producing glacier

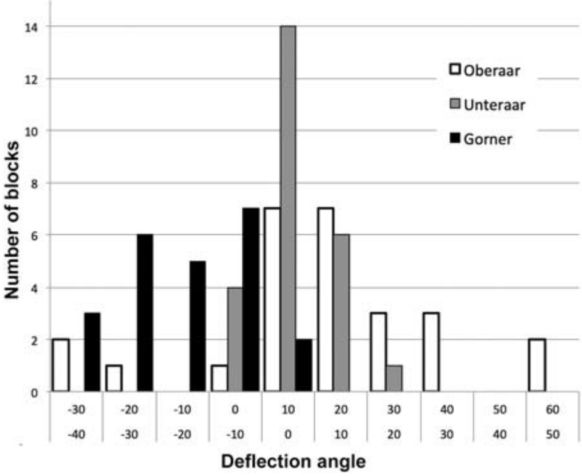

Figure 13. Distribution of measured boulder deflection angles δ from the direction of flow on Unteraargletscher (NE-flowing), Oberaargletscher (E-flowing) and Gornergletscher (W-flowing). Note that a deflection to the south of the medial moraine results in positive values for Oberaargletscher and Unteraargletscher but in negative values for Gornergletscher.

tables have a tendency to move southwards and away from a ‘parent’ medial moraine, whereas smaller debris does not. This happens primarily on the south side of medial moraines which are very roughly aligned in an east-westerly or west-easterly direction. Sometimes a boulder may fall off in other directions because of surface irregularities such as crevasses, meltwater channels, presence of other boulders or even the particular shape of the boulder itself. However, over time such irregularities tend to cancel out, favouring a southward migration, relative to the normal glacier flow. Boulder migration towards the south is caused by preferential ablation of ice pedestals or ice mounds on the south side. This effect takes place in addition to the well-known widening of medial moraines due to slippage of debris.

Glacier flow is typically much faster than boulder migration towards the south. Our measurements on the three glaciers studied in detail show that boulders are deflected, on average, between 6° and 15° from the direction of glacier flow. This is enough to separate them from the southern margin of a medial moraine over several years. For example, on a glacier flowing east or west, a deflection of only 6° causes a particular boulder to migrate 10 m towards the south for every 100 m of ice movement downglacier. If glacier flow is roughly towards the south or north, these effects are absent.

Since ablation is the cause of boulder migration, we can use values of annual ablation to estimate how far boulders might possibly move in relation to the ice over a certain time period. It seems reasonable to assume that boulders falling off ice pedestals will not travel horizontally much further than the height of the pedestal. As a plausibility study, we estimated annual mass balances (metres ice equivalent) in the elevation zone of the investigated boulders for the time period between the aerial surveys. We calculated degree-day factors (DDF) from annual point mass-balance observations and meteorological measurements. For Gornergletscher, data from Findelengletscher (2600 m a.s.l.; GLAMOS (2018), and earlier reports) and monthly mean temperatures from Sion (482 m a.s.l.; MeteoSwiss), for Oberaar- and Unteraargletscher data from Oberaar (2400 m a.s.l.; WGMS (2020), and earlier reports) and daily mean temperatures from Grimsel Hospiz (1980m a.s.l.; MeteoSwiss) were used. A temperature lapse rate of 0.65 °C 100 m^{-1} was used to extrapolate temperature data to glacier elevations. We estimated cumulative mass balances between the aerial surveys in 2012 and in 2015 as −24.9 m ice equivalent for Gornergletscher, −13.9 m for Oberaargletscher and −11.4 m for Unteraargletscher. Using ice velocities determined from boulder displacements and average displacement angles (v_b and δ in in Figure 7 respectively), we calculated an average total lateral migration of the boulders as 13.8 m (Gornergletscher), 3.7 m (Oberaargletscher) and 6.7 m (Unteraargletscher) over the 3-year period. This means that horizontal boulder migration was, on average, 55%, 27% and 58% (Gorner-, Oberaar- and Unteraargletscher respectively) of the cumulative ablation. In other words, ablation in the relevant parts of the glaciers was clearly sufficient to explain the amount of boulder migration.

Boulder migration may have an influence on studies of ice-velocities (cf. Kääb 2005). It is unclear how boulder migration will be affected by the anticipated glacier recession over the coming decades (cf. Haeberli et al. 2019). Some glaciers observed in this study have, in the last few years, lost most or all of their tongues and, thus, well-developed medial moraines. On the other hand, debris cover generally increases (e.g. Mölg et al. 2020), and new medial moraines may appear higher up. This might, at first, lead to an increase of the phenomen of migrating boulders. Later on, when debris cover is almost complete, it may disappear altogether because glacier tables usually do not form on glacier ice which is completely covered by debris. Furthermore, measurements in different parts of the world might yield an ideal geographical latitude and elevation band at which the phenomenon is most pronounced. Of particular interest would be measurements taken in the southern hemisphere, e.g. in Patagonia or New Zealand (cf. Brook et al. 2017), since northward migration would be expected there.

5. Conclusions

We have shown that existing models of medial moraine development do not fully explain all surface features associated with medial moraines on Alpine valley glaciers. Although medial moraines have long been known to grow in width and height relative to the surrounding glacier surface as they travel downglacier, additional effects related to exposure to the sun and ablation need to be taken into account. Indeed, boulders originally part of a medial moraine are affected by preferential ablation of ice pedestals on the south side, either during the formation of classical glacier tables or of modest ice mounds from which the boulder slowly slides more or less continuously. Boulder migration then can lead to sorting according to boulder size along the south side of medial moraines, and may create fields of scattered boulders far removed from the medial moraine. Tails seen on a number of glaciers indicate a tendency for boulders not to migrate strictly towards the midday sun, but also in the direction of greatest slope. Consequently, boulders will tend to migrate towards the SW on a W-flowing glacier in the northern hemisphere.

Further studies should include in situ measurements of a larger number of boulders. Stake positions measured by a differential global positioning system would yield ice velocities against which boulder migration could be more accurately compared. The maximum of incoming solar radiation might not occur when the sun is at its highest apparent position in the sky. Convection clouds that form more commonly in the afternoon would cause an increase of diffuse radiation at the expense of direct incoming radiation. Therefore, direct incoming radiation may be somewhat stronger before noon, which would favour boulder migration towards a more south-easterly direction.

Acknowledgements

We thank Michael Hambrey for feedback on the manuscript, Pamela Alean for editing the English, and the anonymous reviewer for constructive feedback that helped to improve the manuscript. We are grateful to the Swiss Federal Office of Topography (swisstopo; BA20037) and the Federal Office of Meteorology and Climatology (MeteoSwiss) for free access to their data. This study was conducted without funding.

Author contributions

JA and MZ developed the project idea; LS carried out field work during her master's thesis (Schwendener 2017), assisted by JA and MZ; LS and JA analysed the aerial images; JA wrote the manuscript; MZ and LS provided feedback on the manuscript.

Data availability

Glacier photographs, including a section on boulders and glacier tables, are available from Glaciers online (https://www.swisseduc.ch/glaciers/). Aerial photographs are available from the Swiss Federal Office of Topography (swisstopo). In order to extend our photo-documentation of phenomena associated with migrating boulders, we welcome contributions of other photos, especially if they are from other glaciers and other areas of the world. Images from the southern hemisphere are of particular interest. Photos can be submitted to the lead author for publication on Glaciers online and should be accompanied by information about location, time, and direction of view.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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