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NUMERICAL MODELLING OF THE VERNAGTFERNER AND ITS FLUCTUATIONS[1]

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With 8 figures

ABSTRACT

The long historical record and extensive modern observations for the Vernagtferner make the glacier a prime object for modelling of its present state and past fluctuations. Historically, the glacier appears to have passed through two radically different phases, characterized by cyclic surging and by shrinkage back into higher accumulation-favorable regions, respectively. A unified computer simulation of this bimodal behavior on a highly complex bedrock topography remains beyond the power of existing glacier models. However, the essentials of the two phases have been reproduced. It appears that the surging mode of flow could operate only as long as the glacier remained large enough to create substantial basal melting through the combination of high base stresses and rapid flow rates. The velocity and thickness profiles observed during the retreat phase are shown to be well simulated by a deformational flow model including parameterizations of the most essential three-dimensional features. The great retreat of the glacier since 1848 appears to have resulted from a climatic mass balance decrease over its entire surface of order 0.2 ma^{-1} superimposed on an enlarged post-surge ablation region. This interpretation holds the potential for future readvance, and perhaps an eventual return to the surging mode, foreshadowed by the recent general thickening of the Vernagtferner.

1. INTRODUCTION

The Vernagtferner, a small valley glacier in the Oetztal Alps, Austria (46.9° N, 10.8° E), is one of the best known glaciers in the European Alps in terms of both modern scientific investigation and available historical records. This wealth of data made Vernagtferner an immediate candidate for computer modelling studies. Such studies were undertaken during recent years as a cooperative venture between the Meteorology Department, University of Melbourne, Australia, and the Kommission für Glaziologie der Bayerischen Akademie der Wissenschaften, München, BRD. The basis for this modelling was laid in Munich by D. Jenssen. His work was followed up by P. D. Kruss (Kruss, 1976) in Munich, and later by I. Smith (Budd et al., 1979; Smith and Budd, 1980) at the University of Melbourne. W. F. Budd guided this modelling throughout, while O. Reinwarth provided the factual background from his extensive Vernagtferner measurements.

The Vernagtferner is of considerable interest to the modeller for two reasons. It is a

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glacier with a history of cyclic surges, but which no longer surges. Hence, it is suitable for surge-model development and study of the basic parameters important in the surge environment. Further, the Vernagtferner terminus record since 1600 offers the potential for revealing climate change and the transition from a cyclic surging regime to one of steady retreat. However, the modelling of Vernagtferner is not a straightforward process and has not yet been concluded. This paper reviews progress made and problems remaining to be solved.

2. HISTORICAL RECORD

For the purposes of this modelling study, it is necessary to draw together certain relevant aspects of the known history of the Vernagtferner. This history, excellently detailed in Hoinkes (1969), suggests that the glacier's past behavior may be effectively separated into two epochs, the division occurring in the late 1800's. From late in the 16th century, or earlier, until the mid 19th century, the behavior of the Vernagtferner was characterized by periodic rapid advances of the terminus, with major advances occurring at about 1600, the late 1670's, early 1770's, and mid 1840's (Hoinkes, 1969). These major advances involved both Vernagtferner and Guslarferner (fig. 1) and are

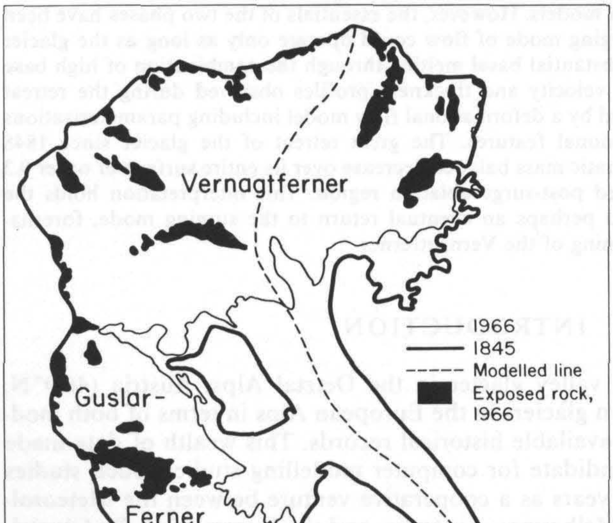

Fig. 1: Map of Vernagtferner and Guslarferner for September, 1966, and for their maximum extent in 1845. The position (approx.) of the modelled central line is also shown (Base map after Hoinkes, 1969)

quite well documented because they considerably affected the inhabitants of the Inn Valley. The Vernagtferner and the Guslarferner would flow together at the Hintergraslen corner and the combined glacier front then descend very rapidly to completely block the Rofen Valley, which joins the Oetz Valley. This resulted in the damming of melt water from the Hintereisferner, the Kesselwandferner and the Hochjochferner, with disastrous consequences when the dams burst (Stotter, 1846; Schlagintweit and Schlagintweit 1850; Richter, 1892).

It is recorded that the residents of the Inn Valley were only concerned about damming of the Rofen Valley when the two glaciers advanced together (Walcher, 1773). This suggests that there may also have been a number of early unreported smaller scale advances during which the Vernagtferner and the Guslarferner did not join. Recorded small scale advances occurred between 1820 and 1822, and between 1899 and 1902. In both instances the Vernagtferner advanced significantly without any corresponding reaction by the Guslarferner.

Hence the first epoch can be described as one of major cyclic surges involving both the Vernagtferner and Guslarferner; it lasted from at least 1600 to the mid 19th century. Since then the glacier has been in retreat (apart from a minor advance about 1900), a retreat which can be regarded partly as post-surge reaction and partly (particularly since about 1890) as a response to secular climate change. This general retreat characterizes the second epoch.

3. AVAILABLE DATA

The end of the 19th century marks the beginning of modern scientific investigation of Vernagtferner and its sometime partner the Guslarferner. Since 1889 a considerable volume of data has been gathered by direct investigation. This section discusses the data available throughout the modelling history of Vernagtferner. The most recent data can found in Moser (1975/77, 1980/83) and in the Zeitschrift für Gletscherkunde und Glaziolgeologie, volume 18 (1).

The first surveys of the entire ice surface of Vernagtferner were carried out by Finsterwalder in 1889 (Finsterwalder, 1897), and Gruber in 1912 (Hoinkes, 1969). During the minor advance of the late 1800's/early 1900's a flowline in the region of the glacier tongue was surveyed frequently. The record obtained spans the years 1890 to 1925 and extends almost 1500 metres back from the glacier terminus (Finsterwalder and Hess, 1926). A further survey was carried out in 1938. The year 1967 marked the beginning of a systematic annual investigation of the glacier and its environment by O. Reinwarth for the Kommission für Glaziologie der Bayerischen Akademie der Wissenschaften. In 1966 the entire bedrock beneath the ice was surveyed using the seismic sounding technique (Miller, 1968). The suggested order of magnitude of the error was ±15 %. Further bedrock information is now available following the initiation in 1976 of a hot-point drilling program by the Kommission.

The earliest surface velocity values now available refer to 1889 when a stone line was placed on the glacier at a mean elevation of 2890 meters, approximately 700 meters from the Vernagt Hut (Finsterwalder and Hess, 1926). Continuous determination of the velocity in this region was maintained until 1925; once again this covered the minor advance period. No further velocity information was obtained until 1967; since then three-dimensional velocity measurements have been carried out annually by surveys of an ever increasing number of points on the glacier.

Of all the data needed for modelling, the shortest record is that concerning the net balance of the glacier. However, net balance contour maps and profiles of net balance versus elevation have been produced annually since 1969 (Reinwarth and Stäblein, 1972; Kasser, 1973; Müller, 1977).

Previous assertions concerning a change in the state of the glacier during the second half of the 19th century are well supported. It will be seen that the beginning of a purely climatic retreat phase may be set at approximately 1920. The only sign of a major surge, predicted for the period immediately after 1925, was a very minor increase in surface velocity between 1924 and 1929 (Hess, 1930). The periodic major advance phase ended with the advance of 1845, while the period from 1845 to 1920 represented a transition.

For the periodic surge epoch, an interesting array of information can be assembled (Hoinkes, 1969). The earliest information available refers to 1599. Since then four major advances to block the Rofen Valley have been recorded. The first sudden emptying of the lake formed by the damming of the Rofen Valley occurred on the 20th July, 1600 (Richter, 1892). Further dam bursts were reported in 1678 (Richter, 1892), 1773 (Hoinkes, 1969), 1845 (Stotter, 1846), and 1847 and 1848 (Schlagintweit and Schlagintweit, 1850). The corresponding times for first formation of the lake are 1599, 1678, 1771 and 1845. The time between the advances thus recorded are 79, 93, and 74 years respectively, giving a mean period of 82 years. Reports by Walcher (1773) and Stotter (1846) suggest that the active period for these advances was 4 to 5 years.

As mentioned previously, an indeterminate number of smaller scale advances also may have occurred. Only two small scale advances are recorded. The first of these lasted from 1820 to 1822, and the second from 1899 to 1902. When these are taken into account, the actual times between advances of the Vernagtferner since 1771 were 49, 25 and 54 years, giving a mean of 43 years. It is interesting to note that the shortest time between advances occurred during a period of apparent maximum positive mass balance (significant melting on the glacier was not observed prior to 1850). This period saw many European glaciers, including the nearby Hintereisferner (Blümcke and Hess, 1899), at their (recent) maximum extents.

4. THE MODELS AND MODEL TUNING

4.1 THE FLOW MODELS

The modelling of any glacier is a step by step process. This particularly so for Vernagtferner as it exhibits considerable bedrock and terminus irregularity. This section deals with the preliminary input and modelling stages which must perforce lead problem-oriented calculation. At this same time, much information can also be gained concerning the general state of the glacier in times past. Two numerical glacier flow models have been used in the Vernagtferner calculations.

The first model may be characterized as a two dimensional time dependent ice deformation model which has been parameterized to include various three dimensional properties needed to adequately simulate glacier fluctuation in response to climate change. Thickness and velocity profiles are calculated at constant time intervals for evenly spaced grid points along a representative central line. This basic model has been extensively described and discussed (e.g., Budd and Jenssen, 1975; Smith and Budd, 1981); the specific formulation used in much of the Vernagtferner work is detailed in Kruss (1983). Glaciers to which the model has been applied include Hintereisferner (Austria; Kruss, 1977), Storglaciären (Sweden; Smith 1975), Aletschgletscher (Switzerland; Smith and Budd, 1981) and Carstensz Glacier (Irian Jaya; Allison and Kruss, 1977).

The second model (Budd and McInnes, 1974) allows the glacier to slide on the underlying rock when basal friction creates substantial melting and a basal water layer. Thorough discussion of this model has been given by Budd (1975); the most detailed application has been to Medvezhi Glacier (Soviet Union; Budd and McInnes, 1978).

The existing descriptions of these model simulations are representative also for the Vernagtferner modelling which, therefore, requires no further elaboration here. It is, however, necessary to summarize the parameters which describe three-dimensional effects not explicitly included in the model algorithms. These parameters acquire special importance for a complex glacier environment such as that of the Vernagtferner.

These parameters are the stress shape factor (s), the valley factor (m) and the cross-section velocity factor (C_v). The stress shape factor appears in the basal shear stress equation

$$\tau_c = s \rho g Z \sin\alpha \qquad (1)$$

where ρ is ice density, g gravitational acceleration, Z ice depth, and α surface slope. This parameter s depends on the shape and dimensions of the valley cross-section and takes into account its frictional effects.

The remaining two, m and C_v, both appear in the continuity equation

$$\frac{\Delta z}{\Delta t} = A - \frac{\delta(\Omega \bar{V})}{\overline{W}_s \delta x} \qquad (2)$$

where the lefthand side is the rate of change of the local ice thickness, A is net balance, $\overline{W}_s$ and δx are the mean width and length of the ice column, and $-\delta(\Omega\bar{V})$ is the net mass influx. $\bar{V}$ is the cross-section mean velocity and Ω the cross-section area. $\bar{V}$ is computed as

$$\bar{V} = C_v U_s \qquad (3)$$

where U_s is the total centerline surface velocity. If the valley cross-section shape is approximated by a simple power fit of order m, i.e.,

$$z \propto W_s^m \qquad (4)$$

where z is some distance above the bed and W_s is surface width, then

$$\Omega = \frac{m}{m+1} W_s Z \qquad (5)$$

4.2 GLACIER DATA USED IN THE MODEL

The first step in modelling is to construct the flowline to be used. Two lines were originally drawn from Taschachhochjoch down the glacier. The first was the central flowline of the 1889 glacier, as defined by the 1889 ice surface contour map. The second was a line through the valley bottom as defined by direct surveying in the regions currently ice free and by the 1969 seismic survey of the ice covered valley floor. It was found that the former flowline was quite similar to a high-frequency smoothed form of the latter. This smoothed flowline was used because it is somewhat more consistently representative in time (fig. 1). A grid point spacing of 150 metres was chosen both to satisfy the stability criterion of the first model (Budd and Jenssen, 1975) and to assure realistic computation times for the modelling of the glacier at its maximum extent.

Mass exchange processes were included in the calculations by specifying the mass balance as a function of elevation and surface widths as a function of distance down

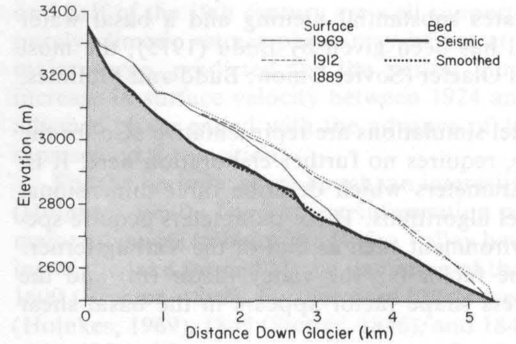

Fig. 2: Surveyed ice surface profiles down the central line of fig. 1 along with the corresponding bedrock determined directly below the 1969 terminus and by a seismic study on the glacier. The computationally more acceptable smoothed bedrock is also included

glacier. It is essential to use a net balance/elevation relationship for the Vernagtferner because very large changes in the glacier occurred during the period of interest. A mean balance profile was constructed from the measured values for 1965/66 to 1967/68.

To allow for the large variations in surface and cross-section areas between given elevations on the glacier, realistic surface width values must be used. These widths were determined from the surface contours. A small portion at the eastern edge of the 1969 glacier was excluded because flow from this region did not contribute to the major glacier tongue.

4.3 TUNING

Due to the irregularity of the bed topography of the Vernagtferner, a direct determination of the valley and cross-section velocity factors (m and C_v) and of the stress shape factor (s) is precluded. Instead, the model was 'tuned' by comparing various velocity and thickness profiles computed for a range of parameter values to corresponding measured profiles. This was completed using primarily 1969 glacier observations which include ice depth, surface velocity, and net balance information. Tuning of the model is possible because, firstly, the stress shape factor is the only independent variable when surface velocity values are computed from known ice depth values and, secondly, a general relationship exists between m and C_v (Nye, 1965b).

Fig. 2 shows the observed surface and bedrock elevation profiles along the central line (fig. 1) for 1969. Surface velocity profiles for 1969 were computed from these measured values for a range of stress shape factors s (fig. 3) to tune the model for s. It is

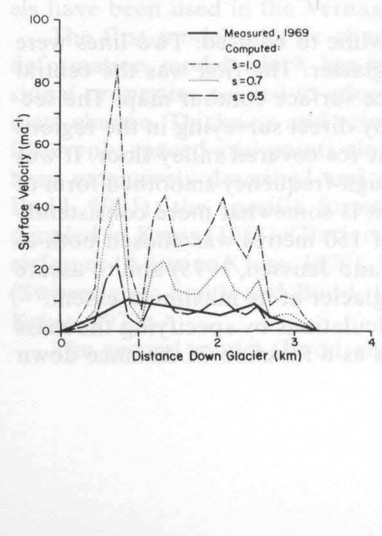

Fig. 3: Surface velocity profiles (along the central line of fig. 1) calculated for a range of stress shape factor s values, and corresponding measured velocity data

seen that the calculated values for a stress shape factor s = 0.5 yield the closest approximation to observed velocities.

Having determined the stress shape factor, velocity profiles can then be calculated for other dates possessing measured surface and bedrock elevation information. This was done for both 1889 and 1912 using as input the measured profiles of fig. 2. Fig. 4

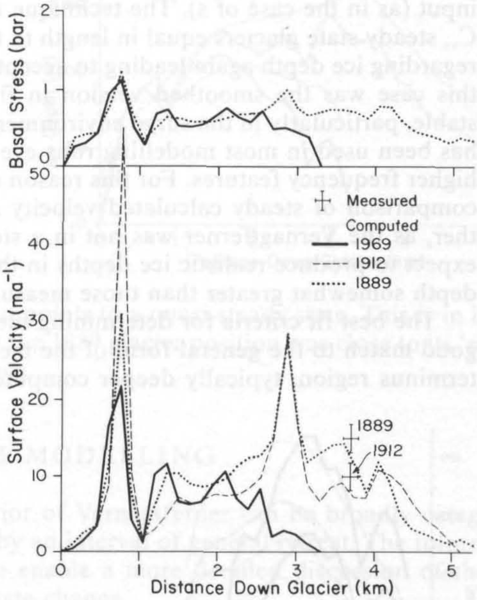

Fig. 4: Surface velocities and basal shear stresses calculated for different years from the bed and surface elevation data of fig. 2 using the best-fit s value. Single point velocity values for 1889 and 1912 are represented by magnitude and position uncertainty crosses

compares the final (tuned) velocity profile for 1969 with results for these two earlier epochs. Also included in this fig. 4 are corresponding computed basal shear stress values. The velocity profiles for these latter two years show good agreement with the single measured values available for each date (shown in fig. 4 with approximate position and magnitude uncertainty bars). Further, the computed and measured velocity changes over this period are very comparable.

Of these two years, the results for 1912 are the most reliable given the modelling approach taken. Terminus position data indicate that in 1912 Vernagtferner was in a comparatively very rapid retreat, with a strongly negative mass balance. This resulted from two events: the minor surge of the turn of the century moved glacier mass down into the ablation region and produced a small advance of the terminus; and the glacier was also generally in a retreat phase in response to climate change. Both these factors created the very rapid retreat during which the glacier terminus recovered from the perturbation brought about by the surge and returned to its equilibrium retreat rate matching the climate change. The very flat 1912 surface elevation profile below 4 km (fig. 2) reflects this. Budd (1975) has suggested that the sliding velocity of a surging glacier drops to nearly zero during such rapid retreat periods immediately after a surge. Hence, the 1912 Vernagtferner can legitimately be treated as non-sliding.

The 1889 glacier, on the other hand, was in a pre-surge state and may have possessed a significant sliding component (Budd, 1975). The comparison between computed and measured velocity in fig. 4 suggests that this was not true in the lower half of the glacier but this does not rule out higher velocities up in the pre-surge buildup area.

With the value of the stress shape factor determined, the model may then be tuned further by determining the appropriate values for the valley and cross-section velocity factors, m and C_v, respectively. The time-change term in the continuity equation implies that this cannot be accomplished using measured surface profiles for direct input (as in the case of s). The technique used was to compute, for a range of m and C_v, steady state glaciers equal in length to the 1969 glacier, with best fit considerations regarding ice depth again leading to accepted values. The bedrock profile employed in this case was the smoothed version in fig. 2. This profile is more computationally stable, particularly in the surge environment, and is well suited to the model. Hence, it has been used in most modelling runs even though it does not allow reproduction of higher frequency features. For this reason the modelling has provided only large scale comparison of steady calculated velocity and ice depths with measured values. Further, as the Vernagtferner was not in a steady state but rather retreating, one would expect to produce realistic ice depths in the upper glacier but calculated values of ice depth somewhat greater than those measured in the lower portion.

The best fit criteria for determining the m, C_v pair are thus, in the upper glacier, a good match to the general form of the measured ice depth profile but, in the general terminus region, typically deeper computed depths are to be expected. Fig. 5 shows

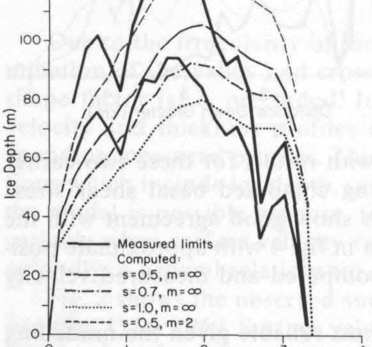

Fig 5: Steady state ice depth profiles calculated (using the smoothed bedrock of fig. 2) for a range of valley cross-section shapes (m = ∞ or 2 indicates a rectangular or parabolic valley) and stress factor s values. The measured ice depth is indicated by an envelope defining the ± 15 % error range

that a rectangular valley shape (i.e., m = ∞, C_v = 0.75) meets these criteria for the 1969 glacier.

Further insight can be gained from steady state modelling for 1969 and 1889. Comparison between computed 1969 steady state velocities (for s = 0.5, m = ∞, C_v = 0.75; fig. 6) and measured values reveals measured values somewhat greater up-glacier and somewhat smaller down-glacier than calculated. This dichotomy, along with corresponding ice depth comparisons, suggests strong retreat during the period immediately following 1969 but also a potential for readvance. The retreat of the Vernagtferner terminus did indeed continue from 1969 to 1979 but the glacier thickened everywhere except for the very near terminus region (Moser, 1980/83).

Comparisons with steady state for the 1889 glacier (fig. 6) give larger computed ice thicknesses than observed but smaller relative differences. This is in accord with the

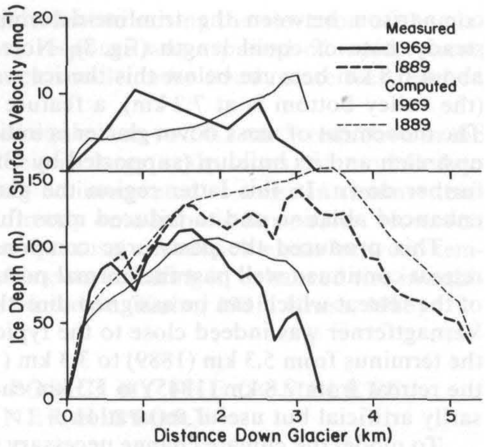

Fig. 6: Surface velocity and ice depth profiles *both measured and steady state* (calculated for smoothed bed using best-fit s, m and C_v values)

observed glacier retreat in this period, but points to a quasi-steady state. This is in line with historical reports which suggest that the 1889 glacier position was close to its 'normal' *immediately prior to sudden advance.*

5. CLIMATE MODELLING

To recapitulate, the historical behavior of Vernagtferner can be broadly categorized into a cyclic surge period followed by an interval of general retreat. The information and modelling techniques available enable a more detailed discussion of these two epochs from the perspective of climate change.

The interval from 1600 to 1850 was climatically favorable for the glacier; this period is considered further below. Since 1850, the Vernagtferner terminus has retreated quite dramatically (figs. 7 and 8) — from a position at 7.8 km in 1845 to only 3.3 km in 1969 (a shortening of about 60 %). Over a similar period, the ice volume was reduced by about half (Hoinkes, 1969). The forcing behind this retreat is in part climatic and in part surge-related.

When, in 1845, the Vernagtferner/Guslarferner pair last surged to block the Rofen Valley, a considerable volume of ice moved into a region of strongly negative mass balance. The post-surge nature of the 1845 surface elevation profile is illustrated by the

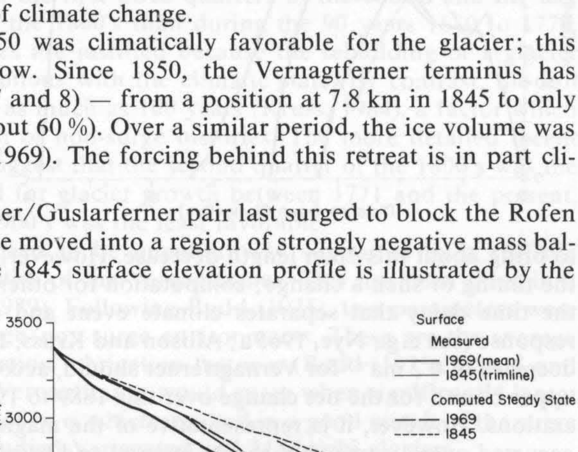

Fig. 7: Measured and modelled steady state ice surface elevation profiles for 1845 and 1969. This latter is a mean for a number of flowlines. Note that the bedrock below 7.2 km does not reflect reality, the Rofen Valley wall rising from this point

comparison between the trimline-determined actual 1845 profile and a modelled steady state of equal length (fig. 7). Note that the comparison breaks down below about 6.8 km because below this the ice was affected by the rising Rofen Valley wall (the valley bottom is at 7.2 km), a feature not modelled (see bedrock profile, fig. 7). The movement of mass down glacier is indicated by the relative lowering of the glacier upstream and its buildup (supported by Guslarferner) to near the steady state profile further down. In this latter region the glacier will tend to thin very quickly due to enhanced ablation and to reduced mass flux from the shallower upper glacier.

This produced the post-surge component of the observed retreat. However, the retreat continued well past the normal post-surge minimum. It is this latter component of the retreat which can be assigned directly to climate change. If the 1889 position of Vernagtferner was indeed close to the typical post-surge minimum, then the retreat of the terminus from 5.3 km (1889) to 3.3 km (1969) may be attributed to climate, whereas the retreat from 7.8 km (1845) to 5.3 km can be assigned to post-surge decay (a necessarily artificial but useful separation).

To model the climate change necessary to bring about the retreat between 1889 and 1969, Kruss (1976) used the technique of creating a steady state glacier equal in length and surface area to the 1889 Vernagtferner and then reducing the net balance such that a steady state glacier equal in length and area to the 1969 glacier was achieved. A net balance reduction of about 0.2 ma^{-1} water equivalent over the entire glacier was found

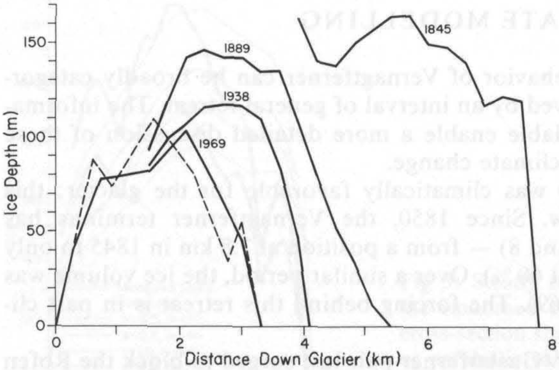

Fig. 8: Measured ice depth profiles for various years including an 1845 trimline estimate from the map of Finsterwalder (1897) and two profiles for 1969: for the specific flowline in fig. 1 (dashed), and a mean of number of flowlines (solid)

to bring about this 2 km length decrease. However, this modelling says nothing about the timing of such a change; computation for other glaciers has thrown some light on the time delay that separates climate event and corresponding definitive terminus response (see e.g., Nye, 1965 a; Allison and Kruss, 1977; Kruss, 1984). The net balance decrease of 0.2 ma^{-1} for Vernagtferner should, according to these studies, represent an upper bound for the net change over this 1889 to 1969 interval due to time lag considerations. However, it is representative of the magnitude of the climate change which occurred over a somewhat earlier interval and brought about the retreat of this epoch.

Smith and Budd (1981) took a somewhat different approach in simulating the large scale features of the recent terminus record. Various near steady state solutions between 6 and 7 km long were generated, on the assumption that the post-surge minimum at this time of general glacier enhancement was longer than the 1889 glacier. Then the curve of net balance versus elevation corresponding to these steady state solutions was suddenly moved up the elevation axis (see Allison and Kruss (1977) for details of this technique). Such a shift is equivalent to raising the elevation of the glacier equilibrium line. The resulting terminus response was a period of rapid retreat, beginning about 30 years later, before a much smaller near steady state was reached after approximately 100 years.

An elevation increase of 100 m (estimated equivalent to a 0.5 ma^{-1} reduction in the net balance) at 1860 gave the best fit, albeit in large scale terms, of modelled to observed terminus record. Such a change can be interpreted as a rise in summer temperatures in the range 0.6 to 1.0° C based directly on adiabatic lapse rates. However, this interpretation leads to inflated numbers because a feedback exists between temperature change and other energy balance elements, resulting in enhanced rise in equilibrium line altitude for a given temperature increase (Kuhn, 1981; Kruss, 1983).

6. MODELLING PROBLEMS POSED BY THE COMPLETE VERNAGTFERNER HISTORY

Though considerable insight can be gained into Vernagtferner using the techniques of the above and preceding sections, a complete study must cover both the surge and post-surge epochs. The climate was certainly changing during the cyclic surge interval and the varying time between surges of Vernagtferner already provides some climatic hints. If the glacier environment is invariant, then glacier surges could be expected to occur at regular intervals. The length of this interval is a function of the time for the glacier to rebuild to its surge-ready form, which is itself a function of the net balance — and therefore of the climate.

Beginning in 1599, major surges of the Vernagtferner/Guslarferner bi-glacier caused readvance after 79, 93 and 74 years. This suggests generally more favorable climatic conditions for the glacier in the first three quarters of the 1600's and the last quarter of the 1700's/first half of the 1800's than during the 90 years 1680 to 1770. Such deductions of climatic phases are justified because the rebuilding of a glacier after a surge is essentially synchronous with the climatic state. By contrast, the full terminus response can be delayed as much as 100 years (Kruss, 1984), a factor which must complicate the interpretation of non-surge histories. The more detailed recent data available for Vernagtferner suggest that the second quarter of the 1800's was the most climatically favorable period for glacier growth between 1771 and the present, and perhaps the first half of the 1900's was the least favorable.

These suggestions, however, need to be quantitatively supported by a realistic modelling of the surge characteristics of the Vernagtferner. This has been done in a preliminary way by Budd et al. (1979). Following Budd (1975), two parameters were varied to explore the range of surge/non-surge environments. These are the average generalized viscosity η and the friction lubrication factor φ (Budd (1975), Eqs. 8 and 12). Budd et al. (1979) found that Vernagtferner would surge when significantly larger than at present for the same range of η, φ which resulted in a good match of the surge characteristics of the more fully studied Variegated and Medvezhi glaciers.

A stress averaging is carried out in the Budd surge model so as to preserve the overall ice equilibrium consistent with the reality of a surging glacier not tending to move en masse down slope (Budd (1975), Eqs. 13 and 14). In the original model, stresses are averaged without regard to glacier widths, a good approximation for many glaciers. However, the Vernagtferner widths vary greatly down glacier and it has been demonstrated that an averaging process using width-weighted stresses produces quite large differences in the surge results. It would appear that a 3D surge model is required to well model the surges of the Vernagtferner; development of such a model is a difficult task not yet accomplished.

Modelling of a range of surging glaciers has suggested that a consistent feature of these glaciers is comparatively high values of the product basal shear stress times mean velocity, $\tau_c V$. From Eq. 1 it can be seen that $\tau_c V$ is a function of the product αZV where α is surface slope and Z ice depth. Hence, high αZV (a term including the mass flux per unit width ZV) may be an indicator for potentially surging glaciers. Further, the ratio net balance to mass flux must be such that at least the upper glacier will rebuild to a pre-surge profile. The Vernagtferner is currently rebuilding in its upper reaches but is not yet approaching high αZV and hence further surging in the near future is unlikely.

7. CONCLUDING REMARKS

The Vernagtferner is an interesting glacier for modelling studies but not a straightforward one. It is of interest because the Vernagtferner historical record embodies the interplay between changing climate and surging ice. Further, the Hintereisferner, a non-surging glacier literally just around the corner, also possesses a long history. Joint treatment of these two glaciers offers the potential for a revealing study of climate and ice interaction.

The Vernagtferner cannot, however, be well represented by a single flowline. In recent years the Vernagtferner has retreated to a number of distinct channels and in earlier times the Vernagtferner/Guslarferner diad could not strictly be treated in two parts. Moreover, its surging process remains an imperfectly understood phenomenon. A complete study of the multifaceted Vernagtferner problem must cover both the deformational and sliding modes of glacier movement from a fully three-dimensional perspective.

ACKNOWLEDGEMENTS

The Vernagtferner modelling project was created in 1971 by Uwe Radok after a sabbatical in Munich. This brought him close contact with Ossi Reinwarth which continued after Radok's election to the Commission of Glaciology in the Bavarian Academy of Sciences. The computer work was initiated in 1972 by Dick Jenssen and since then has benefited throughout its course from Bill Budd's suggestions and creative criticism. All this assistance is gratefully acknowledged. Figures crafted by Bob Tope and word processing by Nancy Kramer.

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