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SOME RESULTS OF RECENT INVESTIGATIONS ON GHIACCIAIO DEL BELVEDERE (ANZASCA VALLEY, WESTERN ALPS) TAKING INTO ACCOUNT THE GLACIER MECHANICS

ABSTRACT: MAZZA A, *Some results of recent investigations on Ghiacciaio del Belvedere (Anzasca Valley, Western Alps) taking into account the glacier mechanics.* (IT ISSN 0391-9838, 2000).

First the geographic position of Ghiacciaio del Belvedere and of the glacier system building the final glacier tongue are reviewed. Some information is given concerning the glacier mechanics, based on the continuity equation, as a basis for the understanding of the glacier evolution depending on ice properties, glacier geometry, aspect, and temperature, and on climatic fluctuations. A short history covering the last 45 years of Ghiacciaio del Belvedere is outlined. It is related to the present and relatively updated maps of Ghiacciaio del Belvedere, which are duly listed. As no information exists on the climatic conditions in the upper Anzasca Valley, we rely upon other sources. The thermal condition and evolution of the subject glacier are then considered, on the base of data surveyed by VAW/ETH Swiss researchers. Some details are provided on the glacier tongue properly called Ghiacciaio del Belvedere, with its two termini. The run-out river system is briefly outlined together with the glacial deposits. The variations in the position of the left terminus from 1914 to the present enhance the need for better surveying of the glaciers, to provide a more accurate knowledge of their behaviour. Finally, the effects of the bed morphology on the glacier response to climatic fluctuations are considered with special reference to Belvedere, Lys and Grande di Verra glaciers.

KEY WORDS: Glacier dynamics, Surveying, Mapping, Ghiacciaio del Belvedere, Anzasca Valley, Western Alps.

RIASSUNTO: MAZZA A, *Risultati di recenti ricerche al Ghiacciaio del Belvedere (Valle Anzasca, Alpi Occidentali), interpretati alla luce della meccanica dei continui.* (IT ISSN 0391-9838, 2000).

Vengono esposte brevi notizie sulla posizione geografica del Ghiacciaio del Belvedere e del sistema di ghiacciai che formano la comune lingua terminale. Viene richiamato il concetto di continuità, alla luce del quale lo scrivente ha eseguito le proprie indagini a partire dal 1980, con accenno alle proprietà del ghiaccio alle quali si rifà l'intera evoluzione dinamica del ghiacciaio, compreso l'effetto delle variazioni climatiche. Considerando quanto già scritto sul Ghiacciaio del Belvedere, a partire dalle notizie di De Saussure, ci si limita ad esporre i risultati delle ricerche, partendo dal 1957. Un elenco della cartografia moderna completa la storia

recente del ghiacciaio in studio. Non essendovi dati meteorologici sull'alta Valle Anzasca, vengono richiamati quelli relativi alle valli dell'Ossola. Sulla base di considerazioni sulla terminologia del sistema glaciale nel versante NE del Monte Rosa, si conclude che il Ghiacciaio del Belvedere è politermico. È stata esaminata in dettaglio la lingua propriamente detta Ghiacciaio del Belvedere, con le sue digitazioni, i torrenti di ablazione ed i notevoli depositi glaciali e sono state riassunte le variazioni frontali della lingua sinistra (Nord) a partire dal 1914. Rinascere il problema della necessità di migliori metodi di rilevamento, al fine di garantire l'omogeneità e l'affidabilità dei dati, come premessa di una migliore conoscenza del comportamento dei ghiacciai. Infine si espone un confronto del diverso comportamento dei tre principali ghiacciai dei versanti italiani del Monte Rosa, Belvedere, Lys e Grande di Verra, completando l'interpretazione con i risultati del calcolo del tempo di risposta del Ghiacciaio del Belvedere alle variazioni del clima.

TERMINI CHIAVE: Dinamica glaciale, Rilevamento, Cartografia, Ghiacciaio del Belvedere, Valle Anzasca, Alpi Occidentali.

INTRODUCTION

The system of glaciers which build the common ablation tongue called Ghiacciaio del Belvedere, flows at an average latitude of 45° 57' N (base of Monte Rosa NE wall), and at an average longitude of 7° 53' E of Greenwich, corresponding to UTM coordinates 32 (TMR) E415000/N5089000.

The glaciers flow in the upper reach of Valle Anzasca, confluent into Val d'Ossola: the water run-out of Ghiacciaio del Belvedere reaches Toce river, Lago Maggiore and, eventually, Ticino river. The aspect of the glaciers varies between North (Gh. Nord delle Locce) and NE (Gh. del Nordend).

The main ice stream, showing a sinuous planimetric development, has a length, measured from Colle Signal, 3769 m to the left terminus, 1785 m, of 5600 m (horizontal value). Its maximum elevation is about 4150 m, under Punta Gnifetti, 4554 m IGM (4558 m CTR).

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FIG. 1 - General view of Monte Rosa glaciers.

TOPOGRAPHY OF THE GLACIAL SYSTEM BUILDING THE TONGUE OF GHIACCIAIO DEL BELVEDERE

The glacier ablation reach, called «Ghiacciaio del Belvedere», is fed, from SW to NE, by the following ice streams:

1) Ghiacciaio Nord delle Locce (No. 321 of Catasto dei Ghiacciai Italiani (CGI/CNR, 1959-1962): with a short (about 50 m) tide-water terminus (Mazza, 1998), but mainly confluent (350 m wide) into the investigated glacier.

2) Ghiacciaio del Signal (322): this is well defined ice stream, flowing in a steep channel, connected top and bottom with Ghiacciaio del Belvedere; its name is but a geographic identification;

3) Ghiacciaio del Monte Rosa (323): the supply of ice to Ghiacciaio del Belvedere takes place only by avalanches, as presently totally disconnected from the main ice system;

4) Ghiacciaio del Nordend (324): this glacier should have an independent terminus, at 2115 m; on surface it is wholly disconnected from Ghiacciaio del Belvedere, which presently flows some 30 m under the Ghiacciaio del Nordend terminal moraine. According to our recent survey of 1999 (Mazza, in press), a possible confluence of Ghiacciaio del Nordend into Ghiacciaio del Belvedere under the morainic cover is still to be proved.

The classification in single glaciers is presently acceptable for Nord delle Locce (321), Monte Rosa (323) and Nordend (324) glaciers as the first (321) has its own tide-water terminus, the second (323) is separated and the third is separated on the surface, even if it may confluence under a

thick morainic debris cover (see above). On the contrary Ghiacciaio del Signal (322), as already written, is but a geographic identification.

The surface continuously covered by ice of the above glacier system, can be estimated in 8 km² according to Catasto dei Ghiacciai Italiani (CGI/CNR, 1959-1962). A surface area of 13,6 km² (Porro & Somigliana, 1918) cannot be accepted even at the last local glacier maximum expansion (1922). Better data of the glacier surficial area are not available; the comparison between IGM and CTR maps cannot rigorously be carried out; in any case the glacier surficial area has not changed too much since 1957 (date of the photogrammetric survey); the largest difference is a retreat of about 120 m of the left terminus, and its elevation, raised from 1755 m to the 1785 m. The very small expansions and retreats from 1980 to 1999 are not enough to alter greatly the surficial area of the whole glacier system.

CONTINUITY

Applying the concept of continuity to the above glacier system, we would like to remember that it was De Marchi (1895) the first to introduce the idea of continuity in glaciology. He wrote «Each continuous matter flux must obey to the general law of continuity». And Hutter (1983) writes: «Basic to the ice mechanics – be it the theory of glacier flow, the response of floating ice to external loading, ice drifting and ice ridging, or the very practical questions of ice forces on structures – are the fundamental laws of continuum physics».

On this basis the glaciers which build the Belvedere tongue (Nord delle Locce, Signal and, may be, Nordend), are an ice continuum. Considering that this subject is basic in glaciology, we just recall the equation of continuity, having the following form (Paterson, 1994):

$$dQ/dx + dS/dt = B * l \quad (1)$$

where:

dQ/dx = variation of the ice volume along the glacier longitudinal axis, x ;

dS/dt = variation in time of the glacier section;

B = ice balance;

l = glacier width.

RECENT HISTORY OF THE GLACIER

We give up reporting the complete history of the glacier, known since De Saussure's times (about 1780), as it has been already outlined in the best way by Monterin (1922). A second paper giving a lot of details on the investigated glacier is due to Sacco (1930). Both papers are provided with a lot of pictures. A revision of the former data, starting from Monterin's work and updating the glacier situation to 1957, was published by Gili-Borget (1961).

The report of VAW/ETH (compiled in 1985; unpublished) gives some data on the past history of Ghiacciaio del Belvedere. The quotation of data contained therein is possible due to the courtesy of «Comunità Montana della Valle Anzasca», Macugnaga.

Therefore it seems unnecessary to repeat the past history of the subject glacier because Monterin's paper is reprinted in his «Opera Omnia» published by care of Cerutti (1988), and Gili-Borghet's (1961) paper can be found in Bollettino del Comitato Glaciologico Italiano (See References). Hence we start our report from 1957.

During the International Geophysical Year (1957/58) Ghiacciaio del Belvedere was selected for a terrestrial stereophotogrammetric survey (EIRA, 1961), the result of which is a map of the Belvedere tongue in scale 1:5000, enclosed to Bollettino del CGI (No 10, 1961). Details of this map will be given in the section «The cartographic record».

The investigations during that opportunity included also a seismic survey (De Visentini, 1961). The report of the employed method was completed by some glacier thickness profiles and by a bathimetric map in scale 1:9 000 which, together with the already mentioned glacier surface map, establish a valid information source on the glacier condition in 1957/58, allowing a reasonable comparison with the present status.

In 1984 the Swiss researchers of VAW/ETH repeated the glacier thickness measurements by radar prospection; the glacier thickness values obtained, on 7 cross-sections, are considerably higher than those assessed in 1957, specially in correspondence with the surface elevation between 2150-2100 m, in part owing to the glacier mass increase assessed in that year, and in part to the different

survey method (radar versus seismic measurements, with differences of about + 5-10%).

The thickness profiles and the CGI map, 1:5000, still have a great dynamic significance, as they allow a reasonable calculation of the glacier surface velocity (Paterson, 1994) in 1957, and allow the comparison of the values obtained with those assessed later by the VAW/ETH (1985) in 1984. The knowledge of the surficial velocity is essential to calculate the response time of a glacier, as consequence of climate fluctuations (Mazza, 1995).

On the base of the seismic thickness measurements in 1957, the maximum surface velocity of Belvedere ice tongue, at an elevation from 2150 to 2000 m, can be calculated in about 30-35 m a⁻¹. The surface velocity values assessed in 1984 by VAW/ETH (1985) in range between 40 and 50 m a⁻¹, and the maximum velocity recorded, 100 m a⁻¹, are the physical evidence of a kinematic wave travelling in those years along Ghiacciaio del Belvedere. The increases in elevation (about 35 m versus the 1977 values taken from the LK (Swiss official map), of the glacier downstream the «Breccia Pedriola» (see later the section «Glacial deposits») fairly well corresponds to the «bulge» characterizing the kinematic wave.

The surface velocity and elevation variations, assessed by the VAW/ETH (1985) in 1984, allowed the Swiss researchers to forecast a terminus expansion of Ghiacciaio del Belvedere which, in fact, took place starting from 1987, but in an order of magnitude smaller than estimated. In 1984 Haerberli published a paper where the terminus advance of Ghiacciaio del Belvedere was also forecast, on the base of average thickness increments of 6 to 20 m.

Eventually a short contribution of Mazza (1986/1999) after his first yearly glacier terminus survey (1985), tried to enlight the strong discrepancies of the retreat values measured by the CGI's surveyors since 1922 versus the values assessed on the base of measurements, even if horizontal, on the available maps. The problem will be discussed later in the section «Terminus fluctuations from 1914 to the present».

THE CARTOGRAPHIC RECORD

Gili-Borghet (1961) has published a complete list of the historical maps covering the glaciers on the NE face of Monte Rosa, with special reference to Ghiacciaio del Belvedere. To update the list we describe the presently available maps covering the subject glacier, including the sketches and profiles prepared by VAW/ETH (1985) after their investigations of 1983 and 1984.

Map of Ghiacciaio del Belvedere, 1:5000

Surveyed in 1957 by terrestrial photogrammetry by EIRA (1961), on CGI account within its activities for the International Geophysical Year (IGY, 1957-58).

The large scale, 1:5 000, of the map grants it a great significance to document size and elevation of the glacier tongue in 1957. The cartesian (metric) coordinates build a

local system; unfortunately, there is no geodetic data (datum, projection, reference ellipsoid, etc.) to relate this map to the official ones (IGM, CTR, and LK).

«Carta d'Italia», 1:25000

Sheet 29 I N.E., surveyed in 1934 and reprinted in 1970, updated on the base of aerial photogrammetric survey in 1968.

Concerning the glaciers covered by the map, the only updating regards the terminus position of the left tongue of Ghiacciaio del Belvedere, and some details of the terminal area of Ghiacciaio Nord delle Locce. The terminus elevations of some glaciers of Valle Anzasca, where quoted on 1934 map, remained unchanged on the 1970 edition of the same map, notwithstanding the strong general retreat suffered by all Monte Rosa glaciers. The UTM km-grid is referred to the International ellipsoid (Hayford); the datum is the ED50.

Landeskarte der Schweiz (LK), 1:25000. Sheets 1348, Zermatt (1977), and 1349, Monte Moro (1982) and later reprints.

Excellent and clear drawing, as usually for the Swiss maps; most of the glaciers covered by them are updated in extension even if they are in Italian territory. The map is drawn in oblique cylindrical projection and on the Swiss reference datum. This makes it difficult to compare the elevation of the LK map on the Italian territory with the values of IGM and CTR maps.

«*Carta Tecnica Regionale*» of Piedmont (CTR), 1:10000 - Sections 071030, Cima di Jazzi; 071040, Macugnaga; 071070, Monte Rosa; 071080, Punta delle Locce.

The map has been surveyed by aerial photogrammetry of 1991; hence the surficial area of the Monte Rosa glaciers is correct and very close to their present extension. The altimetry has been also revised, even if some mistakes of the IGM map remained unchanged (Mazza, 1998). The contour interval is 10 m, but, practically on most map area the contour interval is but 50 m; moreover, on the glaciers the contours are dashed; this adds further uncertainty to reading, losing so some of the interest the maps have for the local glaciology, considering their relatively large scale.

The kilometric grid is the Gauss-Boaga with UTM ticks at the map margins, and the geographic coordinates are according to the ED50 (European datum of 1950).

Topographic sketches of VAW/ETH (1985)

Mostly printed in scale 1:10000, they show the highest interest for the investigation on Ghiacciaio del Belvedere, being compiled on the base of specific surveyings by photogrammetry, radar, and seismology. The map kilometric grid is local and this does not allow any direct comparison neither with the Italian official maps (IGM and CTR) nor with the LK Swiss map. This impairs somewhat their interest to reconstruct the evolution of Ghiacciaio del Belvedere between 1957 (CGI map) and 1991 (CTR map). Also

the problem of the elevations quoted by VAW/ETH (1985) - higher 12.5 ± 1.5 m than those of the Italian IGM map - cannot be solved as the sketches do not quote coordinates and altitude of the benchmark used for the local leveling.

Three maps in scale of about 1:3600, two concerning the final tongues of Ghiacciaio del Belvedere, and one the terminal reach of Ghiacciaio del Nordend, are highly interesting for a comparison with our survey results, even within the above limits.

Climatic conditions in the Ossola valleys

There are no climatic data available (precipitation and temperature) concerning the upper reach of Valle Anzasca. Some data concerning the neighbouring valleys have been already published (Mazza & Mercalli, 1992; Mazza, 1998). The reader interested is kindly requested to refer to the above literature.

Thermal conditions of Ghiacciaio del Belvedere

The vertical extension of the glacier system building the ablation Belvedere tongue, is remarkable; the maximum elevation of the «continuous» ice system is about 4150 m; the glacier thermal conditions are of course very different, as the terminal glacier altitude (left tongue of Ghiacciaio del Belvedere) is 1785 m (in 1999); this means an altitude extension of about 2350 m.

It is known that the ice temperature at Colle Gnifetti, 4450 m (Haerberli & Funk, 1991), varies between -14 °C e -12 °C at a depth of 15 to 50 m. This value is very important as, assuming the ice at melting temperature (273.15 K) at elevation lower than about 3000 m, we can reasonably state that «Ghiacciaio del M. Rosa», with terminus at 3202 m (1994) is «cold»; the same is valid for the upper ice extension under Punta Gnifetti, 4558 m CTR and Colle Signal, 3769 m; surely temperate is the Belvedere tongue, which begins at about 2300 m, at the toe of the Monte Rosa NE wall.

Hence Ghiacciaio del Belvedere is polythermal (sensu Hutter, 1983); this is a quite important conclusion, basic to understand the dynamics and evolution of glaciers, the rheological properties of ice depending mainly on temperature and, hence, on aspect, elevation, and climate fluctuations.

The transition from cold to temperate ice takes place on the ice streams flowing down from 4150 m, under Cresta Signal. To similar conclusions arrived the Swiss researchers (VAW/ETH, 1985), who, in 1983 and 1984, placed the yearly 0 °C isotherm at about 2600 m. However we are to mention that, in the very hot summer of 1992, we could see water running out of the lower margin of Ghiacciaio del Monte Rosa, probably due to ice melting at the glacier base by heat conduction along the underlying dark rocks. This enhances the summer thermal evolution of this cold glacier, caused by scarce precipitations and, hence, higher temperatures.

It is difficult to state a value of snow line. VAW/ETH reports a snow line elevation of 2600 m; we assessed re-

peatedly a quite higher value, say 2900 m, but this figure is uncertain, as slope steepness, crevassing, and the summer snow precipitations, do not allow to assess a definite snow line.

The ice tongue properly called «Ghiacciaio del Belvedere»

As already written, the tongue properly called Ghiacciaio del Belvedere, begins at about 2300 m, at the base of the NE face of Monte Rosa. Its length, from the elevation of 2300 m to the terminus of the left tongue, 1785 m, is about 2800 m, downstream increasingly covered by morainic debris, consisting of big boulders, cobbles and sand, crevassed where ice is under stretching.

At the elevation of 2100 m, upstream of «Breccia Pedriola», caused by the recurring outbursts (the last took place in July 1979) of Lago delle Locce, the ice tongue is strongly crevassed; downstream of the glacier surface altitude of 2050 m, the ice stream surface is centrally higher than the right moraine. In fact, on the right bank, the landsliding of the main right historic moraine built, according to the Swiss geologists, a curious intermoranic small valley.

Further downstream the main ice tongue is again strongly crevassed, owing to the stretching before the partition into the two terminal tongues of Ghiacciaio del Belvedere. Downvalley of about 1920 m no ice can be further seen, the glacier being totally covered by a thick and continuous debris cover.

The crevasse pattern means that the stress distribution (stress tensor) varies along the glacier tongue as easily seen on aerial photographs and on the LK map; the current assumption of extensive flow upstream the equilibrium line,

and compressive flow downstream the same line, is not applicable to Ghiacciaio del Belvedere on which areas of extensive flow (positive strain rate tensor, crevassing), constant flow (the strain rate tensor becomes the vector velocity), and compressive flow (negative strain rate tensor) alternate, probably depending on to the continuously changing glacier direction and to bedrock topography. Our assumption is confirmed by the longitudinal and cross profiles of VAW/ETH survey (1985).

Another feature of the Belvedere tongue are the *ogives*, taking place when there is a transition from constrained flow (plug flow) between the rock walls encompassing the main ice stream of Ghiacciaio del Belvedere, flowing down from Colle Signal, 3769 m, and the ice stream called Ghiacciaio del Signal, to stress relieving conditions (spreading; Brecher, 1986). Along a longitudinal span of about 500 m, we can count up to 10 rounded ogives, with a pitch distance of 40-50 m. They are of «swell-and-swale» type (Sharp, 1988).

According to NYE (1959) the ogives are determined by flux variations during the year, and caused by the different winter and summer ice surface velocity, depending, in turn, on the temperature effect on mechanical ice properties; hence they are an index of the yearly surface velocity of the glacier. In our case the surface velocity of Ghiacciaio del Belvedere is about 35 m a^{-1} , value in accordance with that derived from the glacier thickness which, at the altitude of 2150 m, was close to 300 m, during the VAW/ETH (1985) radar and seismic surveys.

The surface velocity measurements of VAW/ETH again confirm the order of magnitude of the values derived by



FIG. 2 - Ogives on Ghiacciaio del Belvedere at the foot of Monte Rosa NE wall (ice stream spreading).

our calculation. The values assessed in those years (1983 and 1984) were higher, about 50 m a^{-1} , with a local maximum of 100 m a^{-1} in 1983; the contemporary increase in surface elevation of about 20 m and, locally, even 35 m, with respect to the value of 1977 (LK) witnessed, as already written, the passage of the kinematic wave bulge. The wave reached, even if damped, the glacier left terminus in 1987-1991, with a small glacier advance, and later the right terminus, without any possibility of measurement, this terminus being completely covered by morainic debris.

The increase in elevation (thickness) of the glacier surface was later followed by a decrease; the increase however continued at the right tongue, wholly covered by debris and it is still taking place (1999); the tongue surface is centrally higher than the right historical moraine, with young trees (*Larix*) on both sides; some of them, grown on the internal moraine slope and at the toe of the steep terminal debris slope, have been bent by the glacier advance. There is a great difference between the topographic sketch of VAW/ETH (1988) surveyed in 1984 and the present situation. CTR map drawing is closer to the present condition; the minimum terminus elevation - toe of the steep slope - is now about 1820 m (CTR map). Where the glacier surface is now higher than its sides; VAW/ETH (1985) in 1984 measured, by BTS, a debris thickness of 9,5 m; and this is the actual cause of present glacier cross-section. So the increase in surface elevation (thickness) is to be ascribed to less ice melting owing to the continuous accumulation of debris and not to a positive mass balance, as upstream the glacier surface is decreasing in elevation (thickness) with reference to the VAW/ETH (1985) sketch.

The left glacier tongue, is also wholly covered by morainic debris; it is higher at the margins and lower at the center. It is about 350 m wide at the Belvedere partition, where it has an elevation, against the morainic hill of Belvedere, of about 1928 - 1930 m; its terminus is a steep bare ice slope, inclined about $30-45^\circ$, 55 m high in 1999 (60 m in 1990). The terminus of the left glacier tongue, the elevation of which is 1785 m, shows the same planimetric course shown on the VAW/ETH (1985) sketch of 1984.

RUN-OUT RIVERS

The investigated glacier has, of course, two run-out rivers; the bigger, with the strongest turbidity, flows out from the left (North) terminus; the smaller, from the right (South) terminus; sometimes it disappears as it flows under debris; it shows quite low water turbidity.

A third river is to be mentioned, flowing from the big source called «Fontanone», 1538 m, among the internal moraine system called «diversion morainic apparatus» (Capello, 1952). The capacity of this river is sometimes quite high and its turbidity is low; sometimes it happens that the left river is almost dry and then Fontanone river has a very high capacity and turbidity.

THE GLACIAL DEPOSITS

Special attention should be devoted to the investigation of the present and past glacial deposits of Ghiacciaio del Belvedere, as they reflect the past and present dynamics of



FIG. 3 - Right tongue of Ghiacciaio del Belvedere, totally covered by morainic debris.

FIG. 4 - Terminal area of Ghiacciaio del Belvedere, in 1996.



the glacier system. Two long lateral moraines encompass some lower internal morainic ridges and, eventually, the ice stream. The main external moraines are currently attributed to the last glacial maximum of the Little Ice Age ending, in the Western Alps, in 1820, or, according to other sources, in 1855 (mainly in the Eastern Alps).

Right historic moraine: it begins downstream the confluence of Ghiacciaio Nord delle Locce, under its big terminal moraine encompassing Lago delle Locce; the moraine ridge is presently some 30-40 m over the glacier surface; downstream of Cappella Pisati, 2117 m, there is the gap, which we called «Breccia Pedriola», caused by the repeated outburst of Lago delle Locce. The gap can already be seen on Sella's picture of 1895 (in Sacco, 1930); the outburst took place once again in 1916 (Monterin, 1922); the last event happened on July 19, 1979. In the 80's the gap allowed to form a steep ice wall; the hypothesis was made, independently, by VAW/ETH (1985) and Mazza (1986-1999) that a small glacier tongue could develop; after a very short expansion – some 10 m according to the Swiss researches – in the 90's, a gradual decrease of the main Belvedere tongue surface elevation took place; the ice wall disappeared either by melting, or by deposition of fresh debris, or by both causes.

Downstream of «Breccia Pedriola» there is an intermorainic small valley which, as already written, was caused by sliding of the main morainic ridge on a length of 200 m, according to the Swiss investigations (VAW/ETH, 1985). This is one of the reasons (the other is the compressing flow in this glacier reach) why the Belvedere ice stream

flows there higher than the historical morainic ridge; upstream and downstream, the glacier surface, as already told, is some 30-40 m under the morainic ridge. The right morainic ridge is quite high on the external valley, some 100-120 m. It ends under 1700 m but part of it has been swept away during the last above-mentioned outburst of Lago delle Locce.

Close to the main right morainic ridge, there are other lower internal ridges, without vegetation, probably deposited during the glacier expansion between 1977 and 1985; but no record has been taken to confirm our hypothesis. This is likely the effect of the kinematic wave which travelled along the glacier during the above time span. The relative elevation on these internal morainic deposits ranges between 20 and 30 m, corresponding to the increase in glacier surface elevation assessed by the Swiss glaciologists; the debris are very coarse and no accurate measurement can be done.

Left historic moraine: A short morainic ridge, at the foot of Monte Rosa NE wall, joins the right moraine of Ghiacciaio del Nordend; besides the present terminal area of this glacier, the left Nordend moraine joins the long morainic ridge of Ghiacciaio del Belvedere; the moraine is quite regular, some 40-50 m higher on the small plane under the Fillar area, until it is reached and crossed by the rivers running-out from Piccolo Fillar and Castelfranco glaciers; the final joint river has partly removed the Belvedere morainic ridge; it crosses the gap of the moraine and disappears under Ghiacciaio del Belvedere; the heat brought by water flowing from Southern slopes, melts the ice of Ghi-

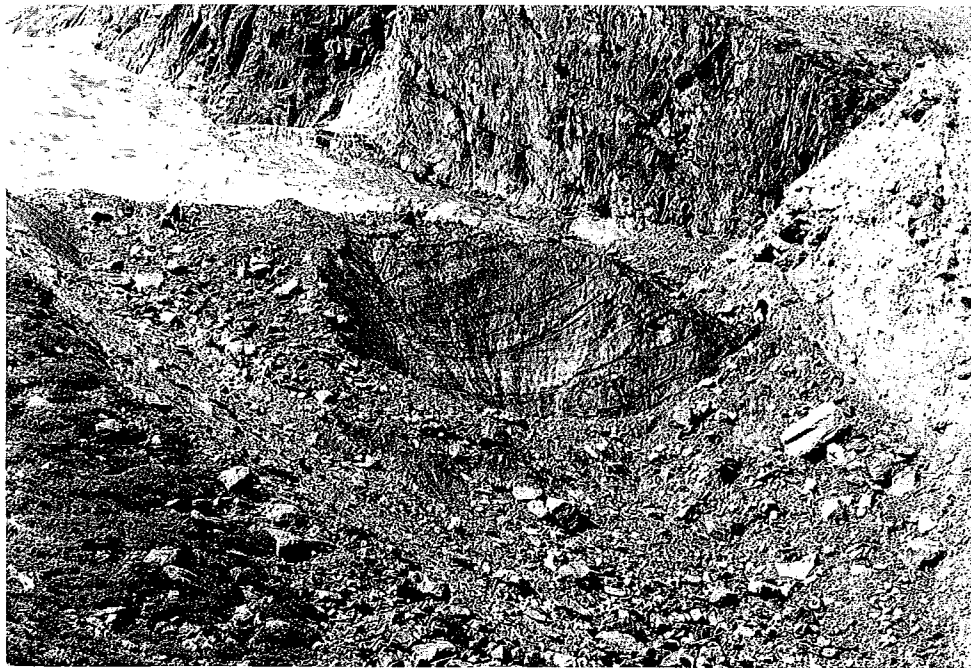


FIG. 5 - The «Breccia Pedriola» with the side ice wall, in 1989; now the wall has completely disappeared.

acciaio del Belvedere, forming a funnel-shaped cavity, with some local crevassing.

Further downvalley, the morainic ridge continues regularly, reaching the present lowest altitude of about 1650 m, externally covered by vegetations and showing internally also some grass; the lowest section of the moraine, probably reaching an altitude of about 1600 m at the last maximum (1820) of the LIA, has been completely removed by creeks flowing down the left-bank mountain slope.

Internal moraines at the glacier diversion: there are two main moraines (Capello, 1952), encompassing a small valley totally covered by trees (Larch); the top of the morainic internal apparatus is the popular «Belvedere», 1948 m CTR. The North morainic border, forming the right moraine of the left ice tongue, was partially overridden by the glacier when, toward 1917, the ice started to flow out of the main tongue, forming a third lobe which lasted as long as 1933 (Monterin, 1926-1938). Its Southern morainic border is less typical, as it was many times partially removed by the periodical outbursts of Lago delle Locce.

The Belvedere «diversion» apparatus (Capello, 1952) encompasses a small plane, residual of an old water pool, the threshold of which is at 1826 m (CTR). The area, as already remembered describing the «Fontanone» source, has been investigated by VAW/ETH (1985) by reflection seismic survey, obtaining some interesting information concerning the water circulation under the whole morainic apparatus of Ghiacciaio del Belvedere.

THE RECORD OF THE TERMINAL FLUCTUATIONS OF GHIACCIAIO DEL BELVEDERE FROM 1914 TO THE PRESENT

Here we take into consideration the terminus fluctuations only of the left terminus, the most important, because only for it there are rather continuous data from 1914 to the present, with two interruptions between 1942 and 1952 as well as from 1974 to 1985. It is presently the only terminus at which significant measurements can be done.

The single fluctuation values are summarized by Gili-borghet (1961) from 1914 to 1956; however, for reader's convenience, the values are repeated in table 1, together with the terminus elevation fluctuations, from 1914 to 1974, adding the data surveyed by Mazza (1986-1999) between 1985 and 1999.

Summarizing the single yearly values, see table 1, the following terminus fluctuations are obtained:

- 1914-1922: advance of 230 m (Monterin, 1922);
- 1922: glacier maximum expansion; terminus at 1627 m (Monterin, 1922); no details are given how and where this value had been measured;
- 1923-1934: retreat of 378 m (Monterin, 1926-1938);
- 1934: IGM surveyors assess the terminus elevation in 1691 m; the geographic coordinates of the terminus can be derived from the IGM map 29 I NE, Monte Rosa; Monterin for 1934 gives a terminus altitude of 1678 m;
- 1935-1939: retreat of 94 m (Monterin, 1926-1938);
- 1939-1940: advance of 3.5 m (Vanni, 1940-1941);
- 1941-1942: retreat of 11 m (Pracchi, 1942).

TABLE 1 - Terminus fluctuations of Ghiacciaio del Belvedere between 1914 and 1999

Year of survey	Variation	Terminus elevation
1914	—	—
1917	27.5	—
1918	—	1691.83 (1)
1919	50	—
1920	62.5	—
1921	28.5	—
1922	12	1627
1914/22	+230.5 (+25.6 m/a)	
1923	-51	—
1924	-45	—
1925	-31	—
1926	-31	—
1927	-21.5	1655
1928	-17.5	1672
1929	-25	1674
1930	-20	1676
1931	-47	1678
1932	-64	1678
1933	-10	1678
1934	-15.5	1678
1935	-11.5	[1691] (2)
1936	-25.5	[1735]
1937	-29.5	1695
1938	-22	1695
1939	-5.5	—
1940	3.5	1700 (3)
1941	-7.5	—
1942	-3.5	—
1923/42	-480 (-24 m/a)	
1) Reina & Somigliana, 1918		
2) IGM, 1934		
3) Vanni, 1942		
1943/52: No measurement; the retreat is estimated in -200 m		
1953	-27.5	—
1954	-15.5	—
1955	-21	—
1956	-20.5	—
1957	-22	1755.8 (4)
1958	-21	1750
1959	-34	1750
1960	-26	1750
1961	-13	1750
1962	-12	1750
1963	-14	1750
1964	-12	(1800)
1965	-18	1750
1966	-10	—
1967	-5	—
1968	0	—
1969	1	—
1970	7	1750
1971	-10	1750
1972	-13	1750
1973	-6	1750
1974	-2	1750
1953/74	-294.5	(-13.4 m/a)
4) Eira, 1961		
1975/84: No measurement; probable steady state or very small variations.		

1985: The measurement are started again (Mazza, 1996-1999) without any possibility of connecting the new to the old measurements, for the reasons already explained (missing any bench mark coordinates).

	Mark 1	Mark 5
1985/1992	-2.5	+6
1992/1993	*	-4
1993/1994		+1
1994/1995		-1
1995/1996		-7
1996/1997		+5
1997/1998		-6
1998/1999		-2

* No further measurements possible.

In 1942 the first set of measurement ends; the total glacier retreat, from 1922 to 1942, is -480 m. After the IGM survey (1934), we are to wait until 1957 to have a terminus elevation, 1755,5 m, surveyed by topographic methods (CGI map 1:5 000; EIRA, 1961). Unfortunately, for the reasons already expressed, the two maps cannot be compared with accuracy (different scale and coordinate systems). The average terminus retreat between 1922/23 and 1941/42, is -24 m a^{-1} .

In the decade 1943/1952 no measurement have been carried out; we suggest an average retreat of -20 m a^{-1} , hence, -200 m ; this value is rather conservative, considering the strong retreat phase suffered by all alpine glaciers in that decade.

Between 1947 and 1952 some CGI operators visited the glacier and assessed that it was impossible to carry out any measurement, as both glacier terminus were totally covered by debris.

In 1953 Demaria & Gatti (1953-74) started again the regular terminus measurements, with the following results:
 - 1953-1967: retreat of 271 m;
 - 1967-1968: steady state;
 - 1969-1970: advance of 8 m;
 - 1971-1974: retreat of 31 m.

The terminus total retreat between 1953 and 1974 amounts to -295 m , i.e. $13,4 \text{ m a}^{-1}$. The terminus elevation is constatly given in 1750 m; no details are supplied how this value has been assessed. So, the total glacier terminus retreat, from 1922 to 1974, should be -975 m but, of course, the retreat value of -200 m for the decade 1943/1952, is only guessed.

But the total retreat for the same time span is much shorter than it would result summarizing the measurement values, if we try to identify the terminus position in 1922 (Monterin, 1922), of course on the contour 1625 m of the available maps (IGM, CTR, LK and CGI map in scale 1:5 000; see the section «The cartographic record»), and we carry out the measurement up to the elevation of 1691 m IGM (1934) and from there, to the present terminus position (1999) derived from CTR (1991) and our yearly surveys.

Between Monterin's elevation (1922) of 1627 m and the present terminus value, 1785 m (our trigonometric leveling), we get the following total horizontal retreat values:

- IGM: about 675 m, with uncertainty of ± 25 m, considering the poor accuracy of the map in scale 1:25000 (sheet 29 I N.E., Monte Rosa, edition 1970);
- LK: about 625 m, with uncertainty of ± 10 m (sheet 1349, Monte Moro, 1982 edition and later);
- CGI glaciological map in scale 1:5000, surveyed in 1957: 475 m ± 5 m between the contour 1625 m and the terminus in 1957 at the elevation of 1755,80; about 120 ± 10 m between 1957 and the present terminus position, giving a total retreat of about -600 m;
- CTR-Piemonte: between the contour 1625 and the present terminus position, the distance, hence the glacier retreat, is 690 m; this value confirms those obtained from the other cartographic sources.

The present terminus elevation, quoted formerly in 1780 m by Mazza (1986-1999) and assessed by altimeter, has been later revised in 1785 m, by repeated trigonometric leveling. No better value can be derived from the CTR-Piemonte, as the glacier terminus details are not enough accurate.

Summarising the *total left terminus retreat* of Ghiacciaio del Belvedere, between 1922 and 1999, we get the following values:

- a maximum of about -700 m (average value of horizontal measurements on maps);
- about -975 m (algebraic sum of all field measurements, including the estimated value of -200 m (1943-1952). The reasonable agreement of the four examined maps, concerning also the elevations, leads us to prefer the map sources in evaluating the left terminus retreat of Ghiacciaio del Belvedere: between 1922 and 1999, it should be about -690 m.

The above problem is typical of all long-date measurements, as only rarely the planimetric position of the terminus marks is assessed by topographic methods at short intervals (3-5 years), with respect to IGM points of known coordinates and elevation. A topographic comparative sketch of the terminus fluctuation of Ghiacciaio del Belvedere is annexed to the report of VAW/ETH (1985); but the Swiss glaciologists express their doubts on the values plotted, considering the discrepancies with the measurements of CGI operators (which, in any case, ended in 1974). An accurate comparison between 1854 map («Carta degli Stati Sardi in Terraferma») and the last Italian (CTR) map surveyed in 1991, is practically impossible from the geodetic point of view if one aims to obtain an accuracy of at least 10-20 m; datum, projection, scale, surveying and cartographic techniques are, of course, totally different.

As already written in another opportunity (Mazza, 1998), we are to point out that the glacier terminus fluctuations, referred to marks the coordinates (either geographic or cartesian) and elevation of which are unknown or known with too much uncertainty, as not referred to fixed points of the official maps (IGM and/or CTR), after long time show reasonable doubts of interpretations and long series of data loose, at least partially, their value.

The problem of determination of planimetric coordinates and altitude, giving to a terminus mark the character

of a bench mark, today can be easily solved by the Global Positioning System, based on artificial satellites. The portable, single frequency *GPS receivers*, operating under the C/A (coarse acquisition) code, allow the positioning with an accuracy, starting from May 2000, of about 10 m (planimetric), as the S/A (Selective Availability, a random function which, when switched on, degrades the positioning accuracy down to 100 m) has been switched off; this value is better than granted by the manufacturers of hand-held GPS receivers, i.e. 15 m RMS, under no S/A.

In 1976 CGI's operator Tettamanti (1977) set some terminus marks and carried out measurements; these were no longer repeated, as far as known from CGI reports. The marks were never found by us probably owing to the instability of the proglacial area of left terminus of Ghiacciaio del Belvedere and the growth of trees (mainly Larch).

Examining our photographic records, starting from 1980, and the left terminus position as mapped on IGM and LK maps, we believe, with reasonable certainty, that between 1980 and 1985 not actual terminus fluctuation took place; however on our 1980 picture there is an area, on the right bank of the left terminus, levelled by a possible glacier lobe advanced between 1975 and 1979, unfortunately unrecorded. After 1985 this feature disappeared, owing to the continuous fall of morainic debris from the glacier surface, at that time slightly advancing.

Between 1980 and 1981 a strong modification in the left tongue terminus took place; it is documented by our pictures; a sort of «revival» of the terminus took place or, probably, the kinematic wave reached the terminus as consequence of a positive mass balance witnessed by the increase in altitude (thickness) of Ghiacciaio del Belvedere since 1977 (VAW/ETH, 1985).

We started our measurement in 1985 (Mazza, 1986-1999) on the right bank of Anza river and, in 1987, also on the left bank, with more accurate results, owing to the better visible bare ice.

On the right run-out river bank we assessed a small advance in 1987 (+7 m) but later, the sliding of morainic debris from the glacier surface, did not allow good measurements and they have been prosecuted only on the left Anza river bank where, from 1987 to 1991, we could assess a slight, but continuous advance of 11,5 m; in Summer 1992 a retreat of 5,5 m was already taking place.

EFFECTS OF THE GLACIER BED MORPHOLOGY ON RESPONSE TO CLIMATIC FLUCTUATIONS

We believe it is interesting a comparison of the response to climatic fluctuations of Ghiacciaio del Belvedere and of two other big glaciers of the Monte Rosa South slope:

- Ghiacciaio del Lys (304); and
- Ghiacciaio Grande di Verra (297).

From their last maximum extension - about 1921/22 - both glacier had suffered a retreat as strong as about 1500

FIG. 6 - Left terminus of Ghiacciaio del Belvedere, where measurement have been carried out since 1914 to the Present.



Ghiacciaio del Belvedere (325)
Left terminus fluctuations from 1914 to 1999
Field measurement versus map evaluation

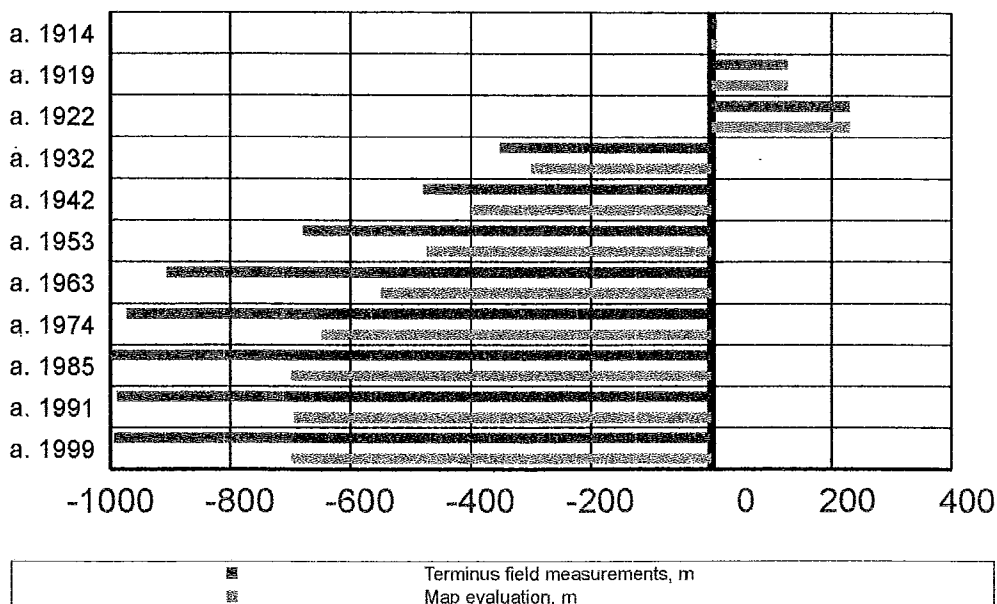


FIG. 7 - Diagram of the left terminus fluctuation of Ghiacciaio del Belvedere, from 1914 to the Present.

m, against about 700 m of Ghiacciaio del Belvedere. Paterson (1994) writes: «... that glaciers advance and retreat in response to changes in climate, is a common knowledge, but the relationship is more complex than is usually assumed. ... But an understanding of the meteorological problems is not enough; the flow characteristics of each particular glacier determine how it reacts to a climatic change». Further he writes (pag. 53): «The climate, along with the physical properties of ice, determines the extent and behaviour of glaciers»

Three chief factors saved Ghiacciaio del Belvedere from a larger retreat:

- its NE aspect;
- the thick morainic surface cover, gradually thicker downvalley, as far as the elevation decreases and the air temperature rises;
- but the most important factor, in our opinion, is the profile of the glacier bed which, along the last 1500 m, loses an altitude of only 50 m (De Visentini, 1961; VAW/ETH, 1985); the gentle slope exerts an effect of stagnation which promotes, together with the other factors, the conservation of ice mass.

RESPONSE TIME OF GHIACCIAIO DEL BELVEDERE TO THE CLIMATE VARIATIONS

We have already mentioned the glacier response to climate fluctuations. For Ghiacciaio del Belvedere, taking into account the relatively uniform ice stream flowing down from Colle Signal (3769 m IGM) along 5,6 km until the left ice tongue at 1785 m, there are two opportunities allowing a calculation, even if approximate (Mazza, 1995), of the response time of it to climatic fluctuations:

a) the depth of the glacier and its variation are quite well known (De Visentini, 1961; VAW/ETH, 1985) and this allows us to calculate the glacier surface velocity (Paterson, 1994) and to compare it with the values assessed in 1984 (VAW/ETH, 1985); the agreement is very good;

b) even if precipitation and temperature data are missing for the upper reach of Valle Anzasca, from values concerning the neighbouring valleys (Mazza & Mercalli, 1992; Mazza, 1998), we know that from winter 1972/73 to 1985/1986 cold season, at least 5 hydrologic years had got precipitations over the average value, specially in 1976/77 and 1977/78.

The algorithms reported by Paterson (1994) and the known values of surface velocity (an average of 30 m a⁻¹ should be very close to the actual value), allow us to assume a theoretical velocity of the kinematic wave of 120-140 m a⁻¹, of course neglecting the intricacy of its diffusion, which, reducing the height of the ice bulge (actually assessed by VAW/ETH, 1985), damps the kinematic wave propagation and lengthen or even, in extreme cases, conceal its effects at the glacier terminus.

The response to the bulge of kinematic wave has been the small advances of the left terminus assessed between 1985 and 1993; and exactly this small advance against the

strong increase in surface elevation of the glacier, could be a proof of the diffusion of the kinematic wave. However, the retreat of -7 m in summer 1996, as consequence of the abrupt decrease of precipitations after 1986 - with contemporary increase of summer temperatures - would confirm a response time of 8-10 years for Ghiacciaio del Belvedere, in accordance with Lliboutry's (1965) statement, that the average response time of the alpine glaciers is about 10 years.

This value is shorter than the average of 12-16 years quoted by Müller (1988) for alpine glaciers; but this Author disregards the problem of the diffusion of kinematic waves.

CONCLUSIONS

To reconstruct the history of a glacier, different sources (maps, reports, pictures and sets of measurements) may be used, as shown for Ghiacciaio del Belvedere; however, we assessed too strong inaccuracies in surveying, both on maps and during the yearly measurements at the glacier terminus and these are the most important causes which impair a correct interpretation of the dynamic behaviour of a glacier.

This is highly important for the investigated glacier and its glacial deposits, because the instability arising from the present increase of global temperature (whatever may be the causes) could cause a risk situation of Macugnaga and its environments.

The problem of the kinematic waves travelling along a glacier, is, of course, still open; more accurate measurement of elevation and velocity variations are needed, to correctly understand the glacier mechanics.

To try to solve the above problems, new surveying methods [mainly GPS under P (Precision) or Y (encrypted) code, digital large scale photogrammetry, and the application of the finite element method, (FEM)] should be urgently taken into consideration both for scientific and practical reasons.

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