Exploring the potential of historical images for the investigation of glacier changes: the case of Belvedere Glacier, Italian Alps

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ABSTRACT

Historical images dispersed in various archives can be instrumental in documenting processes connected to glacier changes in mountains. A series of more than 29 engravings and photographs of the Monte Rosa east face have been found covering the period since 1789. Some images were produced by a combination of photography and engraving, a common approach before practical techniques for printing halftone images were introduced. Using a repeat photography approach, the present study documents the changes in the extent and debris cover of the Belvedere Glacier. Based on visual comparison of images, it appears that the debris cover of the lower part of the glacier developed mainly during the period of the 1860s–1880s. Furthermore, the image series documents the evolution of the terminus both in terms of elevation and shape, as well as a breach in lateral moraine which could be dated back to the end of the 19th century, well before the reported glacier lake outburst flood in 1904.

KEYWORDS

historical landscape images; graphical techniques; repeat photography, extent of glaciation; Monte Rosa

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1. Introduction

Historical landscape drawings, paintings, and photographs of high mountain environments make up a visual record and provide valuable information, especially for the reconstruction of glacier changes (Steiner et al. 2008; Zumbühl and Nussbaumer 2018; Nüsser and Schmidt 2021a). Using various techniques over the last centuries, such pictorial materials were created for various purposes including landscape visualization and cartographic representation, as well as for promoting tourism and aspirations in visual arts.

While scientific attention focused on high mountains, especially the European Alps, towards the end of the 18th century, graphical techniques allowed reproduction by printing using established techniques such as copper plates and aquatint or lithography invented in 1798 (Hopkinson 2017). These early landscape images of the Alps were produced along with a growing interest in the geology and physics of glaciers among European geoscientists. The evolution of photography and photomechanical printing techniques in the second half of the 19th century overlapped with the first efforts to map glaciers in terms of their extent and their changes in the period following the Little Ice Age (LIA). These early scientific studies inaugurated a "glacier fever" and growing interest in glaciers began to spread worldwide (Nüsser and Baghel 2014).

The first sketch maps with a distinct focus on glaciers were compiled by Louis Agassiz, Johann von Charpentier, and James David Forbes in the western Alps (Hattersley-Smith 1966). Detailed glacier maps were produced by the brothers Adolf and Hermann Schlagintweit for different regions in the Alps (Schlagintweit and Schlagintweit 1850, 1854) and by Friedrich Simony for the Dachstein Massif in the eastern Alps in the 1840s (Vukovic and Fischer 2022). In the second half of the 19th century, Sebastian and Richard Finsterwalder introduced systematic and more accurate surveying of glaciers using terrestrial photogrammetry for topographical and glaciological mapping purposes (Finsterwalder 1897; Brunner and Welsch 2002). Historical glacier photographs allowed for bi- and multitemporal comparisons with replicates taken from viewpoints identical to the earlier ones, using repeat photography as a method for detailed change detection (Kull 2005; Nüsser 2001). Especially panoramic images taken from exposed viewpoints form a valuable basis for replication. Repeat photography provides longer temporal coverage than aerial photographs and satellite images (Trimble 2008). Furthermore, the method can be instrumental in debunking environmental myths and can point out the complexity of processes often described in an oversimplified or biased manner (Nüsser 2000; Nyssen 2009; Kropáček 2019). The contemporary or replicate photograph can also be replaced by an image simulated in a 3D viewer of very high-resolution satellite data available in Google Earth. Especially in cases of difficult accessibility of the camera point due to various reasons, including political or administrative restrictions, as well as difficult terrain, bad weather conditions, or frequent cloudiness, this is a valuable option (Kropáček 2019).

In the specific context of glacier research, multitemporal repeat photography has been used to document changes in the Nanga Parbat Massif (northwestern Himalaya) since the 1930s (Schmidt and Nüsser 2009; Nüsser and Schmidt 2021a,b), Bara Shigri Glacier in the Western Himalayas (Chand et al. 2017) since the 1860s and in the Khumbu region (Central Himalaya) since the 1950s (Byers 2007). For the European Alps, studies were conducted to visualize the impact of climate change on glacier retreat (Zängl and Hamberger 2004) and to investigate glacier fluctuations in the western Alps during the 19th century (Zumbühl et al. 2008). For the case of Belvedere, Kääb et al. (2004) repeated a set of photographs from the 1980s and 1990s to document the deglaciation of the east face of Monte Rosa, the volume changes of the lower part of Belvedere Glacier during the surge-type event in 2001–2002 and associated changes of Effimero Lake, which was formed and drained in connection to this event. Hundreds of repeat photographs of retreating glaciers were acquired in high mountains of four continents in the framework of a project called 'On the Trail of the Glaciers' for research and popularization purposes (https://onthetrailoftheglaciers.com/).

This article aims to meet three objectives.

1. To review techniques used to produce images of glaciated high mountain environments.
2. To recover largely neglected visual materials depicting the Belvedere Glacier and the east face of Monte Rosa.
3. To assess the potential of historical graphics and photographs for investigating a glacier under four focal themes (the extent of glaciation, the extent of debris cover, the evolution of the terminus, the evolution of a breach of the lateral moraine).

2. Basic characteristics of Belvedere Glacier

The heavily debris-covered Belvedere Glacier (formerly referred to as Macugnaga Glacier) (Fig. 1), located in the Valle Anzasca in the Piedmont, Italy, is one of the rare surge-type glaciers in the Alps (Truffer et al. 2021). The glacier covers an area of about 4.53 km^2 according to the New Italian Glacier Inventory (Smiraglia and Diolaiuti 2015) and is largely fed by snow and ice avalanches from the Monte Rosa east face, being the most prominent rock face in the Alps. The two lobes of Belvedere reach below the tree line to approximately 1840 m a.s.l., divided by a larch forest

(*Larix decidua*). In many aspects, such as debris coverage, snout position below the tree line, and bilobatism, Belvedere Glacier is similar to Miage Glacier in the Mont Blanc Massif (Stefaniak et al. 2021; Bollati et al. 2013).

The historical phases of glacier advance and retreat in the Monte Rosa Massif were outlined by Monterin (1922). There were two advancing phases towards the end of the LIA, one ending in 1826 and the second between 1842 and 1859, interleaved by a retreating phase. Two more advancing phases occurred in the second half of the 19th century (1878–1893) and the first half of the 20th century (1912–1922). In the case of Belvedere Glacier, the later advance appeared to be larger than in the phase 1878–1893 as is evident by the crossing of the 1880s moraines, however, the moraines from the phase 1842–1859 were not reached (Monterin 1926). Further advancing periods can be figured out from the records of the Italian Glaciological Committee and for instance from the study by Diolaiuti et al. (2003). There was an advance at the end of the 1960s and some minor advances in the period 1986–2000 which were followed by an advance connected to the surge-type event in 2001–2002. This was followed by a strong retreat. The measurements for the period 1974–1985 which was the time of the general advance of Alpine glaciers are unfortunately missing. Since the LIA, the glacier has retreated by more than 800 m (WGMS 2024).

The upper catchment of the Belvedere Glacier has been the source of numerous natural hazards including glacial lake outburst floods (GLOF) and enormous rock and ice avalanches over the last decades. A series of three GLOFs originating from the Locce Lake, dammed by the terminal moraine of the former tributary North delle Locce Glacier occurred in 1970, 1978, and 1979 (Kääb et al. 2004). These floods further incised a breach in the lateral moraine (near the seasonal settlement Alpe Pedriola), which was formed during an earlier outburst flood in 1904 (Mazza 1998). The short-lived Effimero Lake was formed in 2002 and 2003 due to a surge-like event in 2001–2002 (Haeberli et al. 2002; Kääb et al. 2004). The lake reached a volume of 3×10^6 m^3 and its level had to be lowered by pumping in 2002 to prevent an outburst (Tamburini and Mortara 2005). However, a non-destructive outburst flood occurred from this lake in 2003.

Caused by the massive ice loss, various rock and ice avalanches of different sizes have been documented. For example, one rock avalanche (1.2×10^6 m^3) considered to be among the largest rock avalanches in the Alps detached from the Monte Rosa east face at an elevation of 3580–3820 m a.s.l. in August 2005 (Tamburini et al. 2013; Fischer et al. 2013). Another large slope failure occurred in September 2010 in the upper basin of Northern Locce Glacier, which reached a volume of 0.1×10^6 m^3 (Fischer et al. 2013; Paranunzio et al. 2016).

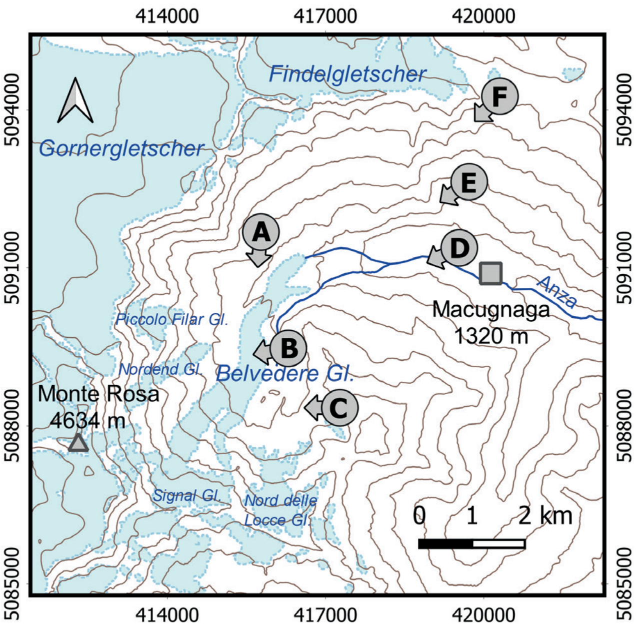

Fig. 1 Map of the eastern part of the Monte Rosa Massif showing the approximate positions of the viewpoints from which most of the images of the east face were taken: A: a point above Alpe Jazzi, B: Alpe Pedriola, C: Punta Battisti, D: Macugnaga, E: slope below Monte Moro and F: Monte Moro Pass.

3. Materials and methods

The search for useful images was started in Google browser using the following keywords: 'Monte Rosa', 'Belvedere glacier', 'Macugnaga glacier' to specify the location and 'engraving', 'aquatint', 'old photography', 'Daguerreotype', 'photo-xylograph' etc. for the technique. Various language variants were tried which appeared to be useful, for instance, the search using the term 'Mont Rose' resulted in further discovery of historical material. The search revealed several archives, which were used for further investigations.

The following archives were searched online or contacted directly:

1. Documentation Center CAISiDoc of the Italian Alpine Club (CAI) in Torino, Italy
2. Archive of Eidgenössische Technische Hochschule (ETH) in Zurich, Switzerland
3. Fondazione Vittorio Sella in Biella, Italy
4. Archive of the University of Lausanne, Switzerland
5. Bavarian State Library (BSB) in Munich, Germany

Websites of various auction houses and vendors of antique prints and drawings such as Pettinaroli and Abebooks were explored in the next step. Amongst the further explored sources, the Web page of the mountaineering club CAI Varallo, Italy can be named.

The images were relocated using Google Earth. An accurate overlap of closer and further topographical features was aimed at. In some cases, the correction of wrongly given viewpoints could be done. Furthermore, based on the relocation, it was revealed that some images were taken from airplanes. The identified viewpoints were used for the preparation of simulation images considering the same view azimuth and elevation angle. Images from approximately the same viewpoints were collated into bi- or multitemporal collections and used for visual image interpretation based on experiences from repeat photography. In addition, some historical photographs were repeated during a field survey in August 2021 and July 2024.

Images showing the glacier terminus were used to estimate its elevational position to get an insight into the glacier's response to climate fluctuations. They were compared with images in Google Earth simulating the view from the same vantage point. To facilitate the elevation reading, contours with a spacing of 50 m were superimposed over the simulated images. The contours were generated from a digital elevation model (DEM) based on airborne laser scanning technique. The model with a grid spacing of 5 m, acquired in 2009–2011 and referred to as DEM 5, was received from *Geoportale Piemonte*, which is a map portal of the region. The expected accuracy of the elevation reading was on the order of tens of meters, which led us to the selection of contour interval of 50 m.

4. Image record of the Monte Rosa east face

Due to its prominence, Monte Rosa is visible from long distances both from the Po plain and exposed viewpoints from the north. It has a long record of visual materials, many of which have been produced by scientists, artists, and mountain photographers from various European countries.

4.1 Engravings

The east side of Monte Rosa has already been visited by pioneers, scientists, and explorers at the end of the 18th century, including Horace Bénédict de Saussure, who travelled to Monte Rosa accompanied by his son Theodore in 1787. They crossed the Belvedere Glacier during their ascent of Pizzo Bianco, from where they carried out a trigonometric measurement of the elevation of Monte Rosa. Theodore authored the sketch, which was elaborated into the probably first engraving showing the Monte Rosa east face (de Saussure 1779–1796; de Saussure et al. 1989). However, this image does not show the glacier snout, and most of the east face is covered by a ridge due to the distant viewpoint.

Another early image of Monte Rosa east face is titled *Ansicht des Monte Rosa von Macugnaga aus*, in the book published by the Austrian army officer Franz Ludwig von Welden (Fig. 10 a) who was in charge of the topographical survey of Piedmonte in 1821 (von Welden and Welden 1824). Some illustrations in the book – probably also the Monte Rosa east face – were drawn using the *camera lucida* technique, as given on some of the image frames. This technique was invented in the early 19th century and is based on a prism attached to the drawing pan onto which the landscape of interest is projected and can be sketched.

Fig. 2 Engraving by J. T. Willmore from 1845 shows the tongue of the Belvedere Glacier reaching far down into the valley at the beginning of the last advancing phase during the LIA (viewpoint D in Fig. 1).

Another painting of the Monte Rosa east face from 1829 was produced by G. Lory using aquatint, a technique that allows the reproduction of grey tones and colours and was introduced in the second half of the 18th century (Tab. 1). A steel engraving showing a view of Monte Rosa and the Belvedere Glacier from Macugnaga was published by J. T. Willmore in 1845 (Fig. 2). It is not known whether a mechanic-optical tool was used to ensure an accurate geometry of these two images.

In 1851, A. Schlagintweit visited the Monte Rosa Massif to investigate the physical geography and geology of the area. In this context, they produced rich material including a topographical map and a landscape panorama of the Belvedere Glacier (A. Schlagintweit and H. Schlagintweit 1854) (Fig. 7).

4.2 Transition between engraving and photography

Shortly after the invention of photography in the mid-19th century, it gradually became an established method of documentation in mountain research (Milner 1946). However, the use of photographs in printed media remained limited due to the lack of a suitable reproduction method for halftone images (Bridson 1987). Therefore, photographs were used as a base for traditional methods of image reproduction rather than direct printing. In the case of photo-xylography, for example, the image was manually engraved on a cross-grain wooden block using the photograph as a template (Levin 1980). As this technique is partially a manual process, the quality of the representation depends on the attitude and style of the engraver.

Fig. 3 Photo-xylograph of the Monte Rosa east face from 1884 by Duruy as an example of a mixed technique, in which the photograph is used as a template for manual engraving (viewpoint F).

One of the first photo-xylographs of Monte Rosa was produced by V. Duruy in 1884 based on a photograph by M. E. Lamy, published in 'The New Universal Geography' by Reclus (1876–1894) (Fig. 3). Only seven years later, another photo-xylograph of the Belvedere Glacier was authored by Edward Whymper (1891), a British explorer, illustrator, and the first who summited the Matterhorn in 1869.

The halftone reproduction process of photography was not introduced until the early 1880s with the invention of photolithography, which was capable of rather grainy reproductions (Sealy 2016). Another image of Monte Rosa east face taken from the Monte Moro Pass in 1860 is authored by Étienne Eugène Cicéri, a French painter and engraver. This image, denoted as a 'lithograph', is, in reality, a photolithograph. It is a part of Cicéri's album *La Suisse et la Savoie* based on photographs by Frédéric Martens taken between 1859 and 1865 (Savale 1994).

A decisive move towards a high quality in halftone reproduction was the introduction of a commercially viable form of photogravure, invented by Karel Klíč in 1878 (Mustalish 1997). This technique, in which a copper plate was etched after its sensitive gelatine coating was exposed and then partially chemically removed, allowed the detailed reproduction of photographs in halftone.

4.3 Photography

From a glaciological point of view, the advent of photography represents a major step towards objectifying reality. Photographs can be taken as most accurate materials in terms of shapes and tonal variations of ice fields, glaciers, debris and snow cover, rocks and vegetation. The beginning of mountain photography can be dated to the decade following the invention of the daguerreotype in 1839, the first practical, albeit technically demanding, photographic process (Jacobson 2015). One of the first photographs showing a glacier-covered mountain in the Alps was a daguerreotype of the Matterhorn, just 17 km west of Monte Rosa, taken in August 1849 by John Hobbs on behalf of the British scientist, writer and art critic John Ruskin, who himself had taken a series of daguerreotypes in the Alps in the 1840s (von Brevern 2009). Further early photographs of the Alps taken by Camille Bernabé and Gustave Dardel in 1849 and 1850 can be seen in the *Collection de 28 daguerréotypes représentant les plus anciennes reproductions héliographiques des Alpes* in the online archive Viatimages hosted by the University of Lausanne, Switzerland (Viatimages 2024).

In the 1850s, the daguerreotype gave way to the wet collodion process, in which glass plates were coated with a sensitive emulsion in a dark tent immediately before exposure. The invention of gelatine emulsion dry plate process in the 1880s brought an increased portability and simplification of mountain photography (Osterman 2013). Adopting the techniques, Bisson brothers from Paris took panoramas from the summit of Mont Blanc using 44 × 54 cm plates and equipment carried by 25 porters and guides (Milner 1946). They also took a number of high-quality photographs of mountain sceneries including glaciers in the Savoyan Alps during the expedition by Napoleon III in 1860, celebrating the annexation of the area by France (Frangne 2010). Some of their photographs such as the panoramas of the Glacier du Géant, the Aiguilles de Chamonix, and of Mont Blanc were used by the French geologist and orographer Daniel Dollfus-Ausset (Frangne 2010).

The first photograph of Monte Rosa east face was probably taken by the French photographer Aimé Civiale (Tab. 1) from Monte Moro Pass between 1859 and 1868, however, the exact date is unknown. This was a part of his monumental effort in which he took more than 40 full panoramas (360 degrees) from medium-altitude summits in the Alps in the period 1859–1868. One of these panoramas was taken from Bella Tola (3023 m a.s.l.) close to Sierre in Switzerland, approximately 37 km from Monte Rosa. The complete panorama was covered by 14 overlapping photographs each exposure taking between twelve and fifteen minutes. He used the technique of dry wax paper negatives and he travelled with 250 kg of photographic equipment. His aim was to produce valuable photographs for geologists and physical geographers, rather than commercial or personal memoirs (Civiale 1882; von Brevern 2009).

The second photograph of Monte Rosa's east face from Monte Moro was taken between 1870 and 1880 by Eugène Lamy, the owner of a well-established photographic studio in Paris. This was followed by a photograph taken by the French alpinist Gabriel Loppé, a member of the British Camera Club. He began to devote himself to photography in the 1880s when his career as a painter of the Alps was already fully developed. Furthermore, Monte Rosa did not escape the

Tab. 1 List of images of the Monte Rosa east face. The positions of viewpoints are shown in Fig. 1 and are marked by letters as follows: A: viewpoint above Alpe Jazzi, B: Alpe Pedriola, C: summit of Punta Battisti, and D: Monte Moro Pass. The images which are oblique aerial photographs are marked by "AP" followed by the closest viewpoint in brackets. The names of the engravers, if known, are given after the slash. Some of the sources are given as abbreviations: M&T 2009 – Mortara and Tamburini (2009); BnF – Bibliothèque nationale de France; BSB – Bayerische Staatsbibliothek; JMFP – John Mitchell Fine Paintings, London; MPV – Museo del Paesaggio Verbania; ÖNB – Österreichische Nationalbibliothek; PPR – Period Paper or Robarts – University of Toronto; CAISiDoc – Sistema Documentario dei beni culturali del Club Alpino Italiano; ETH – Eidgenössische Technische Hochschule Zürich.

Id	Autor	Date	Type	Colour/BW	Viewpoint	Figure	Source	Viewpoint
1	Saussure, Theodore	1789	engraving	BW/colour	D	–	Viatimages	Macugnaga
2	Escher, Hans Konrad	1797	coloured ink drawing	coloured	D	–	M&T 2009	Macugnaga
3	Welden, Franz Ludwig	1824	engraving	BW	D	10	ÖNB	Pecetto Supperiore
4	Birmann, Samuel	1825	drawing	coloured	A	–	M&T 2009	Alpe Jazzi
5	Lory, Gabriel/ Falkeisen	1829	acquatint	coloured	E	11	Pettinaroli	Macugnaga – Passo MM
6	Buhlmann, Johann Rudolf	1835	engraving	coloured	E	–	M&T 2009	Macugnaga – Passo MM
7	Cuvillier, A.	1840	litograph	coloured	E	11	Pettinaroli	Macugnaga – MM Pass
8	Willmore, J.T.	1845	steel engraving	BW	D	2	Pettinaroli	Macugnaga
9	Schlagintweit, A./ Loeillot, W.	1851	lithograph	colored	A	7	BSB	Alpe Jazzi
10	Civiale, Aimé/ Chardon, C.	1859–1868	photogravure	BW	F	4	BnF	Monte Moro Pass
11	Martens/Ciceri, Eugenne	1862	photolitograph	coloured	F	–	Pettinaroli	Monte Moro Pass
12	Rüdisühli, Jakob Lorenz	1870	acquatint	BW	F	–	AbeBooks	Monte Moro Pass
13	Lamy, Eugene	1870–1880	photography	BX	F	–	CAISiDoc	Monte Moro Pass
14	Lamy, M.E./Duruy, Victor	1884	photoxylograph	BW	F	3	PPR	Monte Moro Pass
15	Ashton, Federico	1887	oil on canvas	colour	D	10	MPV	Macugnaga
16	Loppé, Gabriel	1880s	photography	BW	A	6	JMFP	above Alpe Jazzi
17	Carnagbi/Doyen	1889	litography	BW	C	13	Pettinaroli	below Punta Battisti
18	Whymper, Edward	1891	xylography	coloured	F	–	Pettinaroli	Monte Moro Pass
19	Zandonati, A.	1893	photograph	BW	D	10	CAISiDoc	Macugnaga
20	Sella, Vittorio	1895	photograph	BW	F	5	Fondazione Sella	Monte Moro Pass
21	McLeish, Donald	before 1913	photograph	BW	F	–	Media Storehouse	Monte Moro Pass
22	Mittelholzer, Walter	1919	photograph	BW	AP (C)	8	BSB	airplane
23	Monterin, Umberto	1920	photograph	BW	C	–	M&T 2009	west from Punta Battisti
24	unknown	1923	postcard	BW	F	4	–	Monte Moro Pass
25	Sella, Vittorio	1930s	photograph	BW	F	–	Fondazione Sella	Monte Moro Pass
26	Hielscher, Kurt	1930s	photograph	BW	B	–	ETH archive	Alpe Pedriola
27	Fantin, Mario	1953	photograph	BW	AP (C)	8	CAISiDoc	airplane?
28	Fantin, Mario	1950–1960	photograph	BW	AP (E)	9	CAISiDoc	airplane, close to P. Battisti
29	Vespa, Marco	2007	photograph	colour	F	5	Wikipedia	Monte Moro Pass

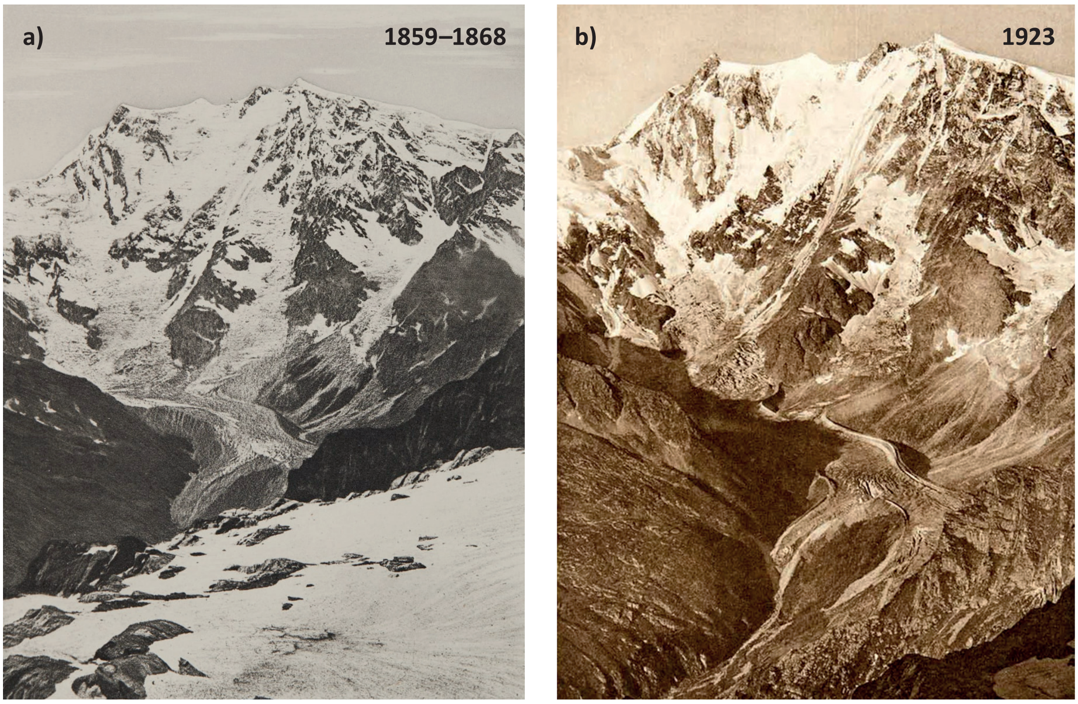

Fig. 4 Photograph by A. Civiale reproduced by photogravure from 1859–1868 (a) and a postcard from 1923 (b) taken from almost the same spot at Monte Moro Pass (2850 m a.s.l., viewpoint F).

attention of the prominent mountain photographer Vittorio Sella, who was born in Biella, at a distance of 45 km south of Monte Rosa. During his career, he photographed glaciers and mountains in the Alps, Caucasus, and Karakoram often from high and exposed viewpoints. He took photographs of Monte Rosa east face from Monte Moro Pass in 1895 and the 1930s. Donald McLeish, a British reportage photographer took a snapshot of the classical view from Monte Moro Pass, which was published in a book by Gibbs (1910).

In 1919, Walter Mittelholzer, a Swiss aviation pioneer, took probably the first aerial photograph of the Monte Rosa Massif (Garimoldi 2005). Other high-quality photographs of the east face were taken by the Italian mountaineer and photographer Mario Fantin in 1953. He was a founder of the documentation centre of mountaineering CISDAE (Centro italiano studio e documentazione alpinismo extraeuropeo) in 1967, now located in Torino, Italy.

5. Results

The results are presented in four focal themes: the extent of glacier-covered area, the extent of debris cover, the evolution of the terminus, and the evolution of a breach of the lateral moraine.

5.1 Focal theme 1: Extent of glacier-covered area of the Monte Rosa east face

For the first photograph of the Monte Rosa east face by Aimé Civiale only a rough date of acquisition between 1859 and 1868 is known, which represents the second decade after the LIA (Fig. 4 a). It can be assumed that the image was taken during mid-summer as the mountain slopes and rock cliffs are snow-free and the shadows indicate high solar elevation. The photograph also shows that Nordend Glacier was still connected to the Belvedere Glacier and the Piccolo Fillar Glacier was still reaching its LIA terminal moraine. The second image is a postcard from 1923, taken by an unknown photographer about 60 years after Civiale (Fig. 4 b). It shows the ice extent after the phase of advance of glaciers during the time of the First World War (Monterin 1926), when glaciological measurements ceased. The second image has a different foreground, but the view of the Monte Rosa east face with heavy crevassed ice in the lower part is almost identical to the first one. The picture was probably taken in September as the shadows are longer and the seasonal snow cover is still minimal. The connection between Nordend and Belvedere glaciers lacks texture and remains unclear. The ice extent is similar in both pictures and the largest differences are caused by seasonal snow cover.

The third example of the Monte Rosa east face is taken by Vittorio Sella from a viewpoint at Monte Moro Pass in the 1930s (Fig. 5 a). A drastic retreat and volume loss of the hanging glaciers can be detected as well as an increase of debris cover in the transition zone between the hanging glaciers and the Belvedere Glacier. These changes are evident also in the comparison of the 1880 and 2017 images (Fig. 6).

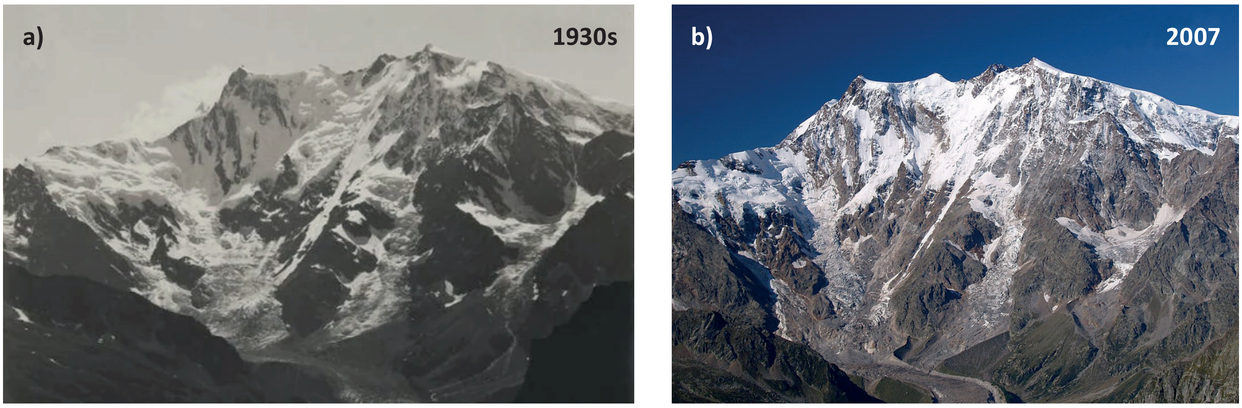

Fig. 5 An almost identical view as Fig. 4 (viewpoint F) taken by V. Sella in the 1930s (photo detail) and by M. Vespa on 9 September 2007 (photo detail).

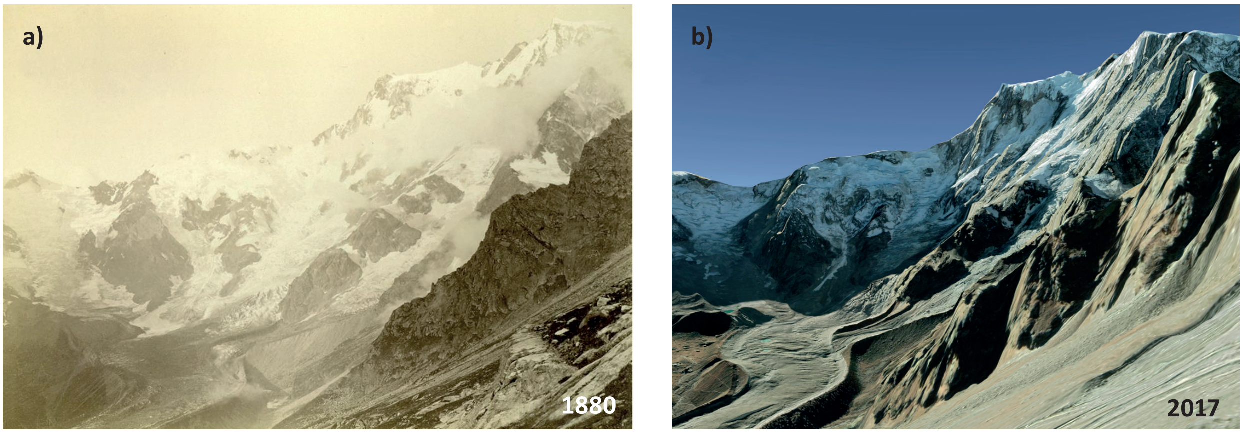

Fig. 6 A heliogravure based on the photograph by G. Loppé from the 1880s (a) and a simulated image in Google Earth (viewpoint E). The image by G. Loppé is courtesy of John Mitchell Fine Paintings, London.

Fig. 7 The lithograph based on a historical drawing of Belvedere Glacier by A. Schlagintweit published in 1854 (a) with the original caption: *Ansicht des Monte Rosa und des Macugnagagletschers (Schlagintweit and Schlagintweit 1854)*. The recent photograph was taken by M. Nüsser on 12 August 2021 (b).

5.2 Focal theme 2: Extent of debris cover

Historical photographs as well as paintings are useful to analyse gradual changes of debris cover on glaciers.

The 1845 steel engraving by J. T. Willmore (Fig. 2) shows a clean-ice glacier tongue. Likewise, in the painting and explanatory sheet by A. Schlagintweit from 1851 (Schlagintweit and Schlagintweit 1854), the Belvedere Glacier appears to be debris-free (Fig. 7). Also their topographical sketch map of the glacier (published in *Atlas zu den neuen Untersuchungen über die physicalische Geographie und die Geologie der Alpen* 1854) indicates that the tongue was only partly debris-covered along the margins, medial moraines and at the lower terminus. A slight increase of debris cover can be seen in A. Civiale's photograph (Fig. 4a), where only the central glacier line appears to be debris-free. Accordingly, the glacier was described as debris-covered at least close to the two terminal lobes by the priest and geologist A. Stoppani who visited the glacier in 1870 and 1876 (Mortara et al. 2009). The increase of debris cover can also be traced in the photographs from the end of the 19th century (Fig. 4–6), a process that continues until the present

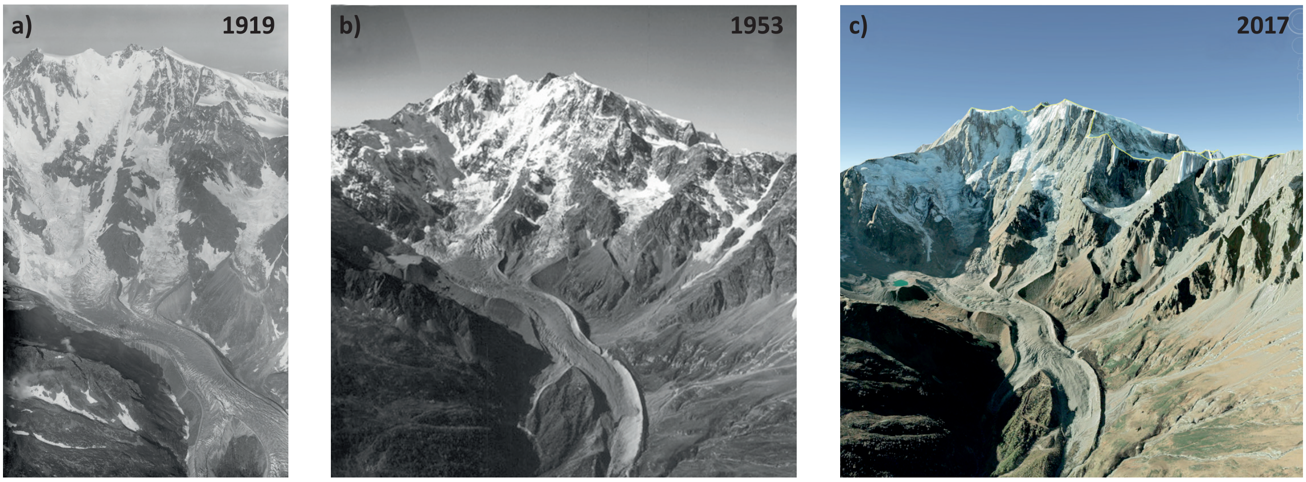

Fig. 8 Comparison of oblique aerial photographs taken by W. Mittelholzer in 1919 (a), and by M. Fantin from 1953 (b), and a simulated image in Google Earth (c). The relocation of the viewpoint indicates that the photograph by M. Fantin was also taken from an airplane.

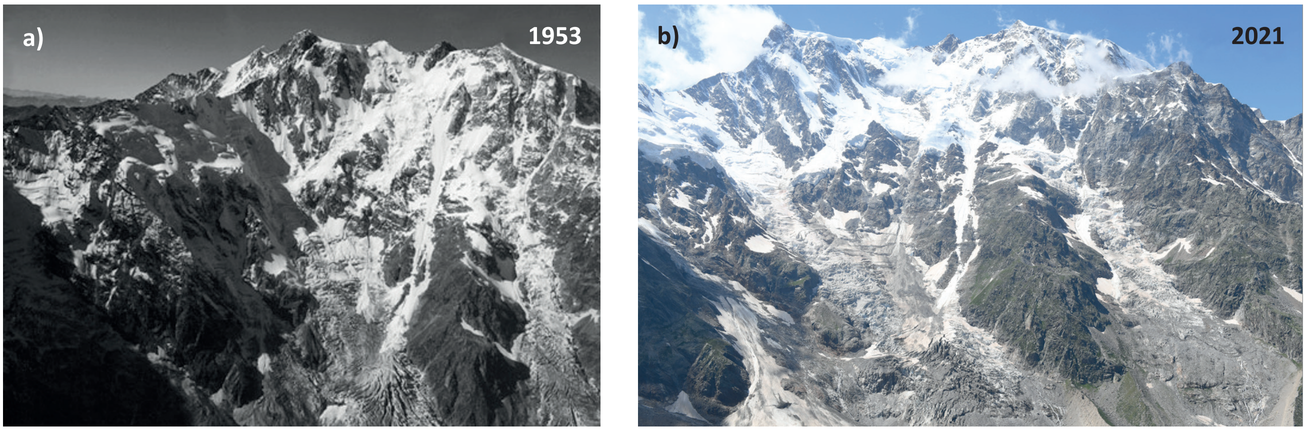

Fig. 9 Comparison of a photograph of Monte Rosa east face taken by M. Fantin (aerial photograph in 1953) (a) and a photograph taken by M. Nüsser from the Punta Battisti (viewpoint C) at 2754 m a.s.l. on 11 August 2021 (b).

day (Fig. 7 b). This multitemporal image comparison suggests that the debris cover of the glacier tongue gradually developed after the LIA.

An upward shift of the upper limit of debris cover and an increase of the debris cover thickness become obvious when comparing the oblique aerial photographs taken by W. Mittelholzer in 1919 and M. Fantin in 1953 (Fig. 8). Another pair of photographs taken by M. Fantin in 1953 and M. Nüsser in 2021 (Fig. 9) shows the debris on the lower part of the east face. The picture from 2021 indicates significantly more snow and rock avalanche tracks, which means that more debris has recently been transported onto the glacier than 70 years before.

5.3 Focal theme 3: Evolution of the terminus

The evolution of the terminus can be traced on several historical images. The engraving by F. Welden in 1824 (Fig. 10 a) based on the 'camera lucida' technique shows a realistic geometry which becomes evident by a comparison with contemporary a photograph (Fig. 10 b). Some features such as trees and the glacier outlet are not shown at realistic scales but rather in a schematic style. The orographic right lobe of the terminus, which probably developed due to a breach of the lateral moraine, is present in the image but absent on the map in Welden's book, likely due to generalization. Welden's image suggests that the right lobe developed before 1824. Another image from a similar viewpoint with a high geometrical accuracy is an oil painting by the Milanese painter Federico Ashton from 1887 (Fig. 10 c). It features highly realistic shapes of the glaciers Nordend and Piccolo Fillar. The glacier outlet of the left lobe is located in a higher position than in Welden's image. A triangular area on the slope between the two lobes is free of trees which is also shown in the photograph taken by A. Zandonati in 1893 (Fig. 10 d). The triangular area is very similar in size and shape, which is further evidence of the high fidelity of Ashton's painting.

The absence of forest in this triangular area can be attributed to the outburst flood in 1868 described by A. Stoppani. This is supported by the account of the pastor of Macugnaga who eye-witnessed the event. He mentioned that about a hundred large larches had been

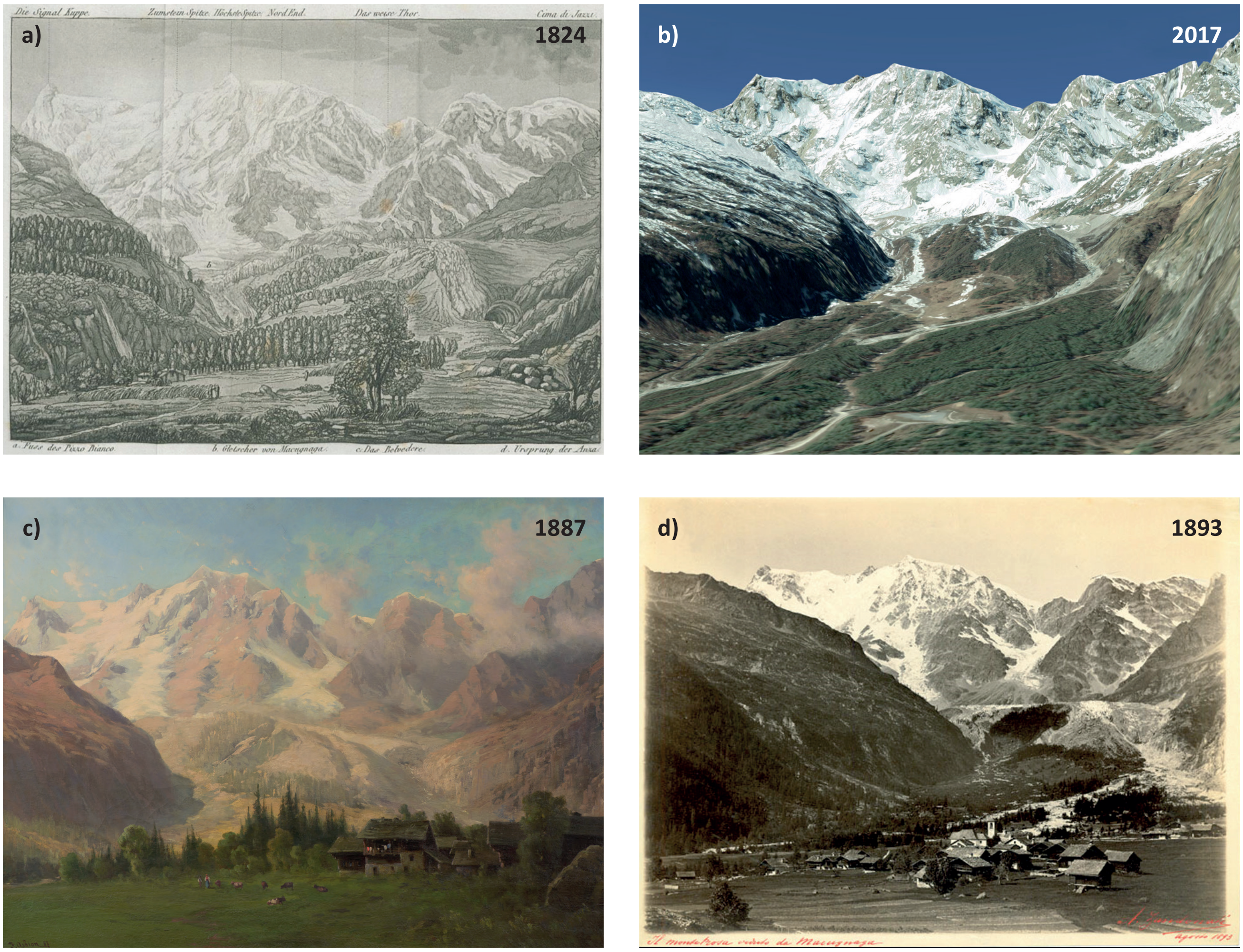

Fig. 10 Engraving from the book by Welden from 1824 showing the Monte Rosa east face from a viewpoint close to the hamlet of Pecetto Superiore (viewpoint D), a part of Macugnaga (a), the same view as a simulated image in Google Earth (b), subset from the oil painting by Federico Ashton from 1887 (c), and a photograph taken by A. Zandonati in 1893 (d).

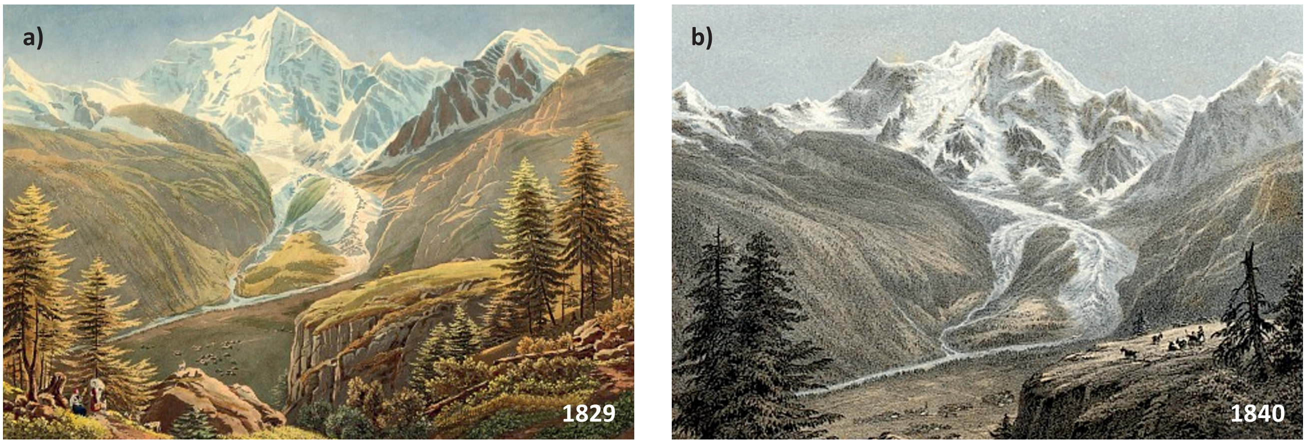

Fig. 11 Two strikingly similar images show the terminus from viewpoint E towards the end of the LIA. An aquatint titled *"Mont Rosa"* by G. Lory was published in 1829 (a) and a lithography by A. Cuviller: *"Le Mont Rose – Vue de la Valle de Macugnana"* from 1840 (b).

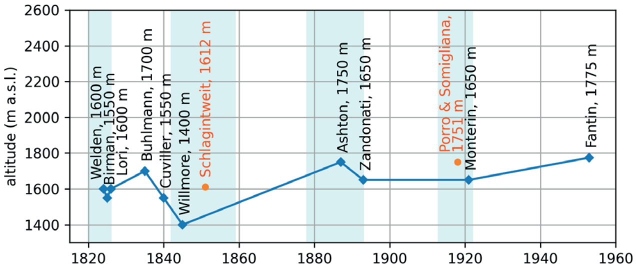

Fig. 12 Elevation changes of the terminus derived from the images. For the dates of the images, see the text and Tab. 1. The light blue stripes represent the periods of glacier advance for Belvedere after Monterin (1922). Orange dots represent field measurements of terminus elevation.

swept by a burst of the lateral moraine in this location following a blockage of the outflow from the glacier outlet for several hours (Mortara and Tamburini 2009).

The evolution of the terminus can also be traced in two landscape paintings from viewpoint E located on the slope between Macugnaga and Monte Moro Pass from 1829 and 1840. The first painting by G. Lory shows the glacier between the two last advancing phases of the LIA (Fig. 11 a), while the second painting by A. Cuviller corresponds to the beginning of the last advancing phase of the LIA (Fig. 11 b). Comparing the geometry and ice-related features of the mountains in the background and the glacier terminus indicates a high degree of realism.

While on the 1840 image, two clearly separated lobes can be recognised (Fig. 11 b), the 1829 image shows a whitish triangle similarly to the photograph taken by A. Zandonati in 1893 (Fig 10 d). Apart from the outburst flood in 1868, this slope was affected by the extension of a third ice lobe during glacier fluctuations in 1896 and the 1920s (Mortara and Tamburini 2009). The third lobe is also present in a map from the 1920s (Monterin 1922) and did not exist anymore at least since the 1950s (Fig. 8 b). The 1829 image suggests the third lobe might have existed already during the LIA long before the advancing period 1878–1893 which can also be detected in the painting by S. Birmann from 1835 (Tab. 1) (Mortara and Tamburini 2009).

The elevation changes of the left lobe terminus (Fig. 12) are well in line with the general pattern of glacier advances/retreats as outlined by Monterin (1922), which in turn reflect the climate fluctuations since the last phase of LIA. The low terminus elevation in the images by Welden (1824), Birman (1825), and Lori (1826) corresponds to one of the glacier advance periods in the Monte Rosa Massif reaching a maximum in 1826 (Monterin 1922). The oscillation in the terminus elevation for 50 m between 1824–1825 and 1825–1826 likely does not reflect the real changes in elevation but rather the accuracy of the method. Another glacier advance phase at the very end of LIA is captured in the images by Cuviller (1840) and Willmore (1845) with the lowest terminus elevation reaching 1400 m a.s.l.

Both the images by Ashton (1887) and Zandonati (1893) were taken during the glacier advancing phase 1878–1893, while the photograph by Monterin (1921) falls into the following glacier advance period in 1912–1921 (Monterin 1926). In 1918 the increase of the glacier mass even reached the crests of the lateral moraines as reported by Porro and Somigliana (1919). The image by Fantin (1953) was taken during the retreating period of Belvedere Glacier (Diolaiuti et al. 2003). Except for the 1835 image by Buhlmann, all images until the 1920s correspond to glacier advance periods. Buhlmann's image is responsible for the peak on the curve between two glacier advance periods during LIA, while the peak caused by Ashton's image is due to the lack of images covering the adjacent glacier retreat periods.

5.4 Focal theme 4: The evolution of a breach of the lateral moraine at Alpe Pedriola

The lithography from 1889 by Doyen (Fig. 13) shows a small breach in the right lateral moraine of the

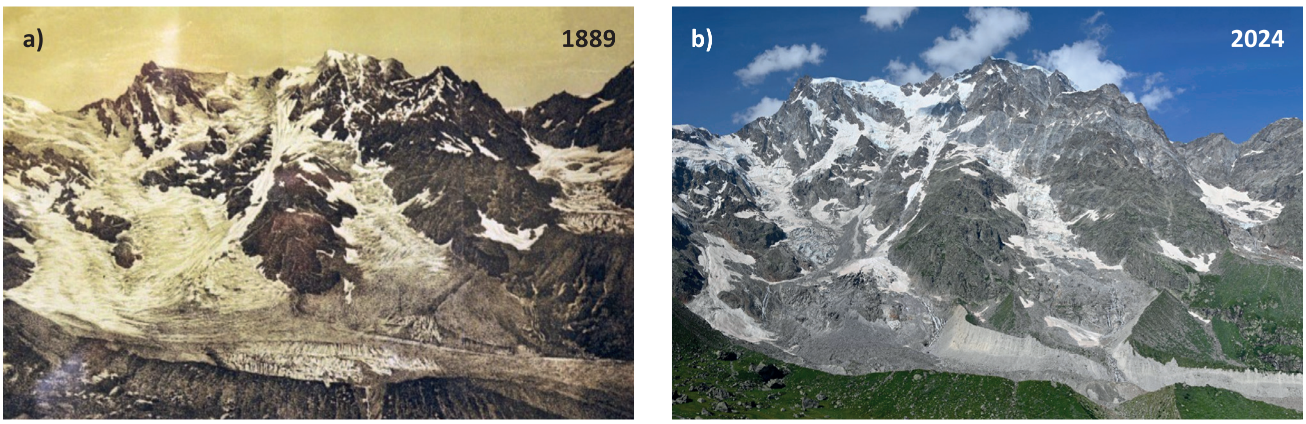

Fig. 13 The east face of Monte Rosa as seen from the pasture hut of Alpe Pedriola (viewpoint E) shows a breach of the lateral moraine on the lithography by Doyen based on a photograph by Carnagbi from 1889 (a) and a photograph by M. Nüsser from 31 July 2024 (b). The breach is below on the right.

Belvedere Glacier. This breach was caused by the 1904 GLOF, in which the flood wave first followed the inner side of the lateral moraine, then breached it, and flowed along the ablation valley at the outer side of the moraine. The breach was further incised by a series of GLOFs originating from Locce Lake in 1970, 1978, and 1979. The small incision on the Doyean's lithography evidences that the breach is much older than 1904 than presumed.

6. Discussion

A large collection of multitemporal visual material, including engravings, paintings, and photographs, documents changes of Belvedere Glacier and the Monte Rosa east face over the last two centuries. This historical material provides evidence on glacier changes since the end of the LIA. The images also provide valuable evidence of the changes in debris cover and document the evolution of the terminus area shaped by a rather complex interplay of ice retreats and advances, formation of the third lobe and GLOF events.

In the presented study, we attempted to assemble and evaluate a long visual record of landscape changes based on images created for various purposes. For such studies, the growing availability of historical landscape images, in particular via online access to various archives, is highly beneficial (Kropáček et al. 2019). The presented and discussed images were produced by various techniques. The oldest engravings and paintings have accurate geometrical frameworks suggesting the utilization of graphical tools such as *camera lucida* as in the case of Welden's image. The accuracy of the painting by F. Ashton reveals a more realistic approach in landscape painting, common for the second half of the 19th century. The common denominator of the images, which were acquired independently of each other are the vantage points which are restricted to a few locations, often in the vicinity to exposed viewpoints with relatively easy access. Surprisingly none of the images shows Belvedere Glacier from the bifurcation point of the lobes – the Belvedere viewpoint.

The image record proved useful for documentation of the evolution of particular features, such as the breach of the left lateral moraine and left terminal lobe. Furthermore, the images allowed us to compile the elevations of its termini similarly as exemplified for instance by Zumbühl and Nussbaumer (2018) for the Lower Grindelwald Glacier and the Mer de Glace. The accuracy of the elevations can be compared to two historical ground measurements. The first measured elevation of the terminus position can be found in a map by the Schlagintweit brothers from 1851 as 1612 m (4960 feet). This can be compared with altitudes based on the engravings by Willmore from 1845 and Cuviller from 1840, which are 1550 and 1400 m a.s.l., thus showing differences of 62 m and 212 m, respectively. While the first difference can be explained by the expected error of the method, the second difference probably indicates an exaggeration of glacier extent in the image by Willmore.

The terminus elevation of 1700 m a.s.l. estimated from the photograph by Monterin from 1921 can be compared with the altitude of 1751 m a.s.l. measured by Porro and Somigliana in 1918 (Monterin 1922). The difference of 51 m could be explained by the inaccuracy in historical image interpretation. However, for this period (1918–1921) glacier advance was reported leading to the terminus elevation decrease of 53 m (Monterin 1922), which almost exactly corresponds to the difference. These comparisons and the experience with the work with the images lead us to the accuracy estimation of the approach to be around 50 m, while higher accuracy can be expected in the case of photographs compared to engravings.

In general, comparisons of photographs need to consider differences in illumination, shadows and snow cover (Nüsser 2001). Especially in our case study, the exact extent of ice on steep slopes of the Monte Rosa east face is biased by seasonal snow cover. It appeared, that graphical techniques and photographs cannot be strictly separated as in some materials, these techniques were combined (Zumbühl et al. 2018), which may explain some inconsistencies.

7. Conclusions

Based on an extensive search in various archives, we found 29 historical images of Monte Rosa's east face and the Belvedere Glacier. They provide a valuable visual record dating back to the end of the 18th century, greatly extending the observation period covered by aerial photography and satellite imagery. As the viewpoints of the images are restricted to a few spots, we could build bi- and multitemporal series of repeat images. The historical images could be complemented by contemporary photographs or by simulated images prepared in Google Earth. These visual records allowed us to investigate the glacier changes since the LIA. We could document the evolution of debris cover, changes at the terminus, and the appearance of the breach of the right lateral moraine further shaped by a series of outburst floods. From the images by A. Schlagintweit (1854), A. Civiale (1859–1868), and G. Loppé (the 1880s) it appeared that the debris cover of the lower part of the glacier developed mainly between the 1860s and 1880s, in the period following the LIA.

The analysis of the terminal part of Belvedere Glacier showed that the slope between the two terminal lobes was affected by the ice movement already towards the end of the LIA and a third lobe likely already existed, similarly to 1896 and the 1920s, as seen in the aquatint by G. Lory (1829). Seven graphics and three photographs were used to analyse the changes in the terminus elevation. Although most of these images fall by coincidence in periods of glacier advance, they document well the general glacier retreat since the end of the LIA. Furthermore, the photolithograph by Doyen/Carnagbi evidenced that the breach of the lateral moraine used by the floods in 1904 and the 1970s existed long before 1904 as previously assumed. All the listed materials not only document the glacier changes and related processes of the study site but also reflect the evolution of graphical techniques used by mountain explorers over the last two centuries.

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