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## GPR AND SEISMIC SURVEYING IN THE WORLD WAR I SCENARIO OF PUNTA LINKE (ORTLES-CEVEDALE GROUP, ITALIAN ALPS)

This work has been carried out in the framework of a collaborative joint project between the Soprintendenza per i Beni Culturali, Ufficio Beni Archeologici, Provincia Autonoma di Trento and the *Comitato Glaciologico Italiano* (Italian Glaciological Committee), and of the Italian MIUR Project (PRIN 2010-11): “Response of morphoclimatic system dynamics to global changes and related geomorphological hazards” (local and national Coordinator: C. Baroni). Research was also funded by 2013 MIUR ex 60% 2013: 60A05 - 8555/13 “Geomorfologia e cartografia geomorfologica di ambienti alpini, di pianura e desertici nel bacino mediterraneo” and 2012: 60 A05-0429/12 “Geomorfologia e cartografia geomorfologica” (Coordinator: A. Bondesan).

R. Francese, A. Bondesan, C. Baroni, M.C. Salvatore, M. Giorgi and S. Landi planned, conducted and interpreted the geophysical GPR surveys, C. Bassi, N. Cappelozza, E. Mottes and F. Nicolis conducted the archaeological research on the Punta Linke site, F. Nicolis and M. Vicenzi coordinated the Punta Linke Project.

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**ABSTRACT:** FRANCESE R., BONDESAN A., BARONI C., SALVATORE M.C., GIORGI M., LANDI S., BASSI C., CAPPELLOZZA N., MOTTES E., NICOLIS F. & VICENZI M., *GPR and Seismic surveying in the World War I Scenario of Punta Linke (Ortles-Cevedale Group, Italian Alps)*. (IT ISSN 0391-9838, 2015).

The Ortles-Cevedale Group was the setting of repeated clashes occurring under extreme conditions and at the highest altitudes of all fightings in the Great War (WWI). The research scenario associated with the group is very challenging because modern research faces a series of logistical and climatic obstacles. The gradual retreat of glaciers has unearthed several archaeological remains of WWI such as barracks, barbed wire, military ammunition, weapons and other materials. The study site is the saddle between M. Vioz and Punta Linke, where the Historic War Museum of Pejo, under the direction of the Archaeological Service of the Province of Trento (Soprintendenza per i Beni Culturali, Ufficio Beni Archeologici), started an archaeological excavation in the year 2009 of some of the infrastructure of the cableway station, which also includes a tunnel section in the bedrock.

The saddle is placed at the head of Forni Glacier. GPR and seismic imaging was the best survey choice to characterize the glaciological and geo-archaeological context and to find structures or remains within the ice mass. Geophysical imaging spanned two campaigns in the years 2010 and 2011. The ice-rock interface was reconstructed in detail to depths greater than 45-50 m. The surface of the bedrock reveals a complex morphology, with several undulations and two rocky ridges elongated in the NNW-SSE direction. They identified some anomalous reflectors within the ice mass located near the western edge of the saddle of Punta Linke. The interpretation of radar profiles seems to indicate the presence of a tunnel in the ice, whose geometry and position is similar to others excavated in alpine glaciers during the Great War.

**KEY WORDS:** GPR survey, Punta Linke, Forni Glacier, Ortles-Cevedale Group, World War I

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Il Gruppo dell’Ortles-Cevedale nelle Alpi fu teatro di ripetuti scontri in alta quota durante la Grande Guerra. Il progressivo ritiro dei ghiacciai ha portato alla luce numerosi siti e resti della Prima Guerra (baracche, filo spinato, munizionamento bellico, armi e materiali). Tra il Monte Vioz e Punta Linke il Museo “Pejo 1914-1918. La Guerra sulla porta”, sotto la

direzione Soprintendenza per i Beni Culturali, Ufficio Beni Archeologici, Provincia Autonoma di Trento, ha dato inizio nel 2009 a uno scavo archeologico che ha interessato le strutture annesse a una stazione teleferica risalente alla Grande Guerra, comprendente anche un tratto in galleria.

Il sito si colloca alla testata del ghiacciaio dei Forni. Al fine di caratterizzare il contesto glaciologico e geoarcheologico e ricercare eventuali strutture o resti all'interno della massa glaciale è stato condotto uno studio geofisico attraverso profili serati GPR (*Ground Penetrating Radar*) e sismica a rifrazione negli anni 2010 e 2011. L'interfaccia ghiaccio-roccia è stata ricostruita in dettaglio fino a profondità superiori a 45-50 m. La superficie del substrato rivela una morfologia complessa con diverse ondulazioni e due dorsali rocciose allungate in senso NNO-SSE. Sono stati identificati alcuni riflettori anomali all'interno della massa glaciale collocati in corrispondenza della sella di Punta Linke. L'interpretazione delle tracce radar sembra indicare la presenza di un tunnel in ghiaccio, la cui geometria e posizione è riconducibile ad analoghe opere realizzate nei ghiacciai alpini durante gli scontri militari nella Grande Guerra.

TERMINI CHIAVE: Rilievo georadar, Punta Linke, Ghiacciaio dei Forni, Gruppo Ortles-Cevedale, Prima Guerra Mondiale.

## INTRODUCTION

The recent period of withdrawal of alpine glaciers is characterized by a significant reduction in the thickness of the glaciers also at higher altitudes, where not only wide portions of bedrock, but also trenches and military infrastructures of the First World War (WWI) are outcropping.

The celebration of the centenary of the Great War (World War I, WWI, 1914-1918) was a major boost to research in all fields of science, including Military Geosciences (Palka & Galgano, 2005) and Conflict Archeology (Saunders, 2012). Mountain warfare at high altitudes assumes particular interest as the purely military issues intersected with extreme environmental conditions, like those on glaciers (Häusler & Mang, 2010).

At Punta Linke (3632 m asl, Ortles-Cevedale Group, Rhaetian Alps) the strong reduction of glaciers thickness revealed several important testimonies of the WWI. After the end of the Great War, these military infrastructures (i.e. the structures archeologically investigated, located at 3629 m) were quickly abandoned and progressively covered by snow and ice, preserving a site-related record both climatic and archeological since the end of WWI.

In 2009 the Historic War Museum of Peio (TN), under the direction of the Archaeological Service of the Province of Trento (*Soprintendenza per i Beni Culturali, Ufficio Beni Archeologici*), started an archaeological excavation at Punta Linke for recovering and restoring barracks, galleries and many other war remains and also for protecting them from looting.

Contextually the Archaeological Service also supported a research project based on a multidisciplinary approach in collaboration with the Italian Glaciological Committee (Comitato Glaciologico Italiano). The characterization of the complex archaeological context required the glaciological and geoarchaeological characterization, realized through a collaborative project with the Italian Glaciologic Committee (CGI, Comitato Glaciologico Italiano) (Nicolis & alii, 2011; Francese & alii, 2015).

Geophysical imaging was a key component of the project in the comprehensive characterization of the Punta Linke

site. Geophysics is a well-established and consolidated tool both in archaeological (Francese & alii, 2009; Bini & alii, 2013) and in glaciological research (Binder & alii, 2009; Ribolini & alii, 2010; Carturan & alii, 2013a; Seppi & alii, 2015). Particularly GPR appears to be always among the best choices to investigate glaciers (Woodward & Burke, 2007) although the nature of the reflected signal in several cases is very difficult to interpret (Eisen & alii, 2003). Seismic imaging is also utilized in glaciers (Picotti & alii, 2015) although the logistic in the Alpine environment could be really complicated (Giorgi & alii, 2015).

Recent advances in the use of GPR for mapping Alpine glaciers focus on the understanding of the internal properties of the ice (Eisen & alii, 2007; Forte & alii, 2013) or on the temperature-dependent response (Irvine-Fynn & alii, 2006). Other authors studied alpine ice caves (Hausmann & Behm, 2010). GPR (Ground Penetrating Radar) profiling with 75 MHz and 200 MHz antennas, and a seismic survey were carried out in the Summer of 2010 and 2011 in the large saddle comprised between M. Vioz (3645 m) and the site of Punta Linke (3629 m) in order to characterize the glaciological and the geoarchaeological context of this area that was part of the high altitude frontline during the WWI.

The surveys, that were part of a wider investigation concerning also glaciological context of the archeological site, had two main purposes: to find evidences of buried military structures and to acquire data on bedrock topography at the bottom of glacier as well as to evaluate glacier thickness.

## STUDY AREA

The study area is located in the Ortles-Cevedale Massif, a mountain range set in the Southern sector of Central Alps between Lombardia and Trentino Alto-Adige (Raethian Alps), included in the Stelvio National Park. The Ortles-Cevedale Massif is formed by Australpine medium grade metamorphic basement of pre-Permian age. The Southern boundary of the Group is marked by the Insubric Line, a tectonic alignment dividing the Austroalpine Domain from the Southern Alps. The investigated area lie on outcrops of Unità di Peio, here represented by micaschists and paragneisses (Dal Piaz & alii, 2007; Chiesa & alii, 2011)

The Ortles-Cevedale Massif hosts at the high elevation several glaciers with a wide range of dimensions, types, altitude and aspect. Most of the presently deglaciated area preserve an alpine morphology inherited from the past glacial phases with well defined deep glacial valleys, cirques, *arêtès* and pyramidal picks (horn).

The archeological site of Punta Linke (fig. 1) is located in a peculiar glaciological context on the saddle between M. Vioz (3645 m) and Punta Linke (3632 m), at 3629 m asl. The WWI remains are nested along the northeastern slope of a pyramidal peak (Punta Linke) from which an ice divide departs between Punta Linke and M. Vioz, splitting the flows of Forni Glacier and Vedretta Rossa to the North and the Vedretta del Vioz to the South (CGI, 1914-2010; WGI, 2013).

Forni Glacier is the most extended Italian valley glacier. It sets up on the area of Tredici Cime, a group of 13

peaks of Ortles-Cevedale Group, from Pizzo Tresero (3594 m) to the Palon de La Mare (3705 m), all exceeding 3500 m (fig. 1). The glacier is classified as a compound basin glacier, formed by several accumulation basins feeding the main glacial system and its main tongue flowing in the Val Furva (Salvatore & alii, 2015). The glacier is coded in the official Italian Glacier's Inventory as 507.1 (before simply as 507, CGI - CNR, 1961) and with ID IT4L01137024 in the World Glacier Inventory (WGI, <http://www.wgms.ch/wgi.html>).

Visited since the second half of the XIX Century for scientific purpose (Stoppani, 1876), the Forni Glacier is one of the most monitored Italian glaciers by Italian Glaciological Committee, recording among the longest series of frontal measurements (CGI, 1914 -2010; Baroni & alii, 2011, 2012, 2013, 2014, 2015).

Since the end of the Little Ice Age, around 1850 A.D., (Orombelli & Pelfini, 1985) Forni Glacier shows a trend of progressive shrinking, underlined by a retreat of its tongue of more than 2.7 km until 2012, reconstructed on the basis

of photointerpretation, and about 1.9 km from 1895 to 2014 on the basis of annual glaciological surveys of CGI. After a small re-advance occurred during the 80s, Forni Glacier experienced a continuous gradual withdrawal of its front (CGI, 1914-2010; Baroni & alii, 2011, 2012, 2013, 2014, 2015) and a progressive loss of volume, highlighted by the gradual expansion of the rocky windows emerging from the glacial body. Merli & alii (2001) estimate a glacier's tongue thickness reduced of about 70 m between 1929 and 1998.

Presently the glacier extends for ca. 10.88 km<sup>2</sup> (data inferred from orthophoto taken in 2012): the enhanced reduction of the last years is splitting the glaciers in tree distinct glacial bodies.

The Vedretta Rossa, coded with the number 697 of Italian Glacier's Inventory and with IT4L00102514 by the WGI, occupies the North-Eastern side of M. Vioz. Fed mainly by direct precipitation, the glacier is a simple basin glacier with a characteristic stepped longitudinal profile marked by several crevasses which follow the topography of substrate.

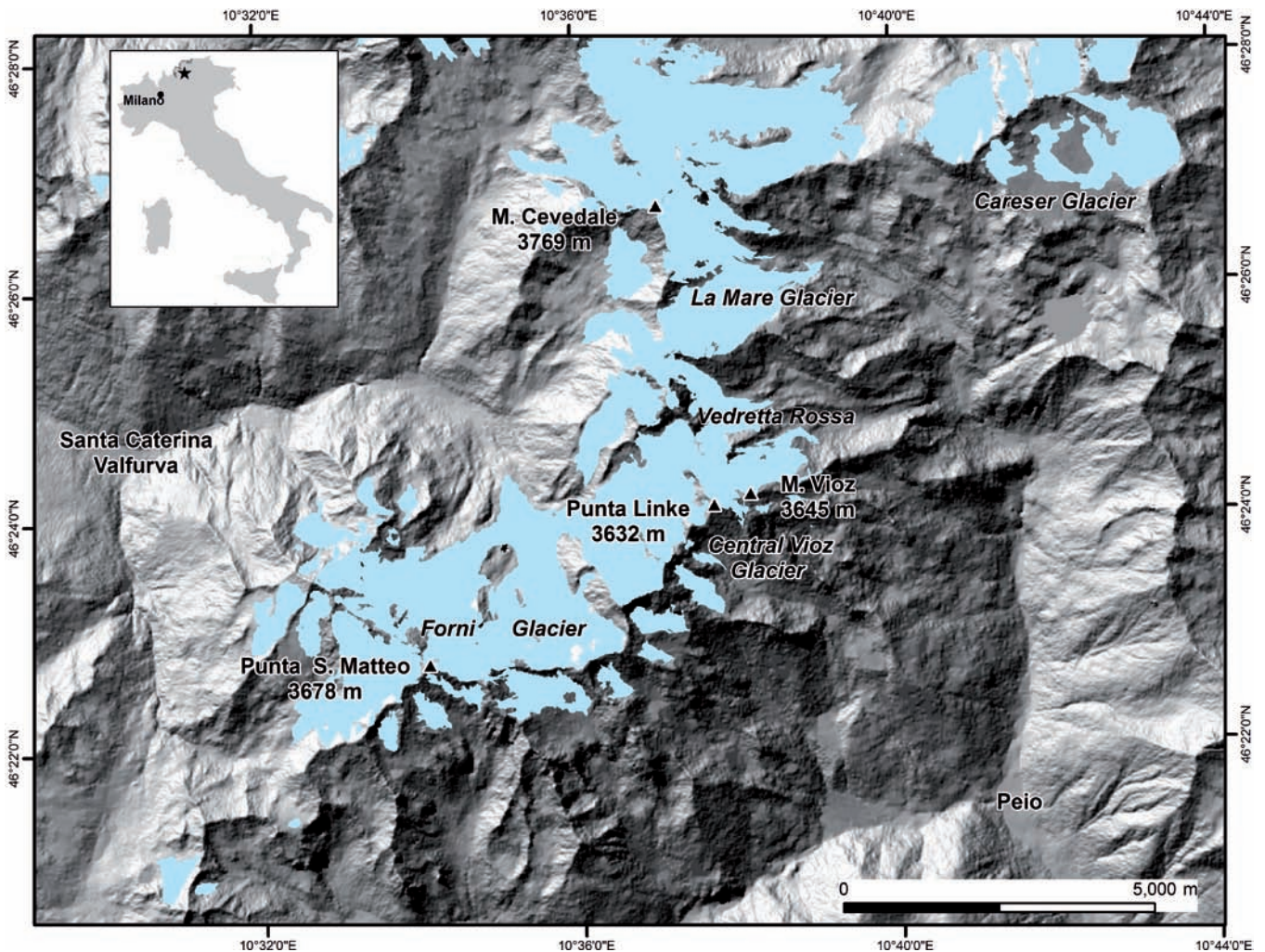


FIG. 1 - Location map of the study area

During the last years the glacier suffered a significative frontal withdrawal and areal reduction: the yearly average rate of retreat calculated for the time interval 2003 and 2006 (0.8 %) is almost four time that recorded between 1990 and 2003 considering the area reported in the Catasto dei Ghiacciai Lombardi (Servizio Glaciologico Lombardo, 1992). The tongue is in fast regression retiring above 2800 m a.s.l. in 2006.

The Central Vioz Glacier (n. 693 in the Italian Glacier's Inventory and ID IT4L00102510 on the WGI) is a small glacier fed by the southern flow coming from M. Vioz-Punta Linke saddle. In 2006 the glacier had an extension less than 0.08 km<sup>2</sup> and the minimum elevation reaching about 3300 m a.s.l. The glacial complex is presently under geomorphological survey through a specific glaciological legend according to Baroni & *alii* (2004).

## THE HISTORICAL CONTEXT

During WWI, the western Italian-Austrian Hungarian front run along the ridges and glaciers of Ortles-Cevedale, Adamello-Presanella and Marmolada.

In this context the Ortles-Cevedale Massif is one of the most evocative and emotional scenarios in the theater of the First World War, with battles fought at altitudes above 3000 m, in extremely prohibitive conditions.

In the Ortles-Cevedale the war front developed for about 50 km from Cima Garibaldi to the north to Gavia Pass to the south along the border presently separating Trentino Alto Adige from Lombardy regions. The Ortles-Cevedale Massif, was occupied by the militia for the whole conflict and since the beginning mainly had a defensive role (Tazzoli, 1997).

The Ortles-Cevedale and Adamello Massifs were sentinels for accessing the Valcamonica and Valtellina (for the Austrian Imperial Army) and for opening the way to Trento for the Italian army. The main alpine passes like Stelvio, Tonale and Gavia were therefore key sites of strategic relevance to be defended also from ridges and peaks in their vicinity.

The war scenario was harsh and very difficult considering the meteorological and topographic conditions. Mules and soldiers were obliged to carry huge amount of supplies, equipment and ammunitions for fighting at elevation exceeding 3000 m. S. Matteo peak saw, only few weeks before the end of WWI, the highest battle ever fought in Europe (Fantelli & *alii*, 2008) but many other battles in the Ortles-Cevedale and Adamello-Presanella Groups were disputed at similar elevation since 1915. During four never-ending winters soldiers from both the sides of the military front experienced bitter environmental conditions. During winter and spring seasons the conflicting armies were exposed to snow avalanches, which resulted in numerous loss of human lives very similar in number to that occurred during the fighting. On 4<sup>th</sup> November of 1918, the WWI finally ended: the alpine military structure were definitely abandoned and the highest sites were later buried by a diffuse snow cover.

In 1915, at the beginning of hostilities between the Kingdom of Italy and the Austrian-Hungarian Empire, the Vioz Hütte, at an altitude of 3545 m under M. Vioz, assumed the role of strategic command for the Austrian army and become during the war one of the highest advanced tactic commands of the alpine front. One of the main roles of this military command was the coordination in altitude operations on the Ortles-Cevedale Group.

Most of all supplies came from Cogolo (1160 m) at the valley bottom by cableway and reached the western fore-peak of M. Vioz, Punta Linke, at 3629 m. Here a second section of the cableway, through a 1300 m span across the Forni Glacier, reached the important military outpost on the southern east ridge of Palòn de la Mare, nowadays called "Coston delle barache brusade" at an altitude of 3300 m. The intermediate station of Punta Linke was excavated into the ice and into the adjacent rocks to prevent Italian observation and artillery fire.

Powerful engines and warehouse were hosted inside the tunnel while barracks for the soldiers were located outside.

An artillery battery was also placed on the northern ridge of Punta Linke. At the end of the WWI the military garrison was quickly abandoned and most of the equipments were left on site.

Over time Punta Linke site was repeatedly visited, especially approaching the Second World War, by the rescuers ("*recuperanti*"), who managed a great recovering operation digging up war wastes scattered in the mountains and selling scrap metals. The cableway was completely dismantled and the barracks were almost emptied.

During the 60s of the last century the external warehouse and the tunnel entrance, preserved by snowdrift, were excavated and the cableway engines and others scavenging parts were tried for being taken away. The recent reduction in thickness of the glacial bodies, after the small re-advance of the 80s of the last century, has determined the outcropping of several finds and structures related to the White War.

Since the 2009, the Punta Linke site was excavated with archaeological technique together with detailed photographic and topographic surveys and analyzed with a multidisciplinary approach. All the recovered findings were listed, partially restored and now in exhibition at the Historic War Museum of Peio. In 2014, the Punta Linke archeological site became a musealized place.

## DATA ACQUISITION AND PROCESSING

The measurements were collected using Ground Penetrating Radar (GPR) and High Resolution Seismics in two different geophysical campaigns.

During the first campaign 6 GPR profiles were collected (fig. 2 and Table 1) using a single channel GPR system, equipped with an unshielded 75 MHz antenna.

During the second campaign 9 additional GPR profiles (fig. 2 and Table 1) with the 75 MHz antenna and 53 higher

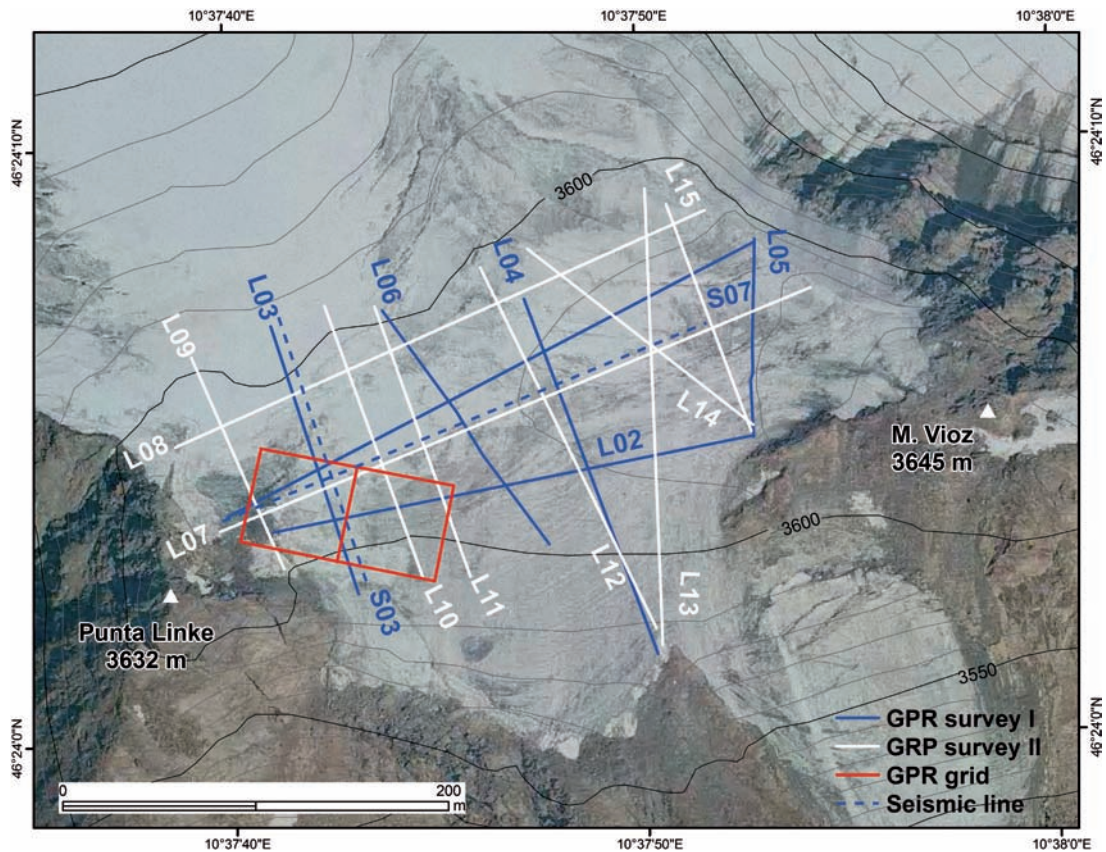


FIG. 2 - Data acquisition grid in the Punta Linke-M. Vioz site. Digital Ortophoto of Regione Lombardia taken in 2003, (authorization:CC-BY-NC-SA 3.0 Italy).

resolution profiles, using a 200 MHz antenna, were collected; they were distributed over a rectangular grid of 51 m by 102 m (fig. 2). Linescan spacing along the grid was 3.0 m. Recording parameters were 0.29 ns sample rate and a total recording time of 600 ns for the scan lines and 0.40 ns sample rate and a total time of 500 ns for the grid lines.

Each antenna was sit on a plastic sledge, with the transmitter/receiver plane being kept approximately 0.1-0.2 m above the surface, to achieve consistent coupling and reduce the amount of random reverberations in the data. Data were recorded in time mode with an inline sampling rate of 32 scans per second.

The Punta Linke-M. Vioz saddle was covered with 2900 m of profiling and 3600 m of longitudinal and transversal profiles were collected along the two axes of the grid.

During the second campaign two seismic lines were also collected along the track of GPR profiles L03 and L07.

Seismic data were recorded using a 24 channel seismograph with a 24 bit A/D converter. The elastic wave was propagated into the subsurface using a 8 gauge Isotta gun, shooting in a shallow (0.5 m) hole, while the incoming signal was detected using 10-Hz vertical geophones spaced 5 m apart. The source spacing was 10 m with some additional external shots. The maximum coverage in the center of the line, using the above geometry, resulted equal to 24 folds.

TABLE 1 - GPR profiles and seismic lines.

TYPE	CAMPAIGN			
	I – 2010		II – 2011	
	Profile/Line	Length (m)	Profile/Line	Length (m)
GPR	L01	310	L07	330
”	L02	250	L08	300
”	L03	150	L09	120
”	L04	210	L10	150
”	L05	105	L11	150
”	L06	150	L12	210
”			L13	240
”			L14	145
”			L15	120
SEISMIC			L03	150
”			L07	330

Georeferencing of the different spreads was achieved surveying several reference points by means of a geodetic GPS in differential configuration. The elevation was cor-

rected using the vertical datum provided by a benchmark point located in the vicinity of the M. Vioz summit.

GPR and Seismic processing was performed entirely in the open-source environment of the Seismic Unix package (Colorado School of Mines-Center of Wave Phenomena) running in the Solaris OS under the Intel architecture.

GPR data processing was somewhat complicated because of the random nature of the ringing occurring in the data. This was probably due to sudden changes in the coupling caused by the relative abundance of melting water at various locations along the profile. The base processing flow included zero time correction, frequency filtering and background removal. Two specific modules were then developed to attenuate the ringing bands (fig. 3). The common running-average filter (Francese & *alii*, 2004) was effective only selecting very narrow trace windows causing the horizontal reflectors to be also fairly attenuated. To overcome the problem an automatic splitting routine was coded, capable of extracting segments of the profile with an homogeneous ringing, computing and removing the mean trace and then recombine the data. Some additional referencing modules were finally coded to correct for the topography and convert the data from time to depth domain. The radar wave velocity in ice was estimated analyzing the curvature of some diffraction hyperbolas. The resulting value of about 16.0-16.5 m/ns was confirmed by other surveys conducted in similar conditions (Carturan & *alii*, 2013a and 2013b). Migration

was not applied to the data to improve target recognition by aid of hyperbola tails. The GPR profiles collected parallel to the long axis of the grid were gathered onto a single volume and some depth slices were calculated. Each depth slice was obtained averaging the amplitude of 5 depth samples.

Seismic processing was mostly focused on mapping the P-wave velocity in the uppermost snow-firn layer. Collected data were overwhelmed by powerful source-generated noise (fig. 4). The flow chart was straightforward and included geometry assignment, frequency filtering and 2D dip filtering to remove linear noisy events from the records.

## RESULTS AND DISCUSSION

The P-wave velocity in the near surface layer appears to be strongly controlled by the high water content as its value is almost coincident with the typical velocity of compressional waves in the water (i.e. 1500 m/s). The P-wave velocity in the underlying ice body ranges from 3350 m/s to 3500 m/s. This value is slightly low compared to other glaciers (Horgan & *alii*, 2012) and also to the Mandrone Glacier (Giorgi & *alii*, 2015) located in the nearby Adamello massif.

The radar wave propagated down to a depth greater than 50 m from the glacier surface and several reflecting horizons, with distinct signatures, have been outlined in this interval. The signal partially penetrated also in the underlying sediments and into the micascists and paragneiss bedrock.

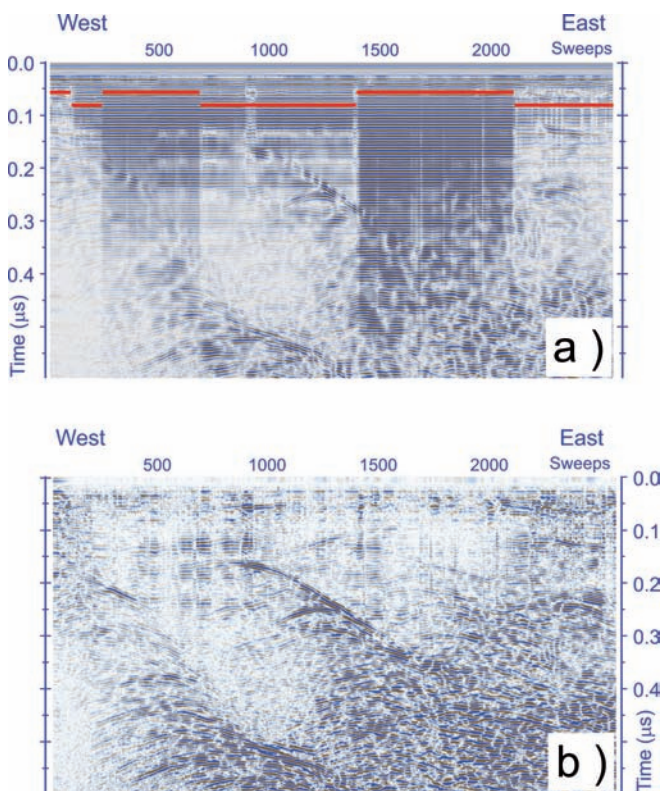


FIG. 3 - Raw record exhibiting variable ringing (a), the red lines indicate segments with homogeneous ringing. Processed record (b).

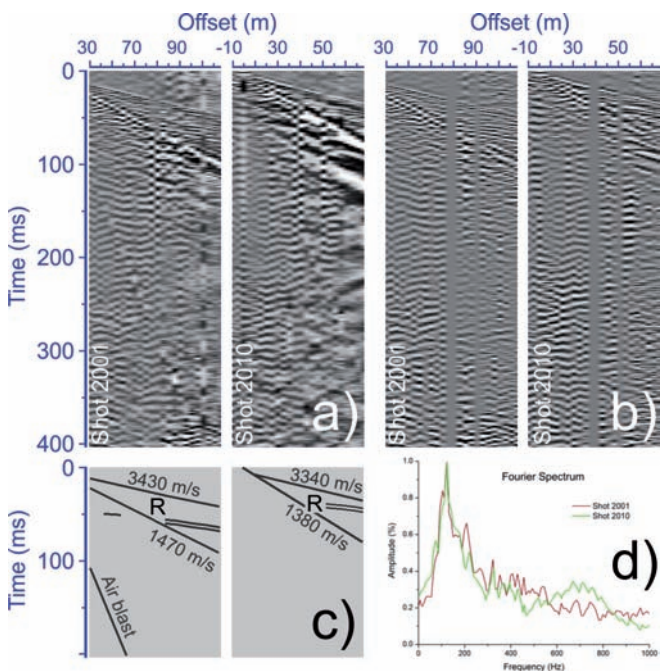


FIG. 4 - Seismic shots 2001 and 2010 collected along GPR profile L07. a) Raw records; b) Pre-processed records; c) Velocity of the different phases is visible in the record: direct wave and head waves, R - reflections; d) Fourier spectra.

THE ICE-BEDROCK INTERFACE

The bedrock signature was less clear than expected (figs. 5 and 6) and the reflected amplitude appears to be strongly dependent on the dip of this interface and probably also on the relative abundance of water and sediments above the bedrock (Carturan & *alii*, 2013a). This thin intermediate layer could be composed of ice, debris and flowing meltwater with sudden changes in its dielectric properties (Carturan & *alii*, 2013a; Seppi & *alii*, 2014). Other reflectors are embedded in the ice and they are mostly due to crevasses and meltwater within the ice.

In the transversal profiles L01 and L02 (fig. 5) the bedrock geometry is clearly undulated with a prominent mound located at the horizontal distance of 200 m and 180 m in profiles L01 and L02 respectively. The maximum depth is about 40-45 m in the Eastern segment of profile L01. In the Western side of both the profiles, the interface gets shallower and the nearby outcrops confirm this. On the eastern side of profile L01, the interface is quite

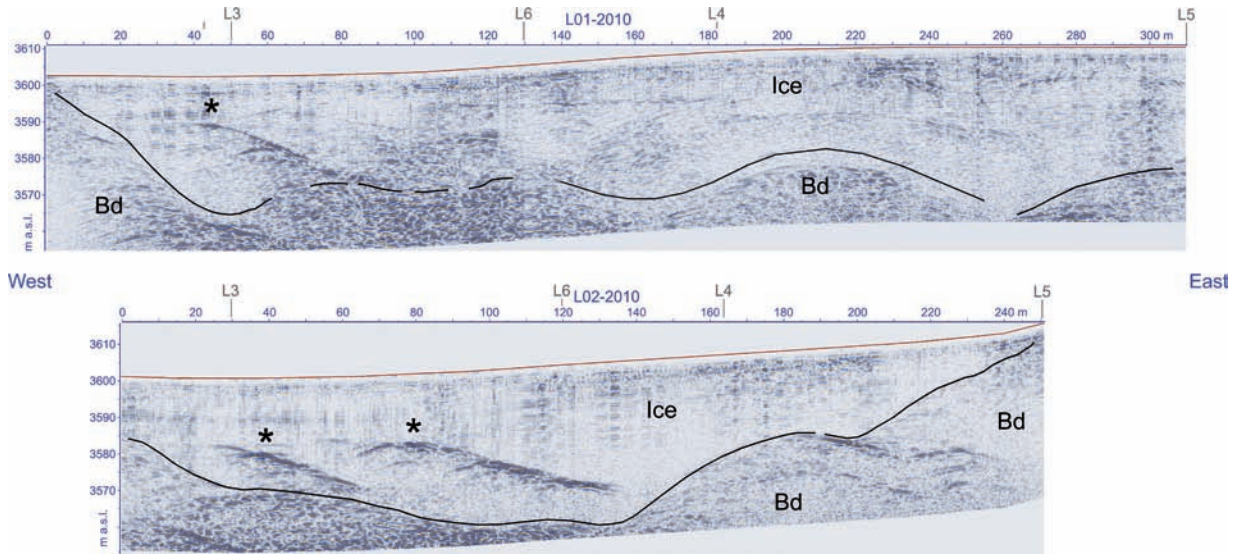


FIG. 5 - Transversal scans L01 and L02. The continuous line marks the complex ice-bedrock interface while the asterisks outline some strong reflectors embedded in the ice body.

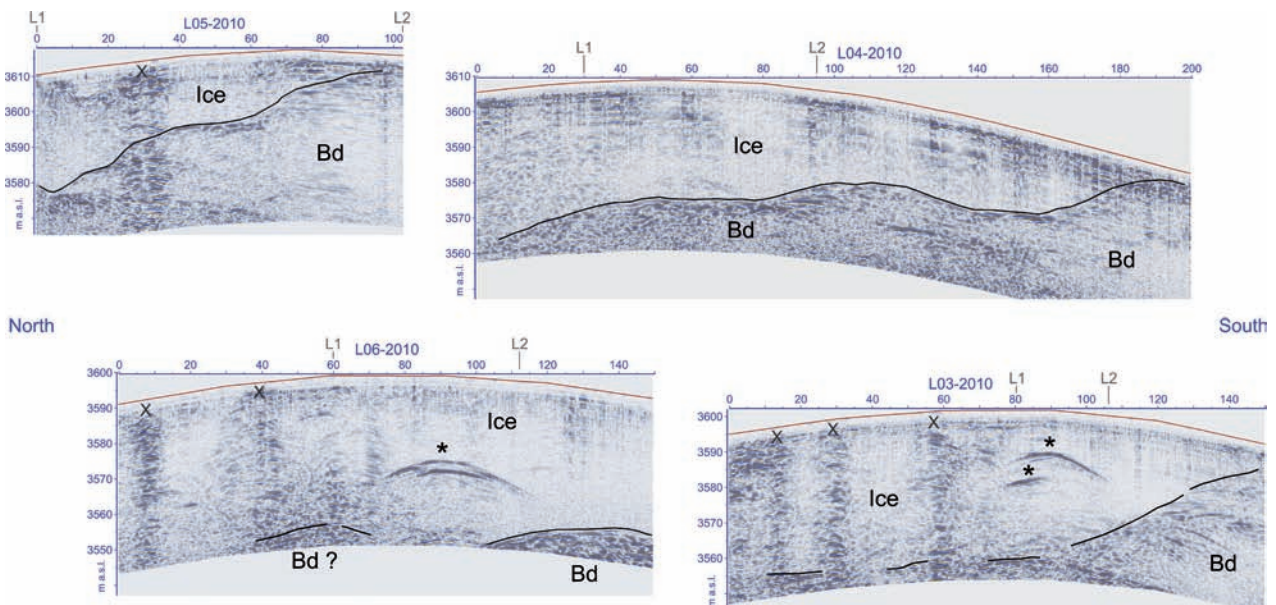


FIG. 6 - Longitudinal scans L03, L04, L05 and L06. The continuous line marks the complex ice-bedrock interface, the X points the scattering and the reverberative patterns generated by crevasses while the asterisks outline anomalous reflectors embedded in the ice body.

deep and the glacier thickness is larger than 35-40 while in profile L02, the interface rapidly gets shallower and again this is confirmed by nearby outcrops. As discussed in the previous paragraph the reflectivity of these steep flanks is very low but an ensemble of diffraction hyperbolas outlines the interface and the nearby outcrops are an excellent constrain for the interpretation. Some confused diffraction patterns visible in the ice body are caused by crevasses almost parallel to the profile direction (see for example the near surface reflections occurring at the horizontal distance of 220-240 m in profile L01).

In the longitudinal profiles the bedrock sinks northwards with some undulations although less prominent compared to the longitudinal profiles. In the southern edge of profiles L05, L04 and L03, the interface gets shallower in the vicinity of the outcrops but for profile L06 that is shorter. The reflectivity of the interface in these profiles is slightly higher compared to the transversal scans. This is somewhat caused by the different polarization of the radar antenna and of its footprint on the target ice-bedrock interface. In the longitudinal profile, a significant amount of energy is back scattered outside the receiving fan of the transducer (Forte & alii, 2015). In this particular context, transversal profiling seems to be more efficient in detecting the target and mapping the interface.

In profile L06 the buried crest separating the North and the South slopes (marked with Bd) is visible. The crest is shifted about 50 m southwards (figs. 6 and 7) with respect to the saddle indicating how the glacier progressively excavated the bedrock on this slope.

A series of vertical scatterers marked by complicate reverberative patterns are caused by crevasses that are also partly visible at the surface. The crevasses could be easily correlated along the longitudinal profiles.

The density of radar profiles (fig. 2) allowed for a first attempt of tri-dimensional reconstruction of the glacier body over the entire M. Vioz-Punta Linke saddle and the higher portion of the Forni Glacier (fig. 7). The ice-bedrock interface, picked in the 15 radar profiles, was initially triangulated via a Delaunay algorithm, using the outcropping ice-bedrock contact as a lateral constrain, and lately gridded using the standard Kriging procedure.

The contour lines show a rather complicate morphology (fig. 7) with two longitudinal ridges in the bedrock with a crest width of about 25 m. The ridges probably developed because of the larger stiffness of the granite rocks at these locations.

The curved geometry of the crevasses, visible just northern of the investigated area, confirm the hypothesis of the presence of a buried ridge in bedrock in the eastern

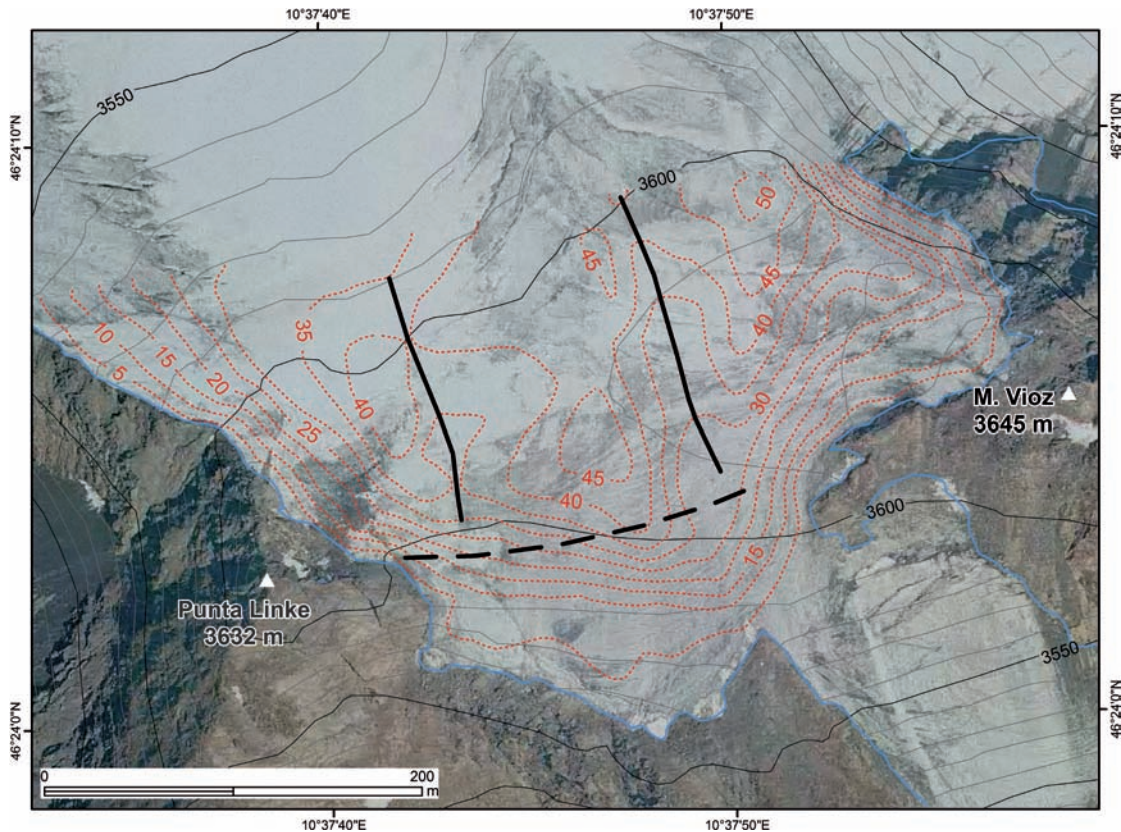


FIG. 7 - Contour lines of the ice thickness (in red); the cyan line indicates the glacier limit in 2003. Continuous black lines mark two longitudinal undulations in the ice-bedrock interface; the expected position of the buried crest is evidenced with the dashed black line.



side of the glacier. The maximum thickness of the glacier is about 45-50 m, as visible in the contour lines (fig. 7), in the central to western portion of the investigated area. The ice volume could be estimated in approximately 2.24 millions of cubic metres.

The confidence in the reconstruction of the geometry of the ice-bedrock interface provided an initial key to interpret some sharp and anomalous reflections embedded in the ice body. These reflectors were mainly visible in GPR profiles L02 and L03 (figs. 5 and 6) and were targeted with the dense profiles of the high-resolution grid (18 by 35 scan lines). The profiles collected along the major axis (fig. 8) clearly depict the geometry of the ice-bedrock interface that is rapidly sinking northward moving from scan 301 to scan 318.

The first reflector appears at scan 304, while a second and third reflector appear at scan 306 and 309 respectively (fig. 8). The reflector at scan 304 is located in the vicinity of the bedrock at a depth of about 19 m from the surface and 9 m above the bedrock. Moving northward it shifts progressively upward reaching a minimum depth of 13 m at scans 309 and 310. At scan 313 the reflector deepens again down to 16 m and it appears to be jammed with other two reflectors. The second reflector initially visible at scan 306 is located at a depth of 29 m and its position is about 7 m above

the underlying flat bedrock. Moving northwards, similarly to reflector #1, the object shifts progressively upward reaching a minimum depth of 21 m at scans 314 and it finally deepens again down to 23 m at scan 318.

A third reflector is visible starting from scan 309 with its top about 16 m deep. The amplitude of the scattered back signal is rather low compared to reflectors #1 and #2. Reflector #3 is visible in the line scan interval 309-313 and its depth does not change significantly in the different profiles. The GPR image gets a little bit confused since line scan 314 and this is due to a crevasse intersecting the survey grid in the vicinity of the north-west corner (fig. 9).

Reflector #1 is the most prominent of the ice-embedded reflectors and its signature is always sharp and symmetric suggesting an artificial origin. The shape of the reflector is a large elongated hyperboloid probably caused by a buried cylindrical object. The backscattered energy on the hyperboloid surface is clearly not homogeneous depending on several factors (varying surface morphology affecting the radiation pattern, varying target nature, varying coupling, etc). This geophysical response is very similar to the response of a non-metallic buried pipe imaged with longitudinal radar scans. Its minimum length is about 25 m as it appears clearly in 9 profiles.

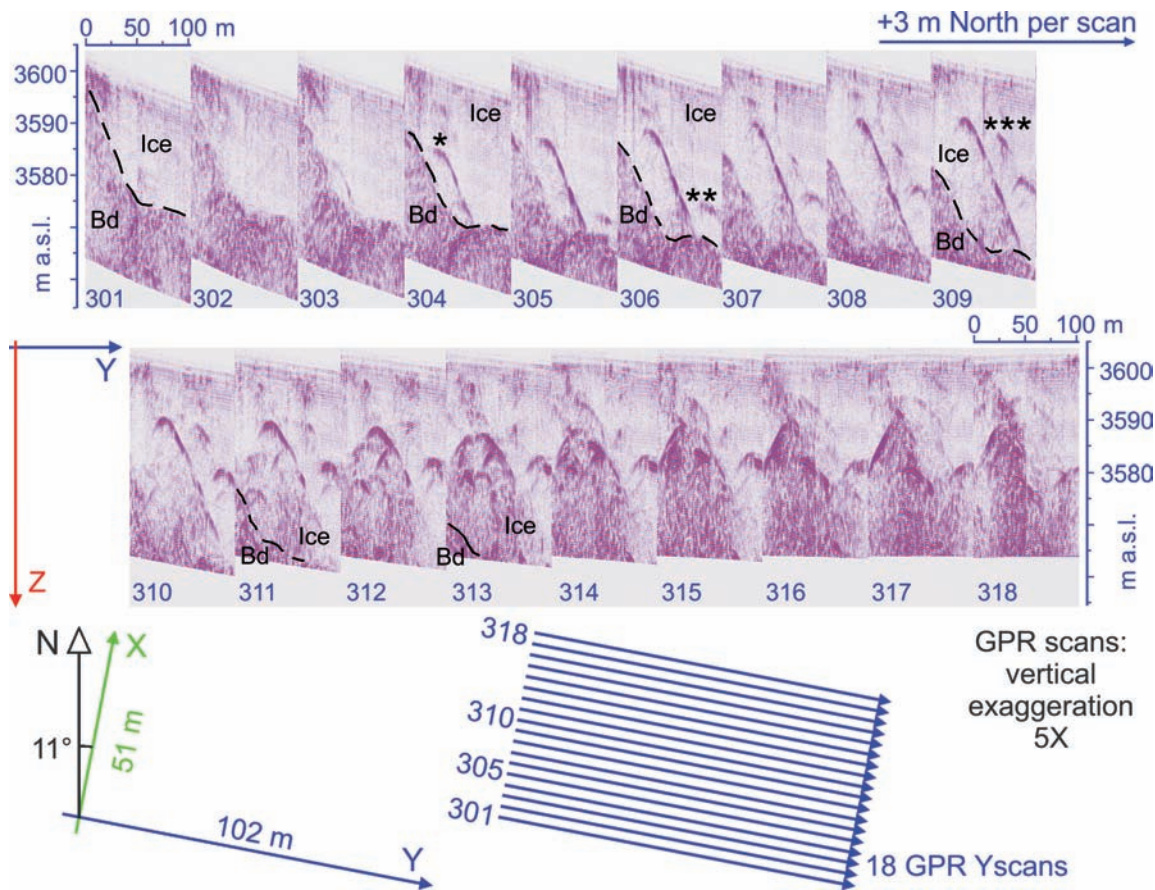


FIG. 8 - Scan lines from 301 to 318 collected along the major axis of the grid. The grid origin is located in the south-western corner. Each line is oriented WNW-ESE, see also fig. 9. The ice-bedrock interface is clearly visible along with some anomalous reflectors marked with asterisks and first appearing at scan 304.

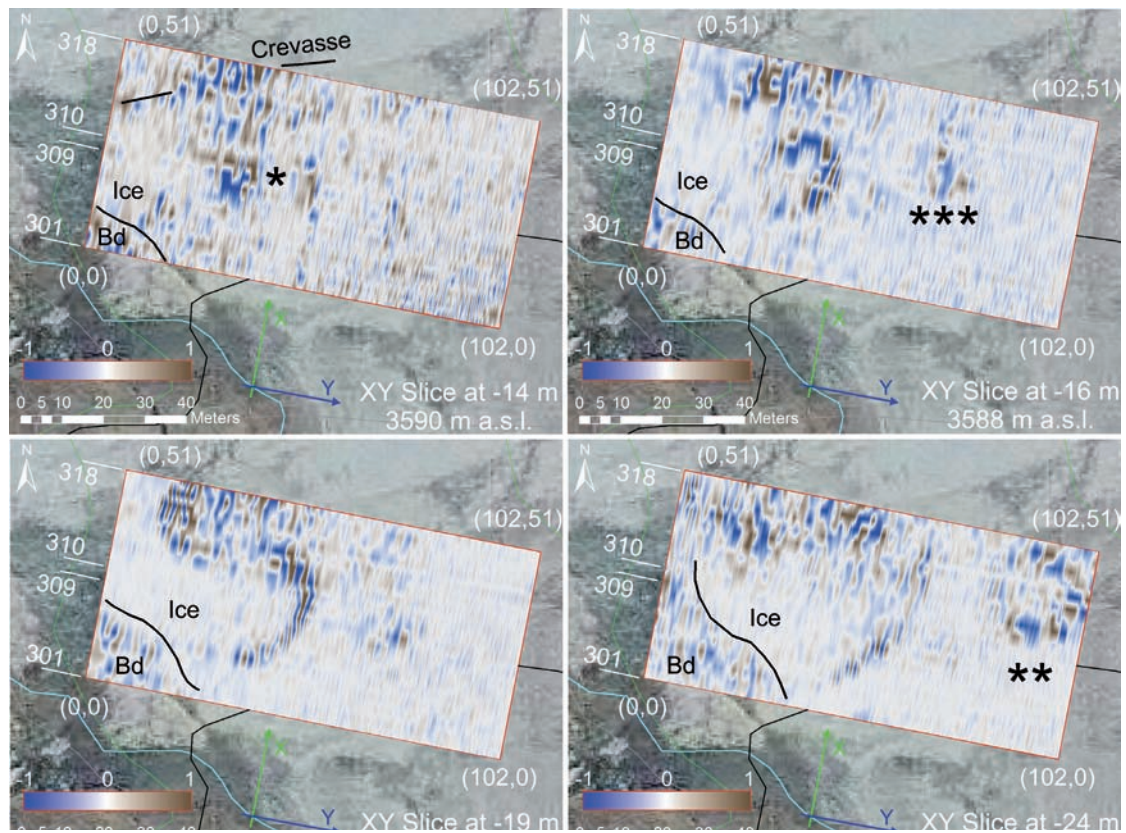


FIG. 9 - Depth slices extracted from the grid at the elevation of 3590 m, 3588 m, 3585 m and 3580 m. Reflectors #1, #2 and #3 are marked with asterisks, see also fig. 8. The reflection amplitude was normalized in each reflectivity plane.

The bedrock exits the target range beginning from scan line 314 about 35 m northern of the grid origin.

The analysis of the depth slices provided a further insight in the understanding of these reflectors (fig. 9). The depth slice calculated at -14 m shows the top of reflector #1 (one asterisk) in the west-central portion of the grid. Other reflections visible in the vicinity of the north-west corner are due to a crevasse that is also visible in the background aerial image. Reflector #1 exhibits a sub-circular shape just 2 m deeper in the depth slice calculated at -16 m. The sub-circular shape probably depends upon the way the large diffraction hyperboloid is cut by the slice (fig. 10). In the same depth slice appears also the top of reflector #3 (three asterisks) in the east-central portion of the grid. Reflector #1, in depth slice calculated at -19 m, switches from circular to spiral with a curved branch elongated towards the south-west corner and origin of the grid. This particular shape is somewhat again related to the combination of the geometry of the slicing plane and of the diffraction hyperboloid (fig. 10). In this slice reflector #3 exhibits roughly the same response as in the slice calculated at -16 m. Reflector #3 disappears in the depth slice calculated at 24 m while appears reflector #2 (two asterisks) and the latter exhibits a sub-circular shape very similar to the one of reflector #1 in the depth slice calculated at 16 m.

Reflector #1 is the most prominent feature in the depth slices also and its geometry, as visible in the xy plane, supports the initial idea of an artificial buried object. Reflector #2 is also promising because of its consistency across the various profiles

A simple numerical model was then created to gain better confidence in the interpretation. The model reproduces the real GPR grid covering an area of 51 m (x) by 102 m (y). A dipping linear reflector was positioned in the middle of the grid (fig. 10 a). The reflector begins at  $x=0, y=-20$  and  $z=-16$  and it ends at  $x=0, y=20$  and  $z=20$ . The ray-tracing response of the reflector (scanning the grid parallel to the y-axis) appears as a large hyperboloid (fig. 10 b). The image of the ray-tracing response of a y-scan (fig. 10 c) is very similar to the shape of the reflector as it appears in profile L01 (fig. 5). Also the image of the ray-tracing response of a time slice (fig. 10 d) is comparable to the reflectivity planes (fig. 9). The amplitude patterns are sub-circular when the hyperboloid is sliced near its top (slices calculated at -14 m and -16 m) and become sub-oval and shifted eastwards slicing the hyperboloid in the middle (slice calculated at 19 m and 24 m).

At the present stage the nature of the buried object is still under investigation. Natural features expected to cause similar reflections could be glacial conduits or debris layers.

A glacial conduit could be excluded because the object is located in the saddle and there is no basin to accumulate the melting water. Furthermore in this area the GPR profiles imaged a buried watershed parallel to the object. A natural conduit is likely to develop quite differently in the ice body. A debris layer could be also excluded because the inclination and the elongated geometry of the buried reflecting object are not coherent with talus or landslide deposits.

The consistency of the radar signature across the different profiles lets also exclude reflections from crevasses or water lenses within the ice body.

In view of these considerations the buried objects do not appear to be natural features and they are likely to be buried remains of WWI. The collapse of a tunnel excavated in the ice seems to be the most convincing hypothesis and this hypothesis is also supported by the results of a simple numerical simulation. Tunnel excavation in glaciers was very common during WWI; the best known case regards the “city of ice” in the Marmolada Glacier (Bondesan & *alii*, 2015).

### CONCLUDING REMARKS

The experimental geophysical survey conducted on the saddle comprised between M. Vioz and Punta Linke provided a relevant insight both in the glaciological and in the archaeological perspectives and also for conflict archeology. Results from GPR and seismic imaging were encouraging

although the abundant presence of melting water was the cause of radar wave dispersion and powerful coherent noise generation during the second campaign conducted during the Summer 2011.

The buried ice-bedrock interface was reconstructed in details down to a depth larger than 45-50 m. The ice-bedrock interface exhibits a rather variable signature depending on dip and on the relative presence of water and fine sediments on the top of the bedrock.

This interface exhibits a complicate morphology with several undulations and two parallel ridges of stiff rocks elongated along the NNW-SSE direction. At a first glance the glacier excavation affected also the southern slope of the M. Vioz and the buried watershed is slightly shifted southwards compared to the surface morphology.

The detailed reconstruction of this interface allowed for a better interpretation of some strong reflectors embedded in the ice and located in vicinity of the saddle. The signature of these reflectors is peculiar and slightly different from other reflectors commonly visible in the Alpine glaciers and associated with glacial conduits, crevasses, boulders, debris and lenses of melting water.

Three reflectors were mapped within the ice body at different distances from the underlying bedrock ranging from few metres to about 15 m. The most interesting feature is a linear sharp reflector that crosses the high-resolution GPR grid in the East-West direction. The reflecting pattern, in the sliced un-migrated data, appears as an oval shape that is

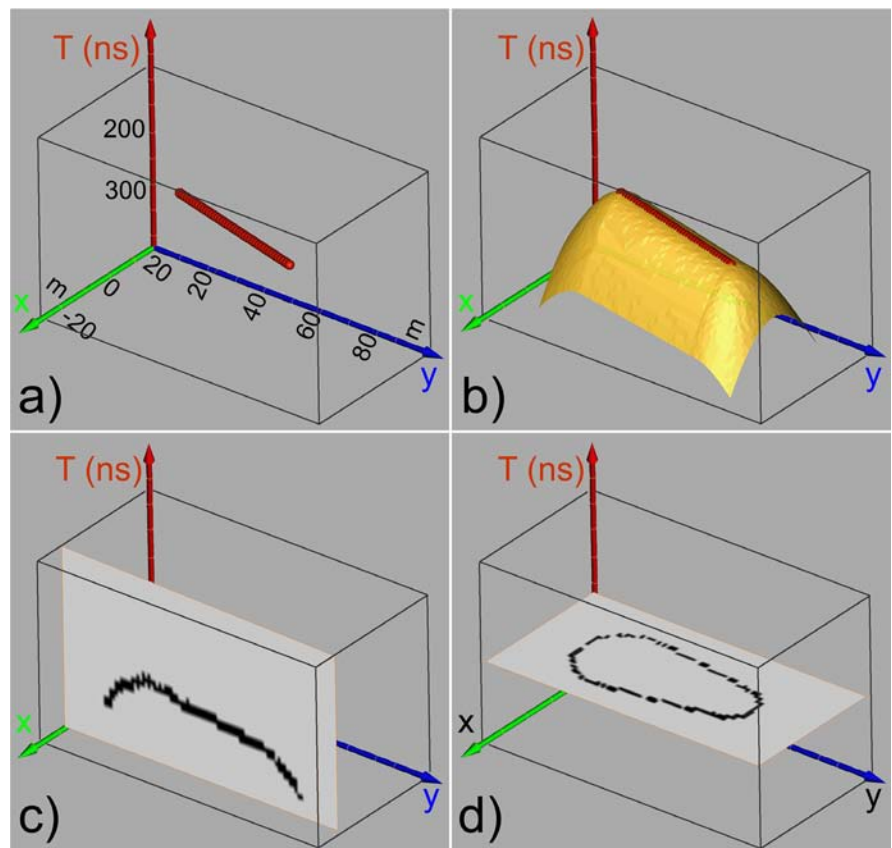


FIG. 10 - a) Numerical model of an ice-buried linear object with its top dipping from 16 m below the surface (near the axes origin) to 20 m below the surface. b) Diffraction hyperboloid computed via ray-tracing scanning the grid along the Y-axis. c) Synthetic response on a Y-scan (similarly to the real profiles 301-318). d) Synthetic response on a time slice.

progressively expanding as depth increases. The reflecting pattern in depth gets confused as it is “jammed” with the signal reverberated by a crevasse located just northwards.

Although the nature of these reflectors is still under investigation, the most convincing hypothesis is the presence of the remains of a tunnel in the ice similar to other tunnels that soldiers dug into several Alpine glacier during the military events of WWI.

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