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"WHITE WAR" AND GLACIOLOGY: ICE TUNNELS IN THE GLACIERS OF THE ORTLES-CEVEDALE GROUP (ITALIAN ALPS)

During the first world war many military operations were conducted on the Italian-Austrian alpine front, some at very high altitude (above 3000 m a.s.l.), in particular in the Adamello and Ortles-Cevedale ranges (the so-called "White War"). Although these operations had only minimal impact on the course of the conflict and overall strategic picture, their geomorphological and climatic context and the techniques used to fight and survive in an environment which is itself totally hostile, makes them extremely interesting. The high altitude operations, in particular in the widely glacialized Ortles-Cevedale group were known as the "highest battles in history" and described in numerous works, from classic accounts such as those by Viazzi, 1977; 1997; Langes, 1981; Magrin, 1994; Urangia Tazzoli, 1995; Lichem, 1996; Marseiler and others, 1998; von Lempruch and von Ompteda, 2005, to more recent ones by Magrin and Peretti, 2007; Fantelli and others, 2008; Martinelli, 2009.
The theatre of events was the largest glacialized area of the Italian Alps, with the highest peaks just under 4000 m a.s.l. During the first year of war imperial Austrian troops occupied the watershed between the Swiss border and Monte Cevedale, with permanent outposts on even the highest peaks - Koenigspitze (Gran Zebrù), 3857 m, and Ortler (Ortles), 3905 m.
Apart from the conditions imposed by the particular morphology of the terrain, such as the considerable differences in altitude (2600 m between Bormio and Koenigspitze) and the huge glacialized areas (the Forni Glacier at the time covered about 17 km^2, now shrunk to 11 km^2), it was the weather conditions that created the greatest problems for the two armies. Winter of 1916-1917 in particular was extremely harsh. Not only were temperatures particularly low (in February 1917 the meteorological station at Sils Maria recorded an average of -9.6°C, one of the coldest Februaries since 1864, and at Passo Gavia temperatures dropped to -32°C), but heavy snowfalls made hostilities all the more difficult and caused the greatest number of victims; the night of 12-13 December 1916 ("Black S. Lucia") 127 men on the Italian Stelvio-Gavia front were buried, and 56 of them died.
The rocky and glacial environment of the Ortler-Cevedale massif and the severe weather conditions meant that new techniques and logistical systems were required, not only to fight the enemy but above all for mere survival. On both sides of the front the experience of local personnel was crucial: alpine guides, mountaineers, and also non-military personnel with alpine experience, often specialists in the fields of geology or glaciology. An example of these techniques and adaptations is seen in the tunnels excavated in glaciers, which, apart from their primary purpose, also provided valuable experimental information to the new science of glaciology. The initial reason for digging the ice tunnels was purely logistical: shelter for troops and depots for materials (Galluccio and Cola, 2001). The best known of these is without doubt the *Eisstadt*, or "ice town", excavated by the Austrians in the Marmolada Glacier, which from early 1915 to late 1917 provided shelter for more than 300 soldiers in 12 km of tunnels.
In the Ortles-Cevedale range many tunnels were dug also for purely offensive objectives, such as the Trafoier in 1917 (Magrin and Peretti, 2007) (Fig. 1).

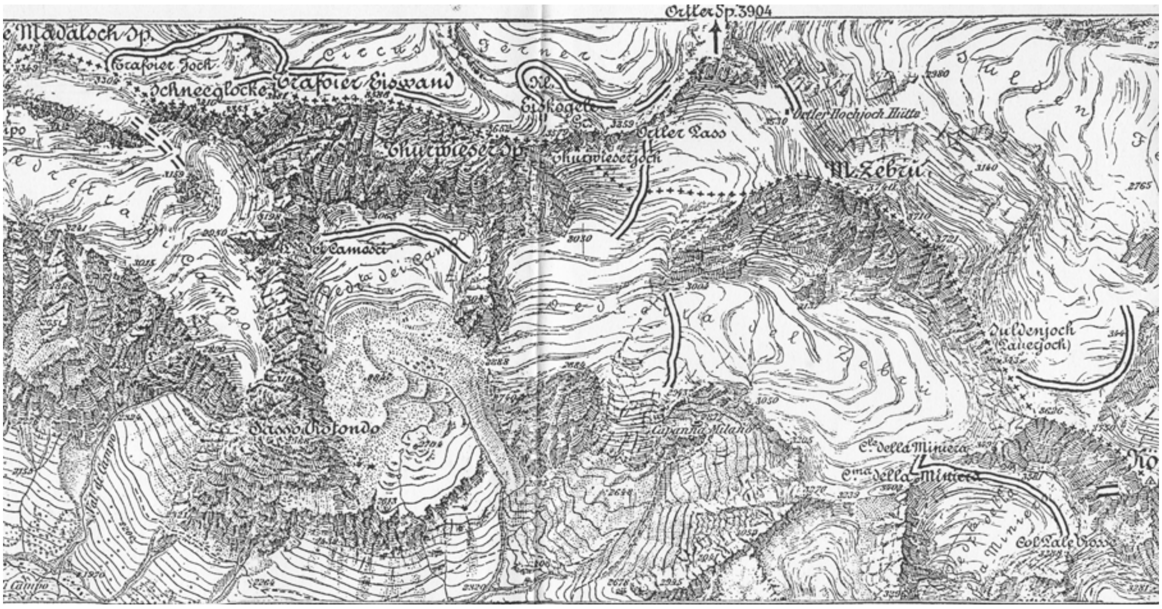

Fig. 1. *Ortler Massif in the map of Bertarelli (1923); the ice tunnels are roughly drawn.*

Bertarelli (1923), who participated in at least part of the works and after the war investigated almost all of the tunnels, summarized the works as follows:

- number of main tunnels excavated in ice: 16
- overall length: 11.4 km
- lowest altitude: 2940 m
- highest altitude: 3857 m (Koenigspitze), with a short section at 3902 m on the top of Ortler
- maximum length: 2000 m (the Colle delle Pale Rosse tunnel); two other tunnels were longer than 1000 m (Camosci and Trafojer Glaciers)
- max section: 3 m in width and 2.5 m in height (Capanna Milano tunnel- Zebrù Glacier) (Fig. 2); in all other tunnels the width was less than the height.


Fig. 2 – *The tunnel Capanna Milano – Zebrù Glacier*
(pictures by Guido Bertarelli, in Magrin and Peretti, 2007)

The tunnels were generally excavated using short-handled picks with at most two men working together. Early experiments with explosives and acetylene flame throwers met with little success; 10

hours of work per day by teams of 6-8 men advanced a tunnel section 2 x 0.80 m by 4-5 m. In addition to the mechanical difficulties of digging and the harsh work environment (such as, for example, lack of air), other problems faced included disposal of waste material (normally small fragments of ice chipped with the pick, removed with rudimentary wooden sledges), high temperatures and humidity in the tunnels and deformation of the galleries due to ice flow, entailing constant maintenance work (at least in the case of tunnels dug directly in glacier bodies and not through ice walls). Only a few years after the end of the war (between 1919 and 1921) many tunnels had already disappeared or were no longer practicable, in particular those excavated in glacier tongues. In 1921 two were still in good repair: one climbing from the Zebrù Glacier to Colle della Miniera and another dug in the south-west wall of the Koenigspitze (Bertarelli, 1923). Evidence of another tunnel was found in 2009 by one of the authors of this article (G. Magrin): traces of the transverse section of an Austrian tunnel 200 m long connecting Passo di Campo (3334 m) and Cima di Campo (3480 m). The section shows dislocation of ice layers and numerous metallic wires (Fig. 3).

Fig. 3 – *Last evidence of the Austrian tunnel*
Cime di Campo- Punta Spiriti (picture by G. Magrin, 2009)

The excavation of the ice tunnels, their maintenance and use provided useful information for the new science of glaciology, as described by Bertarelli (1923) and mostly by von Klebelsberg (1920).
As Bertarelli (1923) observed: "A specialist in glaciology would have learnt much from the significant experience of two years of conflict which, from the point of view of some habits and practices, had already been put into practice under the profane and watchful eyes of the rugged soldiers intent in fighting the valorous enemy at such high altitudes. An observer would, from the variety of positions, altitudes, and directions of tunnels, have been able to make some significant deductions for the study of alpine glacier movements".
In the early years of the 20th century glaciology had not yet moved on from the "Lewis school", which emphasized geographical, physical and geological aspects of glaciers, to the "Nye school", which emphasizes mathematical and physical factors, and the "Röthlisberger school", which favours geophysical aspects (Clarke, 1987). Nevertheless most of the fundamental concepts for the study of glaciers were soon established, enabling further development of the discipline (Knight, 2011). By the middle of the 19th century there were already heated discussions underway on topics such as the mechanisms of glacial flow, involving Agassiz, Forbes, Hopkins and Tyndall (Walzer & Waddington, 1988) and subsequently taken up by Marchi, Hess, Weinberg, and later again by Deeley and Parr, who wrote about the viscosity of glacier ice in 1914.
The observations made in ice tunnels during the first world war, especially in the Ortles-Cevedale group, while not rigorous and systematic, except those by von Klebelsberg, 1920 on the Austrian side (their primary function was obviously not scientific), nevertheless provided a rich source of empirical data for the fledgling glaciologists (it should be noted that the most noteworthy and influential works by Somigliana date from the 1920s and those by Nye and Glenn from the 1950s).
One of the most important "practical" data acquisitions concerned glacial flow and its viscoplastic or "non-linearly viscous" characteristics (Cuffey & Paterson, 2010), observed by Bertarelli (1923) in the

Capanna Milano tunnel on the Zebrù Glacier. In particular he described the rapid movement and crushing of the tunnel, with intense lateral torque and evident pressure pushing from below to above (this is the emergent component of ice velocity postulated by Reid (1896), which seemed a paradox to many contemporaries). Bertarelli (1923) also describes observations he made of the greater rigidity of superficial ice, along with its greater velocity compared to deeper ice, which has a higher plasticity, and the reduced velocity of flow in ice-cap areas, such as the peaks of the Ortles or the two peaks of the Eiskogele (Coni di Ghiaccio).

Other interesting observations concerned the various components of glacier mass balance, in particular the importance of supplies of wind-drift snow in accumulation basins, compensating for ablation effects at lower altitudes, and the rapid processes of metamorphism which also in winter – again in ice-cap areas - transform snow into ice. These observations were made at the two Eiskogele, where the tunnels were excavated exclusively through compacted ice and not snow, and showed only very few variations in section width. Avalanche snow, while abundant, showed instead only very slow metamorphism and even when compacted was too weak and unstable for excavation of tunnels, as was seen at the Camosci Glacier tunnel.

Finally, Bertarelli made some particularly interesting observations concerning differences in flow and the resulting differences in lifespan of the tunnels dug in glacial tongues, i.e. in the body of the glaciers themselves, as against those excavated in ice walls above terminal crevasses. The former, as seen in the Capanna Milano tunnel on the Zebrù Glacier, required laborious and constant maintenance work, due to the movement of the glacier (10-30 m per year), with most flow due to basal sliding; the ice wall tunnels on the other hand, although steep, were, according to Bertarelli (1923), "almost completely static and remain unaltered, at high altitude, for many years". In particular the tunnel from the Zebrù Glacier to Colle della Miniera never needed any maintenance during the year and a half it was in use. Despite the considerable gradient of the upper section (40°- 60°), movement was practically imperceptible and it was still in good condition in August 1921. These were probably the first experimental observations of the different mechanisms of accumulation and ablation, and therefore of flow, between glacier tongues and ice walls. In the case of the latter, flow is extremely slow, due mainly to internal deformation, a characteristic of cold ice. It is highly likely that these tunnels were excavated in cold ice. Considering the altitudes of the tunnels and their exposure (3410-3588 m north face, for the Scheneeglocke-Trafojer Eiswand tunnel; up to 3553 m northwest face for the Zebrù Glacier - Colle della Miniera tunnel; 3434-3444 m northwest face for the Passo Sulden (Solda) – Mitscherkopf tunnel), the presence of cold firn and cold ice seems highly probable. According to Suter and others, 2001, based on calculations made using a multiple linear regression model and input data provided by measurements of the temperature of the firn, altitude and exposure, the lower limit for *probable* presence of cold firn in the Alps should be 3400 m for north faces and 3600 m for northeast and northwest faces. The limit for *possible* presence of cold firn is 3000 m for all the above exposures. In fact even in the tunnel excavated at about 3400 m in the south-west wall of the Koenigspitze, Bertarelli (1923) observed that the ice was quite static and the tunnel still intact in 1921.

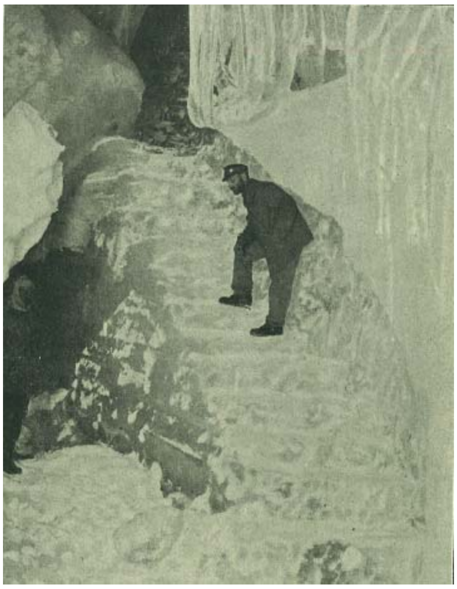
Fig. 4 – *The tunnel in the Cristallo Bergschrund*
(picture by Von Klebelsberg, 1920)

Many deep and thorough field observations were made on the tunnels of the Austrian side (especially Cristallo, Madatsch, Trafojer, Ortler and Koenigspitze), by Von Klebelsberg (1920), who between 1914 and 19I7 served his country as an artillery officer, and in 1918 as a war geologist (fig. 4). Von Klebelsberg is one of the "father" of glaciology and glacial geomorphology and the results of his observations mainly on the structure of firn and ice and on the glacier dynamics collected in the war ice tunnel (Von Kleberlsberg, 1920), were really significant and innovative, even if their international dissemination was rather limited.
After the direct observations in and about the ice tunnels made by Bertarelli in the immediate post-war years, no other surveys were made for the purposes of acquisition of scientific data. As Bertarelli (1923) wrote: "It would be interesting to be able to observe the state of repair of these military tunnels for a few more years, until they disappear. They could provide further information useful to glaciology. But for those who lived in them for three long winters, their scientific value must take second place, for us the tunnels evoke a kind of bitter nostalgia. The loss of these relicts of war is, at least in part, melancholic. But perhaps the obliteration of these reminders of tragedy brings hope for the future: they return to nothing, distant memories, never to return".

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