The Italian Military Tunnels in World War I*

Le gallerie militari italiane nella Prima Guerra Mondiale

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Abstract
During World War I, particularly in the years 1915-1917, all along the Italian front, spreading from the Aosta Valley to the Gulf of Trieste, intense tunnel excavation works were carried out for diverse military purposes. Some of these underground works, many of which are still well preserved and can be visited thanks to the constant effort in conservation and restoration done by local Authorities, are impressive considering the difficult environmental conditions and the technical challenges that had to be faced for their realization. A remarkable literature exists on this subject both from the historical and biographical point of view. This paper, instead, focuses on technical and technological aspects, on material resources, manpower, design and construction means and methods used to build tunnels which nowadays seem to be extraordinary in relation to the period in which they were completed and to the difficulties encountered during the execution.

Sommario
Durante la Prima Guerra Mondiale, particolarmente negli anni 1915-1917, lungo tutto il fronte italiano che si estendeva dalla Valle d'Aosta al Golfo di Trieste, furono portate a compimento intense attività di scavo di gallerie per diversi scopi militari. Alcune di queste opere sotterranee, molte delle quali ancora oggi ben conservate e visitabili grazie al costante sforzo di mantenimento e restauro delle Autorità locali, sorprendono in considerazione delle difficoltà ambientali e delle le sfide tecnologiche che hanno dovuto essere fronteggiate per la loro realizzazione. Sussiste una vasta letteratura che tratta questo argomento soprattutto sotto i punti di vista storico e biografico. Questo lavoro vuole invece focalizzarsi sugli aspetti tecnici e tecnologici, sulle risorse umane e materiali e sui metodi di progetto e di costruzione utilizzati per lo scavo di gallerie che, oggi, appaiono straordinarie in relazione al periodo storico e alle difficoltà incontrate nel corso degli scavi.

Keywords: war, military, tunnel, mine, explosive.
Parole chiave: guerra, militare, galleria, mina, esplosivo.

1. Introduction

This paper deals with the tragic relationship between the art of tunnelling and war, the latter synonymous with death, suffering, deprivation. This relationship deserves to be recalled, beyond the mere technical interest of the topic, in honor to all soldiers who took part in this tragedy.

In its present form, this paper represents a further improvement and elaboration of that presented at the World Tunnel Congress 2020 in Naples [29], that was inspired by two interesting articles appeared on Tunnels&Tunnelling [6] [27] and from watching the Australian movie *Beneath Hill 60* directed by Jeremy Sims, both relating to the military tunnels excavated during WWI on the Franco-German front of the Marne. For this reason, the first part of the study refers to experiences that were gained in theaters of war having different geological and geomechanical contexts as well as very different boundary conditions compared to the Italian-Austrian front.

Along this last theater of war, tunnels were built in a mountainous territory, often at altitudes above 2000 m a.s.l. and therefore in logistical and environmental conditions decidedly more difficult (think about the extremely snowy winters back then, with very rigid temperatures), in generally good rock masses, requiring the continuous and massive use of explosives. Their construction covers a period that extends from a few years before the declaration of war (24 May 1915), for the preemptive preparation of defensive fortifications, until the end of war (4 November 1918) and their geographical location involves the whole front the Gulf of Trieste to eastern Lombardy and extends further West to include the Ticinese region (Figure 3). The paper only concerns the works carried out by the Italian Army, although the Austrian works can certainly not be considered inferior both from a technical point of view and for the commitment and value shown in their accomplishing. This essay will focus primarily on the most relevant underground works, completed in the period 1915-1917 on the eastern-central portion of the front itself, bounded on the West by the Adige valley and on the East by the Tagliamento river (Dolomites region). This is in fact the sector where, with few exceptions, the opposing

armies have mostly exploited the underground, not only for logistic purposes (deposits, walkways, shelters, etc.), but also as a real offensive tactical tool. Indeed, the most articulate and demanding works are represented by the Mine tunnels, used to reach a point below enemy defensive positions and create a breach by blasting huge quantities of explosives.
On the contrary, the cavities built further West, on the Swiss border, in anticipation of a German invasion through this nation, were not used; nevertheless, they still constitute a peculiar example of strategic foresight and represent a significant technical and financial commitment for that time, even if fewer than those on the real war front.

2. First experiences of "tunnel warfare"

Based on Enrico Fossa Mancini's fundamental study in 1925 [15] the origins of both the passive (refuges, warehouses and infirmaries) and the active underground works (Mine tunnels) can be traced. For example, during the American Civil War in Pittsburgh, the Unionist Army, in order to conquer the Confederates fortifications, dug a system of tunnels through clayey and sandy-clayey layers down to the enemy entrenched field. These tunnels were filled with gunpowder and on the morning of July 30, 1864 they were blown up, causing the formation of a huge crater and heavy losses to the enemy [28].
The real development of the "tunnel warfare", however, began with the First World War on the northern European fields. Underground works, both defensive (shelters dug perpendicular to the trenches and directed towards the rear, used as headquarters, dormitories or warehouses) and offensive (Mine tunnels) [6] [11] [27] on the western front, were mainly excavated in soft rocks and cohesive soils, in which manual excavation techniques were possible (Figure 1) and where the main obstacles were represented by the presence of surface aquifers or low-depth resistant bedrocks.
A German military manual of geology cited in [15] classified soil according to six degrees of workability: 1° - with the shovel only; 2° - with the hoe; 3° - with the pickaxe; 4° - with sledgehammer, crowbar and iron wedge; 5° - with the above mentioned means and the aid of explosives; 6° - with explosives only.
In the case of defensive works, the natural thickness of the covering ground had to withstand the artillery bombing [15]. It was generally believed that either a layer of compact soil of about one and a half meters, or a rock layer of about seventy centimeters, was needed to make light artillery ineffective. For heavier artillery the thicknesses were much higher. According to the Germans, medium to high calibers would require eight meters of ground, while for safer shelters at least twelve meters of ground were required. The British, who had to sustain calibers up to 420 mm, needed fourteen meters of soil, or seven meters of rock. Favorable events were those where resistant layers alternated with soft layers: in this way it was possible to dig the shelter in the soft rock, having the most tenacious rock at the ceiling. The Germans in Flanders have thus exploited limestone banks alternating with Eocene argillites to build efficient shelters.
In an article also presented in WTC 2019 (Figure 2), M. Diederichs and D.J. Hutchinson [11] have studied the stability of the tunnels of Vimy Ridge, North of Arras (France):
«During WWI, the Allied and German troops faced each other from trenches located across a narrow strip of land known as No-Man's Land. A network of long subway tunnels, driven from a distance of several kilometers away constructed by hand and used to transport equipment, materials and troops to the front line in the relative safety afforded by covered, under-ground access. Shallow communication tunnels were constructed at shallow depths under very thin crown pillars. Troops found shelter in larger dugouts excavated adjacent to the network of trenches. The type of construction depended upon the depth below surface and the earth material into which the structure was excavated. The deepest of these dugouts were built to withstand direct shellfire and therefore needed an adequate cover of undisturbed rock overhead, usually between a minimum of two meters for light artillery fire and 16 meters to withstand heavy fire. The fresh intact chalk had strengths of UCS = 5 to 13 MPa and Young's modulus between 10 and 20 GPa.»

Figure 1. Clay kicking, a tunneling technique from the North-West of England that found application in the trenches in soft rocks and cohesive soils on the Marne front [27].

3. The Italian - Austrian front

3.1. Geographic and geological framework (see [1] – [5] e [8]])

Figure 3 shows that at the opening of warfare the active Italian-Austrian front covered over 800 km, from the border with Switzerland in the Upper Valtellina to the Gulf of Trieste, mostly mountainous with definitely alpine stretches. In some cases, the emplacements were at altitudes of over 3000 m a.s.l. (Adamello and Marmolada massifs).
As shown in Figure 4, the area included in the southern Alps South of the Periadriatic Fault is a tectonic unit with characteristics clearly different from those of the other Alpine structural units. The schistose-crystalline rocks, mostly phyllite, are common only in the basement, while the powerful sedimentary caps, mostly from the Mesozoic age, are dominant. The covering layers are small, whereas in the western part décollements and slidings are frequent. The structural movement is given by a succession of folds, fold-nappes, and tilted scales, mostly verging to the South. There are impressive magmatic masses both intrusive, like the Adamello tonalitic mass, and effusive like the powerful castings of Permian Quartz-porphyry of the Porphyric Atesina Platform [10].

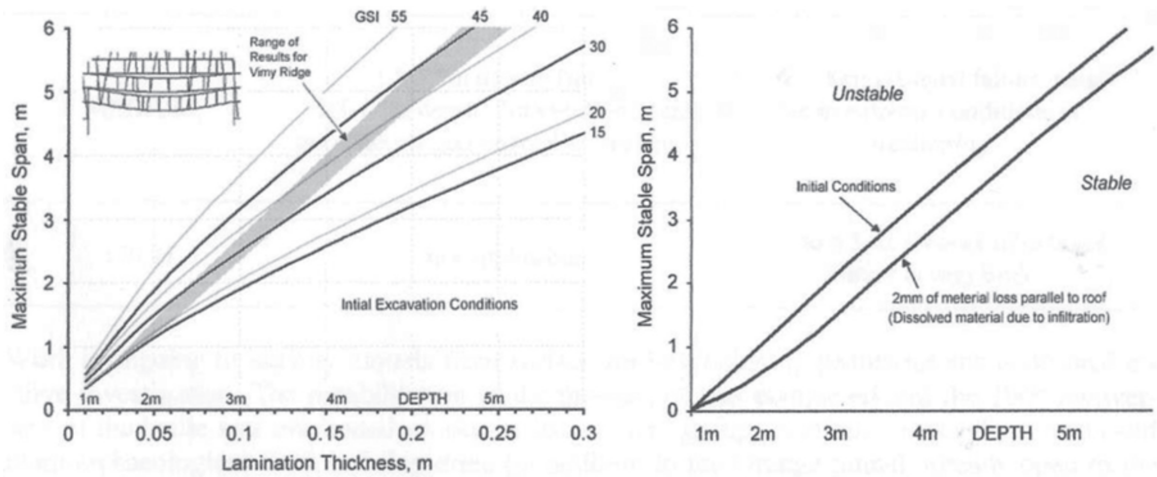


Figure 2. Voussoir beam analysis of vertically jointed, horizontally laminated chalk roof (left), including (right) material loss in vertical jointing [11].

Information about the rocks crossed by the main underground operations carried out during war are provided below, marked with the letters in Figure 3, proceeding from West to East.

A. Monte Zugna - The underground works cross metric layers having a structure composed of dolomite and limestone rocks referable to the Dolomia Principale and the Grey Limestone Unit, which are often subject to important karst phenomena.

B. Pasubio - The Pasubio is a carbonate, dolomitic and, in the upper parts, also partly calcareous massif: the tunnels therefore cross both limestone and dolomites, as the excavations were numerous, spread and very articulated. The formation characterizing the area is the Dolomia Principale: dolomite sediments of carbonate platform, reaching over eight hundred meters in thickness. These are crystal-dolomite rocks in large banks, alternated with micritic dolomites (fine-grained) and stromatolite dolomites.

C. Monte Grappa - Sedimentary organogenic carbonate rocks, formed by accumulation of algae and shallow sea organisms (limestone): they are compact and fine-grained. The units crossed are those of the Gray Limestones. Some outcrops confirm a non-massive but largely grainy texture, with a rock that is not very compact and tends to flake apart.

D. Marmolada - Here we have massive gray limestones, debris and stromatolites. It is the Marmolada Limestone Formation, resulting from coral cliffs, at whose bed appears at times the Livinallongo Formation composed of nodular and tuffite limestones, also found in the area of Col di Lana, described below.

E. Col di Lana mountain - In the area affected by the tunnels, the Wengen Formation and, more occasionally, the Volcanoclastite Submarine Landslide Accumulations Unit are crossed. The Wengen Formation includes mixed volcanic carbonate (tuffite) deposits with massive texture. Immediately in the bed of these two formations there is the Livinallongo Formation often heterotopical to the Sciliar Massif.

F. Lagazuoi and Castelletto di Rozes - The tunnels are located in the well-layered light gray Dolomia Principale, having at its base silts, shales, and multicolored marlstones of the Raibl Formation and further underneath the crystal and massive Cassiano Dolomites

G. Carnia - The Carnica or Paleocarnica chain is mainly made up of Paleozoic rocks like metagraywackes, metaconglomerates and metamudstones. These formations are overlapped to the South by marble, limestone and metalimestone. The Carboniferous is characterized by deposits of argillites, sandstones and blackish brown siltstones that form the so-called Pontebba Permian-Carboniferous, shaped by over 2000 m thick delta and marine platform sediments, that lie with discordance on the Hercynian substrate, and the post-Hercynian Paleozoic sequence represented by continental sediments with red beds (Val Gardena Sandstones).

H. Monte Rosso - Monte Nero Chain (Krn – currently in Slovenian territory) - Massive limestones, with regular and massive layers, sometimes in banks. Among the crossed formations it is worth mentioning the Scaglia Rossa (sedimentary fossiliferous marine rock, siliceous-calcareous lithology) and the Dachstein Lime-

Figure 3. Austrian-Italian front 1915-1918. A: Monte Zugna. B: Pasubio. C: Monte Grappa. D: Marmolada. E: Cima Col di Lana. F: Lagazuoi and Castelletto di Rozes. G: Carnia. H: Catena Monte Rosso - Monte Nero. I: Carso. Drawn up by the authors on image from [13].

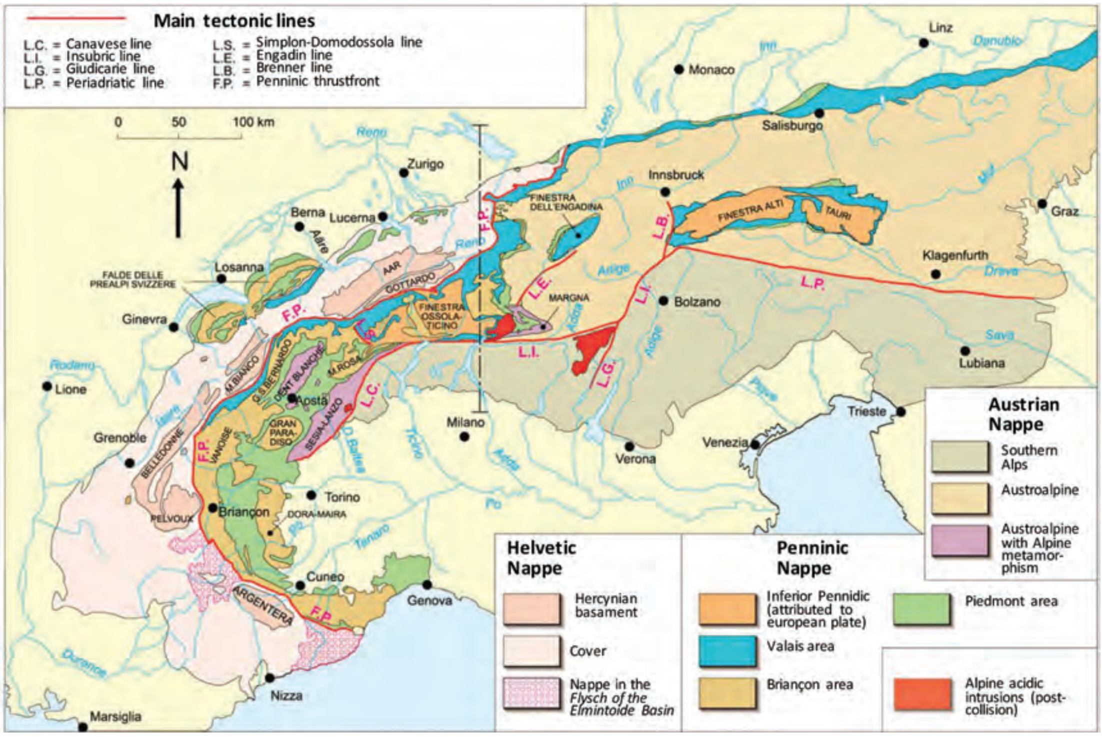


Figure 4. Tectonic Scheme of the Alps. Drawn up by the authors on image from [14].

stone, the latter outcropping on Monte Nero and almost similar in its composition to the Grey Limestones of Monte Grappa.

I. Carso - Here we have white bioclastic limestones, massive or rubbles with dolomite clasts as well as whitish stratified limestones with residual clays. The main outcrops are the Liburnian Formation, the Aurisina Limestones, the Monrupino Formation, and the Monte Coste Limestones. There is a widespread and imposing speleogenesis.

3.2. The forces in the field

Compared to all previous conflicts, the peculiarities of this war consist in the use of the most recent technological innovations and, above all, in the presence of a huge number of men and vehicles close to the front barely moving and exposed to the shooting of cannons and machine guns. The defense works carried out before 1915 were punctual and spread over a few stretches, ending up for not being useful to the economy of the conflict: many were located at the border of Switzerland and France, thus anticipating different strategic scenarios.
The Italian Army faced the first war operations mobilizing 31,000 officers, little over 1,000,000 troopers and 11,000 civilians. At the end of the war, these numbers reached three times higher values [20]. In particular, the Military Engineers rose from about 12,000 units in 1915 to 110,000 (equal to one ninth of the Infantry) in 1917, reaching at the end of the war 170,000 mobilized (equivalent to one fifth of the Infantry) [23]. No other corps underwent a similar increase, a clear sign of the importance of engineering and, above all, of underground works (Figure 5). For example, before war the 5th Specialist Miners Regiment (Figure 6) had 13 units but in 1918 ended with 53 [23], reasonably meaning about 11,000 men, plus the *centuriae* (civilians directly dependent on the Army) and private companies still working behind the lines. An approximate reckoning of workers, involved by the Military Engineers but not part of its troops, was of 110,000 men in 1917 for the *centuriae* and 650,000 civilian workers throughout the war [23]. During operations a subspecialty "Motorists" of the 5th Military Engineers Regiment was created, along with a test center in Milan in contact with the national supplier of drilling groups. Each Italian Army set up a repair workshop with the task of training personnel [23]. It is evident, that what at the beginning of the war had a punctual and unsystematic use, at the end of the war had turned into a real industrial sector.

3.3. The works

It is almost impossible, at present, to analytically quantify the action of the Italian Army in the field of underground works during World War I. Neverthless, we will try to give, through the most striking examples, a picture of the effort.
It is on the Carso that the Italian Army faced the new type of war in July 1915, when the High Command considered the opportunity to resort to underground works. But everything remained hypothetical because of the lack of skilled labor and technical means until January 1916, when the High Command, also seen the experiences of the cobelligerents, gave broad and prevalent development to mine works for offensive purposes on the heights of Santa Lucia di Tolmino at the base of Mount Krn, of Podgora in front of Gorizia and of San Michele del Carso. It should be noted that only then the High Command ordered the requisition of materials suitable for that purpose from firms operating in the mining

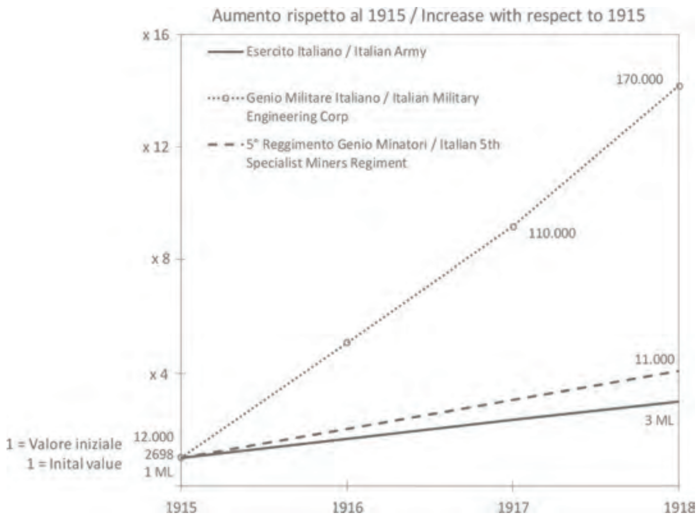


Figure 5. Increase in Italian forces during the war [20] [26].

sector and gave the Army Technical Office a mandate to make a census of the existing equipment at national level.
A first project concerned "Cima 4" of San Michele del Carso (Figure 7a), where two 80 m long Mine tunnels had chambers loaded each with 125 kg of explosives. Many other proposals were made, but the works proceeded slowly even for the lack of specialized men: consider that the 1st Unit of the 5th Specialist Miners Regiment did not have the necessary fleet and only 10 soldiers were miners by profession [12] [37].
These data give the idea of the organizational effort then carried out by the Italian Army: from isolated and local episodes at the beginning of the war, the tactics of underground warfare became general and organized at the end of the war, with part of the Italian industry that specifically produced new explosives, drillers, electricity generator, pumps, fuses, and anything else that was required. The experience was gradually spread through memos, manuals and books, involving also the Italian mining schools.
On the Monte Zugna, a massif comprising Coni Zugna (1772 m a.s.l.) and Cima di Levante (2020 m a.s.l.), the Mines and Countermines warfare continued until September 1918 through wells and tunnels. The following data on the excavations as of December 31, 1917 are given as an example: a steep slope 20 m long tunnel for hearing out the Austrian works; a 8 m deep shaft from which a 14 m tunnel and another 24 m tunnel with a 25% gradient start. A great number of natural cavities came upon during the works [7].
On the Pasubio (2239 m a.s.l.) (Figure 7b and Figure 8a), around 10 km of tunnels and 500 km of roads were built, 1500 explosive charges were burned every day, 100 km of compressed air pipes and 60 km of water pipes were laid [23]. Among others, the works included also a 110 m long helical tunnel with a 2.2 x 2.5 m section, a 190 m long tunnel with a 2 x 3 m section and another one of 140 m with a 2.5 x 2.5 m section (Figure 9). Excavations were carried out with an average production of 6 m^3 per day. Five hammer drills were used, while electricity was supplied by a Ballot generator together with a portable generator for ventilation [12]. This massif is mainly famous for the "Road of 52 tunnels" which starts at Bocchetta Campiglia (1216 m a.s.l.) and ends at the Porte del Pasubio (1928 m a.s.l.) with a total of 2300 m of tunnels along a 6300 m long path [16]. Daring works are to be seen also on Mont Cengio, at the edge of the plateau of the Sette comuni (Asiago) (Figure 20).
On the Monte Grappa (1775 m a.s.l.) there is the "Vittorio Emanuele III" tunnel system (Figure 8b), built in just 10 months, which has a main branch of 1400 m and 5100 m of underground works; it housed 23 artilleries of which six 105 mm cannons, plus machine guns, food storages, water tanks and ammunitions [34]. It could accommodate 1500 soldiers and the deposits, along with the 50 to 200 m^3 water tanks, guaranteed 15 days of self-sufficiency [25]. It is worth remarking (Figure 3) that Monte Grappa is much further South of the front line at the beginning of the war. The defensive system was built well before the advance of the Austrian Army in October 1917 and, together with the Piave River, it represented a strategic bastion that proved to be insurmountable allowing to stop the said advance.
The Marmolada is famous for the tunnels excavated within the glacier, even above 3000 m a.s.l., although the military engineers of the two armies also excavated hundreds of meters of limestone rock tunnels: the approx. 230 m long "Rosso" Tunnel can still be visited today. (Figure 10a).
The Piccolo Lagazuoi (Figure 10b, Figure 11, Figure 12, Figure 13, Figure 14) was not only the theater of Alpine warfare, but also of

a)


b)

Figure 6. (a) Old postcard of the Mining Corps of Engineers (authors' property). (b) Frieze of the 5th Engineer Regiment [32].

a)


b)

Figure 7. (a) Tunnel "Generale Papa" at the Pasubio. (b). The tunnels of San Michele del Carso (authors' photos).

daring engineering achievements. Consider that to load the Mine with 33,000 kg of explosive Italian soldiers dug a helical tunnel about 1100 m long, with a difference in height of 250 m and a gradient up to 60%, that required the use of steps (reaching 2660 m a.s.l.). The tunnel was 1.90 m high and equally large and the excavations advanced at a rate of 5.5 m/day [12]. Here the engineers did not use dynamite for charging the Mine, but gelatin and Echo (please refer to par. 3.4).

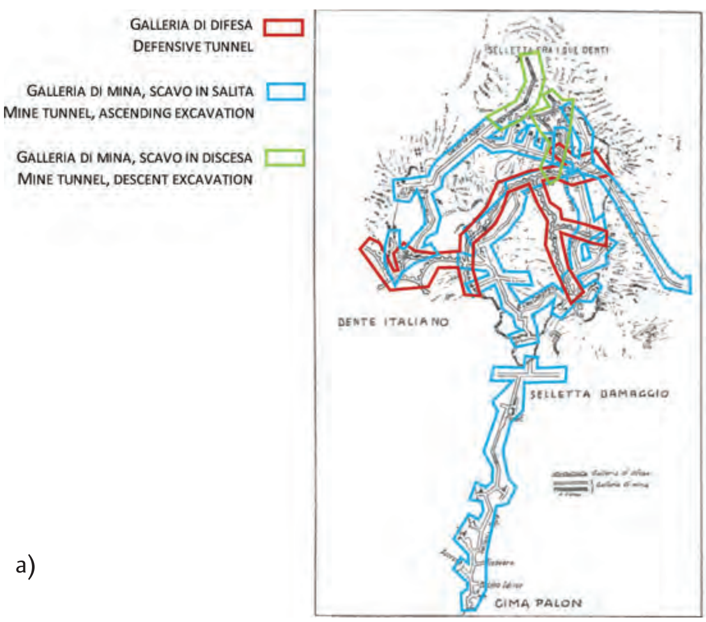
At Castelletto (2657 m a.s.l.) of the Tofana di Rozes (Figure 15, Figure 16a) a 500 m long tunnel was excavated in a very steep slant for 2200 m^3 of total rock, with a large Mine chamber in which 35,000 kg of explosive were blasted on 11 July 1916 [30]. The explosion destroyed the enemy lines, but the huge amount of toxic smoke also caused the fainting of many of the aggressors crowded underneath the Mine chamber, apparently without sufficient distance and with decidedly poor ventilation. The attack was resumed after some time and the Castelletto was conquered, since the remaining part of the Austrian garrison had not yet reorganized and recovered from the daze due to the explosion rumble.

With regard to the shooting of enemy lines on the top of Castelletto, the tunnel adit (Figure 16b, Figure 17) was placed in a sheltered position within a natural ravine; it required the overcoming of significant difficulties in logistics.

As previously mentioned, Mine tunnels are among the most complex and demanding works carried out. Table 1 summarizes the main data of the most important Italian Mines and Counter-mines. We must not forget that the opponent was equally busy digging tunnels and caverns: worth mentioning are the Mines at Monte Cimone (14,200 kg), the one at the Lagazuoi (24,000 kg) and that at Monte Sief with 45,000 kg of explosives (Figure 18) exceeded only by the 50,000 kg Mine at the Pasubio.

As described above, underground works mostly involved rock masses belonging to dolomitic- limestone contexts with discrete, and often good, geomechanical properties. Compact gneisses were crossed in the Mine tunnel of San Fedele di Verceia at the mouth of Valchiavenna and porphyries in the cave of Monte Piambello (Varese) [35].

The underground environment visited by the authors (tunnels,



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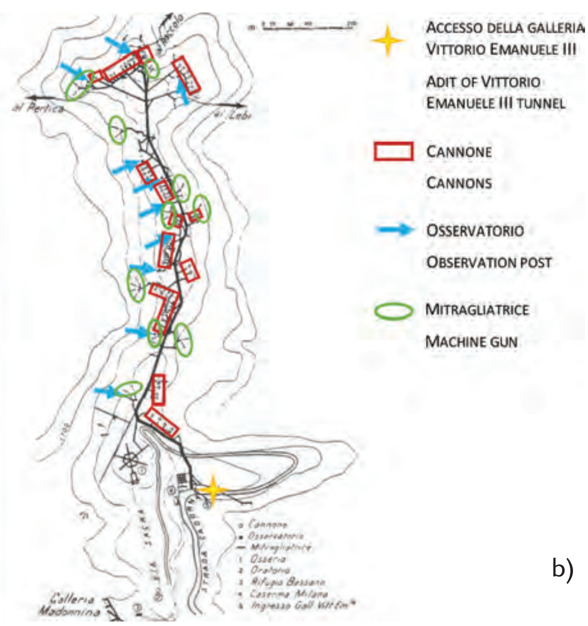

b)

Figure 8. (a) Network of Italian tunnels on the Pasubio. Drawn up by the authors on image from [31]. (b) The complex of tunnels of Monte Grappa. Drawn up by the authors on image from [34].

Figure 9. Road of 52 Tunnels on the Pasubio massif. (a) Twentieth tunnel. (b) Scheme of the Twentieth tunnel [18].

underground passages, shelters, road tunnels, caves for protection or artillery) at Pasubio, Lagazuoi, Castelletto, Monte Mrzli, Monte San Michele and Carso, are unlined and after more than 100 years still remain mostly undamaged. They were affected by releases only along small stretches in particularly fractured areas, especially at the entrances.

The reports regarding the construction of these tunnels, either for shelters and warehouses or Mines, provide exclusively the description of the threats caused by the enemy with the Countermine tunnels. The rock characteristics or the need for stabilization operations are almost never mentioned: an obstacle was rather the mechanical resistance to the drilling slowing down works.

An exception is the Monte Nero area, belonging to a complex of Italian and Austrian tunnels in the Julian Alps, starting from

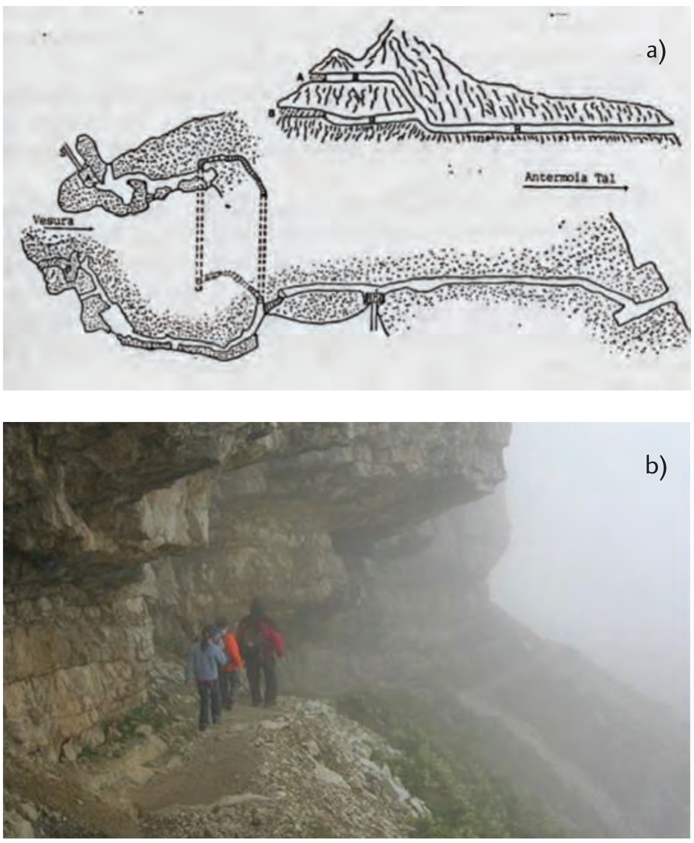

Figure 10. (a) A sketch of the “Rosso” Tunnel on the Marmolada massif, whose entrance was freed from the ice a few years ago [12]. (b) The Cengia Martini still testifies the professional skills of the Italian Army in providing defense works: here too the toughness of the rock mass has preserved this road, nowadays used by those who visit the war tunnels (authors’ photos).

a)

b)

Figure 11. (a) Lower entrance of Lagazuoi tunnel (authors’ photos). (b) Lagazuoi tunnel (photo by Giacomo Pompanin).

a) b)

Figure 12. (a) The Lagazuoi massif (authors' photos). (b) Lagazuoi from an old publication[17].

Pontebba, Val Dogna, Rombòn, Canin up to Monte Rosso, nearby Monte Nero itself. Indeed, for this area the records describe incoherent and very fissured rock that required major reinforcement works; not far, East of Caporetto, the excavation on Mount Mrzli also unearthed brittle mass, and on Mount Zugna, reports describe excavations in fissured rocks [12].
A unique case is the tunnel in the Popena torrent (Figure 19), in the Cristallo group: in 1916 some units of the 54th Infantry Regiment dug an about 350 m long tunnel, partially located under the bed of the torrent and in loose materials [12] with a ten meters cover. The advancement speed, despite water inflow and incoherent soil, reached 2 m/day. The coating consisted of 6 cm thick planks, with an excavation section up to 2.2 x 2.0 m. Unfortunately, on the 19th of June the entrance caved-in, blocking the tunnel, while on the 9th of July great parts of the tunnel were destroyed by the opposing artillery causing it to be abandoned.

Figure 13. Lagazuoi tunnel (photos by Giacomo Pompanin).

3.4. Technological aspects

3.4.1. Explosive

Many types of explosives were used during warfare depending on the need [12]:
- gunpowder (75% potassium nitrate, 13.50% charcoal and approx 11.50% sulphur);
- dynamite (nitroglycerine);
- explosive gelatin (92% nitroglycerine and 8% colloidon);

Figure 14. Lagazuoi tunnel (authors' photos).

Figure 15. (a) Castelletto tunnel. (b) Access to Castelletto tunnel (authors' photos).

Table 1. Some of the Italian Mines and Counter-mines.

Date	Type	Location	Amount of Explosive [kg]
17/4/1916	Mine	Col di Lana	5000
12 in 2016	Counter-mine	Carso	
11/7/1916	Mine	Castelletto	35,000
31/7/1916	Counter-mine	M. Mrzli	
1917	2 Counter-mines	M. Sief	3600 and 5000
1917	3 Mines	Colbricon	
8/6/1917	Mine	M. Zebio	1000
10/6/1917	Mine	M. Rotondo	
23/6/1917	Mine	Lagazuoi	33,000
1917	2 Mines	M. Mrzli	
16/8/1917	2 Mines	M. Rosso	
1917	2 Mines	Pasubio	13,000 and 1000
1917	2 Mines	Marmolada	500 and 1000
1918	3 Counter-mines	Pasubio	1200 in one
1918	2 Counter-mines	M. Zugna	825 and 2100

– Echo (60% ammonium nitrate, 25% aluminium powder, with percentages of nitrocellulose and coal);
– cheddite (a chlorates-based mixture);
– sabulite, nitranite or siperite (mixtures of over 70% ammonium nitrate and gunpowder).

The trigger could be made of either 1.2 gram mercury fulminate caps or pyroxylin (nitrocellulose with a high nitrogen content) – Table 2.

The Italian monthly production of gelatin was 80 t per month in 1916 [12]: it is thus possible to comprehend the organizational effort needed to provide the Mine tunnels (please refer to Table 1). With explicit regard to Mines, the Manual [21] outlined the effect of dynamite in underground excavations, with the formula: (1):

$$C = a \cdot m \cdot h^3 \qquad (1)$$

where C = charge necessary to create a crater on the surface; *a* = type of explosive; *m* = parameter depending on lithology; *h* = depth of the Mine chamber. The Manual provides, among other things, a first classification based on the quality of the rock masses, indicating the data required for excavating tunnels. Some of the *m*-values are shown in Table 3; total explosive consumption is summarized in Fig. 20.

3.4.2. Drillers

The Manual [21] also illustrates that before drillers came out, two workers were needed to open a Mine hole: one holding a long steel rod and propping its end shaped for cutting, and the other hitting its head with a bat. The rod had to be rotated at each hit and the resulting hole needed to be repeatedly cleaned up; with a rod diameter of 3 cm a 4 cm hole was obtained. Moreover,

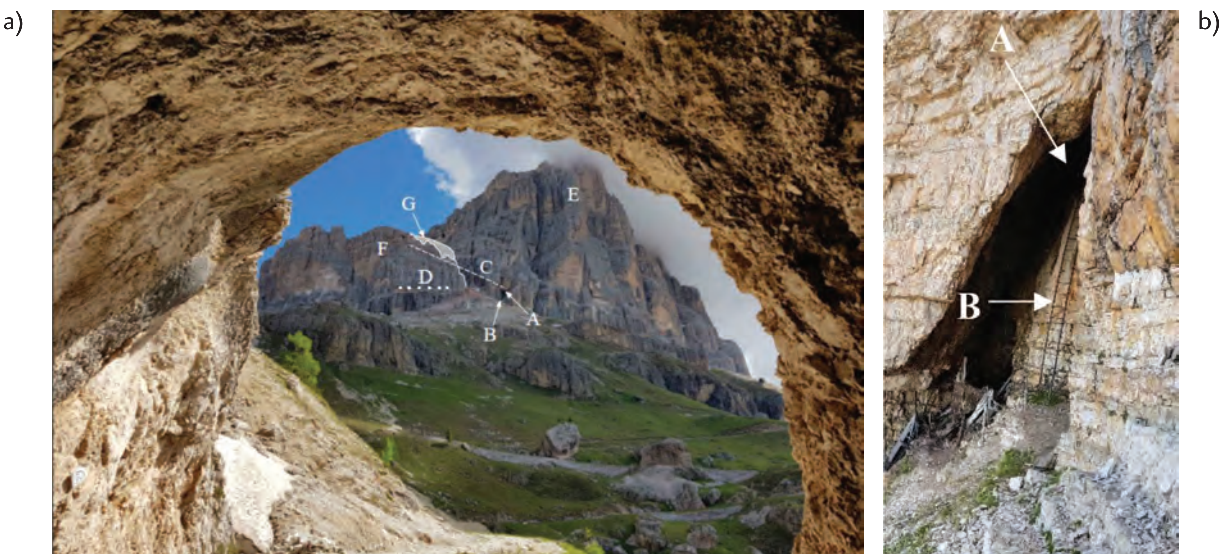

Figure 16. Castelletto Mine Tunnel, Tofana di Rozes: (a) Overview from a tunnel placed below. (b) Adit. (authors' photos). A = Tunnel adit (Figure 15b), B = Ladder to tunnel adit, C = Castelletto Tunnel (Figure 15a), Austrian Embrasures, E = Tofana di Rozes, F = Castelletto, G = Ridge destroyed by Italian Mine.

a) b) c) d)

Figure 17. Castelletto Mine Tunnel, Tofana di Rozes: (a) Tunnel adit. (b) Lower wooden ladder, original. (c) Upper ladder. (d) Sullivan compressor chamber (authors' photo).

(in these holes) *"up to one meter long, the cartridge occupies from … to | of the hole, depending on the quality of the rock. Each squad has 2 or 3 men with 3 or 4 chisels, 1 hammer, 1 scraper for cleaning the shot hole, 1 dryer, rags and water; a forge, an anvil and a hammer are required every 5 or 10 squads.… in an hour one squad digs a 0.12 to 0.2 meter long hole in granite rock; a 0.2 to 0.25 meter deep hole in compact rock and a 0.75 to 1 meter deep hole in limestone rock".* The IV Italian Army corps, unit Mrzli – Monte Rosso, tested a 3

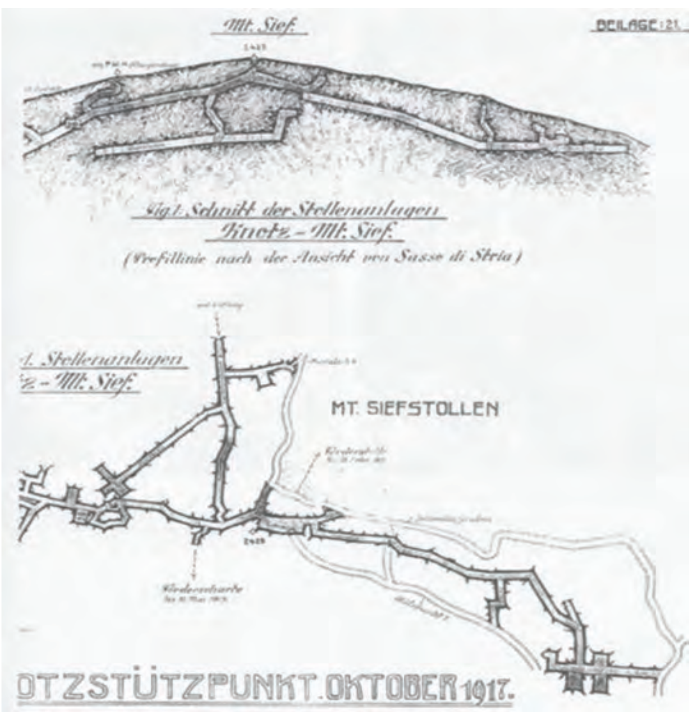

Figure 18. An Austrian tunnel under the Monte Sief summit[33].

Table 2. Quantity of explosive and time needed to dig 1 m^3 of rock with firecrackers 0.5 to 0.8 m deep [21].

Rock type	Gunpowder [kg/m³]	Explosive gelatin [kg/m³]	Excavation time [hours]
Quartzite	1,0	0,25	20
Granite	1,0	0,25	16
Silica (sic)	0,8	0,19	12
Marble	0,7	0,18	7
Hard Limestone	0,6	0,18	6
Sandstone	0,6	0,17	5
Soft Limestone	0,3	0,10	5
Puddingstone	0,2	0,08	4
Tuff	0,2	0,08	4

cm steel pipe equipped with a diamond-drill mechanically pushed and rotated against the rock; debris were removed with a water jet pumped through the pipe, thus also cooling down the device. In this way 50 m long holes could be drilled, while the explosion of gelatin cartridges could excavate a small Mine chamber at the end of the hole. Nevertheless, the difficulties in removing the debris and in pushing the cartridges inside the hole recommended the use of a 5 cm pipe and of a device to create a Mine chamber having 25 cm diameter; this lowered the advancement speed from 40 cm/hour to 150 cm/day. No engines were used; instead, there were only two men at the auger and two at the pumps and the required quantity of water was 400 l/h. However, even if a 50 kg charge was successfully placed at a distance of 30 m, this practice only remained at test level [12].
As for the mechanical drillers, as already mentioned, war financed the research for new technologies. Production began to assemble equipment that was less unwieldy, lighter and safer to operate compared to that received from abroad or previously manufactu-

Figure 19. The tunnel under the bed of the river in Val Popena [12].

red in Italy. One type of motor-compressor giving excellent results and was implemented by the French and English armies also [23]. We provide a summary of some types of mechanical drillers that were used, acquired from the work by Basilio De Martino already quoted several times [12]:

– 45 Hp Aquila-Sullivan used at Castelletto and then at Lagazuoi;
– 30-40 Hp Sullivan used at Castelletto (refer to Figure 17d);
– 75 Hp Sullivan used at Lagazuoi;
– 15 Hp Alfa-Ingersoll for additional works at Lagazuoi;
– 15 Hp Diatto used at Lagazuoi;
– Romeo, Sullivan and Consolidated Pneumatics Tools, on pack animals' transportable groups Marelli-Brusa.

The Manual [21] describes a hammer drill:

«It consists of:

1. *a single-cylinder four-stroke 7 Hp petrol engine with high voltage magnet ignition, water cooling and centrifugal force regulator;*
2. *a dry air compressor cooled with water by means of a centrifugal pump that draws 820 liters of air per minute and compresses them at 7 atmospheres;*
3. *a carriage with rotating front-end for transporting the engine and the compressor;*
4. *a compressed air tank (in three cylinders) with pressure gauge and safety valve, 4 drain cocks and connection with the hammer pipes;*
5. *two hammer drills (Valveless by hand-type) each including: the handle, the cylinder and the self-dispensing piston which strikes 800 strokes per minute; there is also a small hammer with automatic advancement of the chisel;*
6. *chisels or hex head sinkers, that enter the cylinder of the small hammer; there are empty and full ones; the latter made for bottom to top holes.*

In medium-hard rocks a one-meter long hole is made in an hour. A motorist and two miners are required to take turns in handling a hammer».

3.4.3. Advancement in tunnel

For rock tunnels, the Manuals [22][21] suggested a width of 1 m and a height between 1.5 and 2 m for two miners working on a 1-hour shift, or width and height between 1.8 and 2 meters for two pairs of workers. Those who visit the existing tunnels of this size may easily understand the effort that the men employed had to face because of the uncomfortable position in which they had to operate, the dripping, the dust and the bad temperatures.

The drill & blast technique was already like to the current one [24]:

In tunnels and shafts, work is carried out according to the following stages:

Table 3. Some figures of the m values for calculating the required charge according to lithology; from the Manual [21].

Rock/Soil type	*m* parameter
Soft soil	1.20
Dense sand	1.75
Soil with stones	2.00
Clay with tuff	2.25
Bad masonry	1.88
Poor masonry	2.42
Excellent masonry	3.27
Ancient masonry	3.63
Roman masonry	4.24
Good concrete	4.24
Poor rock	2.50
Massive rock	3.27
Hard rock	4.24
Fractured rock	5 to 6

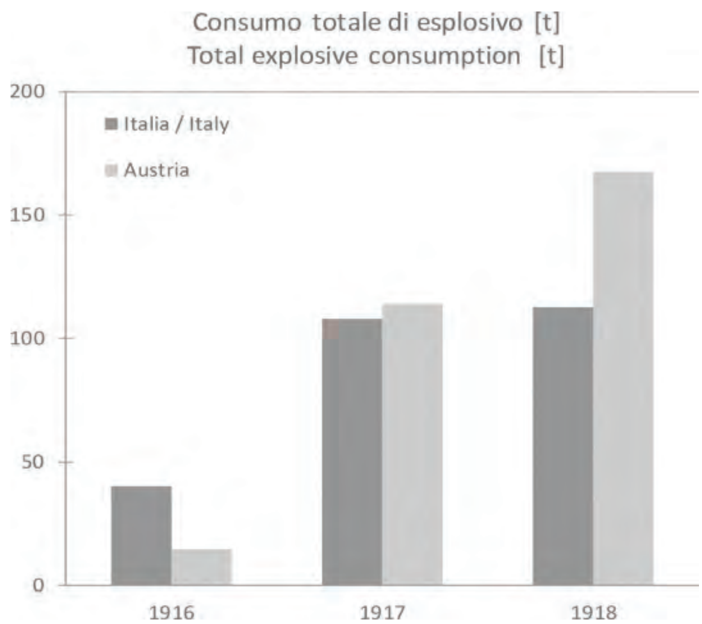

Figure 20. Total explosive consumption estimate.

1. *provision of firecracker holes;*
2. *loading and stemming;*
3. *explosion of charges and subsequent phases;*
4. *ventilation;*
5. *removal of rock fragments still attached to the assault front and quick removal of debris.*

Or from the Instructions [22]:

In case of a front consisting of a homogeneous rock wall, holes must converge towards the center of the section: the lateral holes with a greater inclination than the central ones; these must be detonated first, then the uppermost (called crown) and then the lateral holes proceeding from the top to the bottom. The length of the holes should generally not exceed 80 cm; if the rock is hard and compact, the length must be limited to 50 cm. The holes must be washed and dried before loading.

As shown in Table 4, collected data show an extreme heterogeneity, obviously depending on the drilling method (by hand or with drillers), the lithotype, the rock mass fracturing, the tunnel size, the type of explosive, the ventilation and the presence of water. Works were generally carried out by teams over two or three shifts within 24-hours. Other specific conditions may have influenced the excavations, given the need of avoiding noise that the enemy could distinguish, the difficulties of clearing the waste material without being seen and the extremely difficult logistic conditions in which materials had to be supplied.

4. The Cadorna Line

The first studies regarding the construction of an Italian defensive line along the Italian-Swiss border against possible invasions, date back to the second half of the 19th century. But it is at the beginning of 1915 that the Guardia di Finanza, the Carabinieri and the Territorial Militia, together with some units of the Mining Corps of Engineers, begin to arrange shelters and emplacements in caverns as well as military roads.
In 1916, 150 km of entrenchments and 150 km of roads for artillery were planned between Domodossola and Colico, employing 15,000 workers for three months. A feared Austro-Germanic outlet through Switzerland, alike to that attempted in May - June 1916 on the plateau of the Sette Comuni, and Italy's declaration of war on Germany (August 28, 1916) urged defensive works on what will then be called the Cadorna Line [36].
To reflect the geographic location of this part of the front, that would never be used, the 1916 sectors division is described as follows: (Figure 22):
1° Mont Dolent – Monte Rosa;
2° Monte Rosa – Verbano;
3° Verbano – Ceresio (Lake Lugano);
4° Meda – Adda.
Between Mont Dolent in the Aosta Valley and the Reschen Pass in South Tyrol, the border runs for about 700 km, of which only 220 km are accessible for an invasion [36]. The underground works were distributed where the morphology would have allowed the penetration of enemy armies, in particular on the barrier of Val d'Ossola, Valchiavenna and on the defense of Lake Maggiore [35] (3rd and 4th sector).
In the period from 1916 to 1918 the overall costs of works, considering the employment of 15,000 - 20,000 workers, were 104 million Italian Lire; however, other reports indicate for the year 1916, 35,000 civilians plus 1000 soldiers of the Mining Corps of Engineers and the Territorial Militia [35].

Figure 21. The excellent characteristics of the rock mass in the access trail to Monte Cengio [9].

4.1. The geology

The large-scale structural layout is shown in Figure 4; it should also be considered that the upper Varese area is essentially characterized by a crystalline metamorphic basement of mica schists and gneiss, with a porphyry and tuff coating, while limestone and dolomite outcrop southwards [35].
The research done by Antonio Trotti [35] shows that 11 emplacements were built in caverns, such as the one of Monte Piambello (Figure 23a), having a 52 m long main tunnel in part covered at the entrance area, ammunition storage dumps (3.4 x 5.2 m) and ventilation chimneys.
A particular type of work, which cannot be found on the Italian-Austrian front, consists of Mine tunnels for the demolition of transport infrastructures: in the Municipality of Brienno (Como), where the Antica Strada Regina overlooks the Lario lake, road tunnels allowing to shortening the coastal path existed since the nineteenth century. In the compact dolomites, just five meters above the calotte of one of the road tunnels, underground compartments were built comprising a warehouse-shelter and the machines room, two reservoirs (one for primers and one for explosives), six Mine wells, seven lateral access ducts and three stemming water storage tanks (Figure 23b).

Table 4. Advancements and tunnel's sections with 3 or 4 shifts a day, each of 6 or 8 hours [12].

Tunnel	Advancement [m/day]	Section [m]	Notes
Monte Cimone	3.2	1.1 x 0.8	With drillers
Col di Lana	1.2		By hand
Monte Sief	4.0		48 men, 4 drillers, 4 shifts
Lagazuoi	5.5	1.9 x 1.9	With drillers
Castelletto	5.0 – 6.0	2.0 x 1.8	120 men, 4 shifts per day
Monte Piana		2.0 x 1.8	Listening tunnel
Monte Rosso	1.2 – 1.5		With drillers
Carso	0.4 – 1.5	1.5 x 1.0 / 1.0 x 0.8	By hand

Figure 22. Eastern sectors of the Cadorna Line [19].

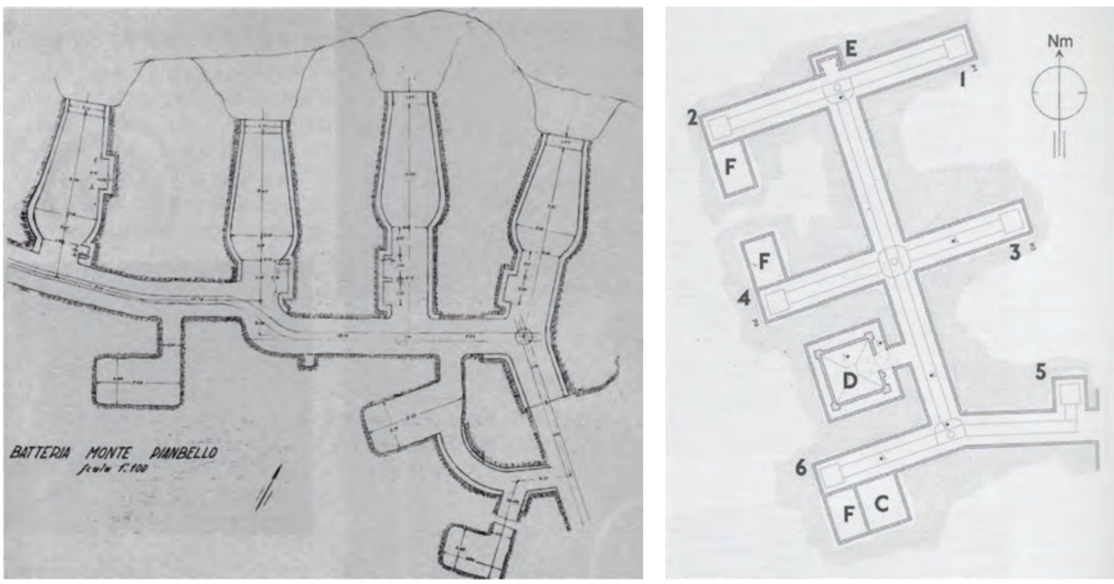

Figure 23. (a) Plan of a cavern stationing in Boarezzo (Varese) for four medium caliber cannons, called " Monte Piambello Battery" [35]. (b) The Mine tunnel of Brienno; the main tunnel is 30 m long [35]

5. Conclusions

To date, it is still not possible to provide a complete quantification and classification of the achievements of the Italian Army in the field of underground works during World War I.
This legacy would deserve greater scientific analytical commitment in terms of inventory, classification and study, as exposed, for example, by M. Diederichs and D.J. Hutchinson for the tunnels of Vimy Ridge in France [11]. Hundreds of kilometers of unlined tunnels are available to be transformed into real laboratories for geomechanics.
With this essay we have highlighted how, from the beginning until the end of war, the exploitation of underground military potentials went from limited and punctual cases to the realization of impressive and technically challenging works that required the parallel development of a real and dedicated industrial sector. It

is sad to note that war, along with its death burden, often involves significant technological development. This testifies that progress does not always correspond to civilization.
It is even more sad to think that many of the described works, which were realized at the price of enormous sacrifices in the first two years after the beginning of the hostilities, proved to be almost useless due to the breaking of the front at Caporetto, which cut the fighting line from the East.
The underground excavations carried out by the Italian Army during three years of war are still largely visible, so as to become a heritage not only historical but also as regards the landscape, appreciated by tourism more and more attentive and attracted by the possibility to directly verify the difficulties involved in their construction.
World War I military tunnels, especially those in the Dolomites, are worth a visit as they offer the opportunity to appreciate beautiful panoramas from surprising points of view, along itineraries of all levels of difficulty, from a simple walk to the most demanding *via ferrata*. Those interested can contact the Mountain Guides Group of Cortina (info@guidecortina.com, www.guidecortina.com) and the authors will be happy to join them to visit the tunnels they know best, such as those of Castelletto delle Tofane and Lagazuoi.

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