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THE GEOMORPHOLOGICAL CONSTRAINTS OF THE ITALIAN/AUSTRO-HUNGARIAN FRONT IN THE DOLOMITES DURING THE FIRST WORLD WAR

Abstract: Vergara M.N., Carton A., Francese R. & Bondesan A., *The geomorphological constraints of the Italian/Austro-Hungarian Front in the Dolomites during the First World War.* (IT ISSN 0391-9838, 2020).

Many documents within the enormous historiography of the First World War on the Italian Front highlight the importance of physical geography, yet specific and systematic studies of the influence of morphology on war in the Alps are scarce. Geomorphology influenced the battles that occurred on the main passes in the Dolomites. Geomorphological and military history maps were created for four of the most important areas on this front. The steep and high valley sides, part of the unique geomorphological setting of the Dolomites, determined unassailable positions from which the defenders, with protected and sometimes relatively accessible rear lines, could control and hinder enemy transit through the valleys by use of crossfire. From this point of view, the alpine terrain, as the result of the morphogenetic processes that took place in the region, can be considered as one of the key geographical aspects that controlled the conduct and the outcomes of the fighting in the valleys and passes.

Key words: Military geosciences, Mountain warfare, Alpine geomorphology, Dolomites, First World War.

Riassunto: Vergara M.N., Carton A., Francese R. & Bondesan A., *I condizionamenti geomorfologici sul fronte Italo-Austroungarico nelle Dolomiti durante la Prima Guerra Mondiale.* (IT ISSN 0391-9838, 2020).

Quasi ogni testo del cospicuo corpus storiografico del fronte italiano durante la Prima guerra mondiale pone l'accento sull'importanza della geografia fisica, ma sono relativamente scarsi gli studi specifici e sistematici tesi a valutare l'influenza della morfologia sull'andamento della guerra nelle Alpi. Questo lavoro si concentra sul condizionamento generato dall'assetto geomorfologico sugli scontri avvenuti in corrispondenza dei principali passi dolomitici. Per raggiungere questo obiettivo sono state redatte carte geomorfologiche e storico-militari delle quattro aree più importanti relative a questo tratto di fronte. I versanti ripidi e particolarmente elevati delle valli, peculiari dell'ambiente dolomitico, costituivano posizioni di fatto inattaccabili da dove i difensori, con retrovie protette e talvolta scarsamente accessibili, potevano controllare e precludere al nemico il transito lungo le valli potendo ricorrere al fuoco incrociato. La caratteristica geomorfologia delle Dolomiti ha rivestito pertanto un ruolo fondamentale nel condizionare lo sviluppo e l'esito degli eventi bellici che hanno interessato i passi e le valli alpine.

Termini chiave: Geoscienze militari, Guerra di montagna, Geomorfologia alpina, Dolomiti, Prima Guerra Mondiale.

INTRODUCTION

The centenary of the First World War (WWI) represented an opportunity for reinterpreting military events (Pozzato, 2015a, 2015b) as well as for interdisciplinary investigations (Note & *alii*, 2018). In this sense, the study of the battlefields and theaters of war not only through the

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A. Bondesan coordinated the research; geomorphological mapping was mainly performed by A. Bondesan and A. Carton, and partly by R. Francese and M. Vergara; M. Vergara carried out historical and GIS analysis. All of the authors participated in the field survey, data analysis, and conclusions.

This paper has been selected for publication among those presented at the ICMG19 - 13th International Conference on Military Geosciences held in Padua (Italy) from the 24th to the 28th of June 2019 on behalf of the International Association for Military Geoscience (IAMG).

examination of documentary sources but also by means of direct geographical-physical surveys supported by new technologies is proving to be a useful and innovative approach for the reconstruction and understanding of military events.

Geomorphological settings, among many physical issues (e.g., hydrography, meteorology, forestry, etc.), can influence military action from different points of view (e.g., field works, movements of troops and vehicles, defenses, deployments, etc.) (Anderson & *alii*, 2005; Rose & Willig, 2004; Rose & *alii*, 2006; Sivertun & Gumos, 2006; Hubacek & *alii*, 2014; Rybansky, 2015; Vergara & *alii*, 2018).

Various geomorphological contexts provide different challenges for military activities. A main morphological distinction of terrains divides plains from mountains based on a fundamental principle of warfare of WWI: the mass action. The main characteristics that mountainous terrain present are high absolute elevation and significant differences in elevation between mountain peaks. From these attributes stems, in part, another very important factor: the harshness presented by the mountainous terrain itself (Porro, 1898; Zečević & Jungwirth, 2007).

Before WWI, mountainous terrains, according to General Dellmensingen (Langes, 1981), commander of the *Deutsches Alpenkorps* until February 1917, represented just areas of passage. The battles that occurred in mountainous terrain primarily took place on the roads leading to mountain passes and on the peaks flanking the sides of these roads. Only exceptional military action occurred in high mountainous terrain (Tazzoli, 1997; Angetter & Hubmann, 2015; Bondesan & *alii*, 2015; Fizaine & Porchier, 2015).

This situation radically changed during WWI, in particular throughout the war fought between Italy and Austria-Hungary from May 24, 1915 to November 4, 1918. The two armies clashed along a stalled front that crossed the Eastern Alps from the Swiss border to the Adriatic Sea. The front line was approximately 600 km long. The elevation was lower than 100 m for a length of approximately 40 km, and lower than 600 m for approximately 60 km. Battles occurred along the entire front, from the valley bottoms to the mountain peaks to the surrounding glaciers, up to altitudes higher than 3000 m ASL in the Alps, the harshest mountain group in Europe (Langes, 1981; Lichem, 1995; Viazzi & Mattioli, 1997; Viazzi & Adreoletti, 2014).

The asperity of the Dolomites, located in the Italian Eastern Alps and in the central part of the front, depends on altitude, lithology, tectonics, and climate (Panizza, 2018). These factors facilitated the creation of a unique landscape where "the mountains rise as peaks with intervening ravines, in some places standing isolated but in others forming sweeping panoramas. Some of the rock cliffs here rise more than 1500 m and they are among the highest limestone walls found anywhere in the world." In this landscape are even more "spectacular vertical forms such as pinnacles, spurs and towers, with contrasting horizontal surfaces including ledges, crags and plateaus, all of which rise abruptly above extensive talus deposits and more gentle foothills" (World Heritage Committee, 2009).

In the Dolomites, the Italian 4th Army had to mount attacks against the Austro-Hungarian defenses to reach the Puster Valley. The main attacks were launched along the valleys and mountain passes, where larger masses of troops could be concentrated.

The geomorphology of the Dolomites played a crucial role in WWI events. This study focused on four areas pertaining to the valleys and mountain passes where some of the most important attacks were launched by the Italian 4th Army. These areas present different characteristics in terms of altitude, morphology, and the Austro-Hungarian defense system. As the total stretch of the studied front is about 50 km long, we concentrated our attention on tactics and not on overall strategy.

The current approach constituted an integrated study of military geography (see Appendix 2) that jointly analyzed site morphology and historical events. Better insights were generated through the scrutiny of historiographical sources and via integrated analysis with a geographical information system (GIS) of military historical and geologic-geomorphologic cartography, with particular geographical information processing conducted *ad hoc.*

GEOMORPHOLOGICAL SETTINGS OF THE DOLOMITES

The Dolomites are enclosed in the Eastern Italian Alps. They extend from the Adige River in the west to the Piave Valley in the east and belong to the Southern Alps. The latter is a structural unit of the Alpine chain that is composed of a complex type of south-vergent fold-thrust belt, bounded on the north by a segment of the Insubric Line, also known as the Puster Line, and on the south by the Neogenic and south-vergent thrust of the Valsugana (Winterer & Bosellini, 1981).

The region's limestone formations are often detached along the plastic Triassic levels and overthrusted with remarkable translations. This allowed the Permian and Triassic sedimentary formations to be exposed to erosion. With regard to the tectonics, the direction of the major valleys is controlled by the orientation of the fault lines and from the associated cataclastic bands, which are prone to erosion processes.

The raising of the Dolomites began during the Eocene, but the real deformation started in the last 15-20 Ma, while the current geomorphology, so extraordinary and typical – and famous around the world – is due to the erosion that occurred over the last 2 Ma.

The Dolomites on a regional scale and in relation to the morphostructural landforms have a high degree of geomorphodiversity when compared to other alpine mountains, as well as from a morphoclimatic viewpoint (Panizza, 2009, 2018).

The history of the Dolomites is one of changing landscapes that, from the Paleozoic volcanoes that gave way to tropical Triassic atolls particularly rich in marine invertebrates, survive to the present day in the form of fossils.

Repeated oscillations of the sea level caused overlapping processes to occur in both submarine and subaerial environments; lava flowing from Ladinian volcanoes covered vast areas, erupting from deep within the crust or mantle through fractures and faults, filling depressions and valleys (Gianolla & *alii*, 2008). Finally, the collision of the Adriatic and Eurasian plates created deformations, faults, lifts, and folds, shaping the high peaks and cutting the valley furrows, creating a unique landscape of extraordinary interest, so much so that the region has recently been recognized by UNESCO as a World Heritage Site (Panizza, 2018). The rock formations in the Dolomites originated in a period extending from the Permian to the Ladinian.

The spectacular mountain scenery of the Dolomites is the result of the overlapping of several geomorphological processes that together shaped the high peaks and wide valleys. Some of these phenomena are still active, altering the landscape, disrupting old formations, replacing others with new debris accumulating from the degradation of mountain slopes (Carton & Soldati, 1993; Soldati, 2007).

In the Dolomites, the geological structure plays a particularly effective role in the morphogenetic processes that gave rise to the mountain range and its features. This structure includes tectonics – namely, the processes through which the Earth's crust is deformed and fractured, creating features such as folds and faults, as well as lithology, which determines the arrangement of layers, the fragility of rocks, and the overall geolithological composition.

The resistance to exogenous agents, which are responsible for the erosion of the dolomitic relief, also depends strongly on the composition of the outcropped rocks: dolomites and limestones are more resistant and compact, whereas conglomerates, sandstones, marl, and volcanic rocks are mechanically weaker. Erosion is thus selectively expressed on softer rocks. The first group results in rough and steep slopes, while the second tends to form gentle hills.

Such differential erosion is also visible on smaller forms, such as, for example, the volcanic dikes of the Ladinian limestones of Costabella, which are responsible for the formation of some of the forks and saddles that cut the crest.

During the maximum glacial expansion of the last Ice Age (about 18 ka BP), the valleys were filled with ice, which only the highest peaks managed to penetrate, forming isolated nunatak (Seppi & *alii*, 2014). Various adjoining glacial flows spread across the current main Alpine passes. The subsequent degradation processes obliterated over time the typical glacial morphologies, such as the typical "U" valleys. The fluvial and slope processes altered the original morphology, mainly through accumulations of sediment. The glacial deposits along the valley slope, which, albeit discontinuous, are often present on the sides of the great Alpine valleys as well, marking the farthest extent reached by the glaciers.

The retreat of alpine glaciers began about 15 ka BP but was typified by several interruptions as well as stages in which small glacial advances resumed. Few traces of the oldest fluctuations remain, while the most recent episodes are clearly still visible. In particular, glacial deposits have been preserved at the heads of the valleys, cirques, and leveled summits (Carton & *alii*, 2009; Castiglioni, 1964).

As the glaciers were gradually retreating, turbulent water flows supplied by glacial melting carved the valley furrows with tremendous force. Sediments rapidly accumulated on the valley floors, flattening valley sections, now crossed by meltwater-fed streams, while rocky steps were crafted, forming ravines and narrow gorges. In some places, alluvial fans resting on one of the valley slopes would occupy the entire hollow, reaching major segments of the opposite slope. Alluvial fans generated by affluent valleys were occupied by early human settlements because of their elevated position, thereby avoiding the danger of flooding. These fans also offered gently inclined surfaces that could be easily exploited for agricultural use and were composed of loose materials such as gravels, sands, and silts. Most of these ancient settlements were situated on alluvial fans. Slope processes constitute another great postglacial morphogenetic agent (Francese & *alii*, 2013). These processes comprise different phenomena, from run-off to the action of frost and thaw to avalanches and landslides. Additionally, slope processes are responsible for the formation of the fans and scree deposits that extensively cover the foot of the slopes, often with the contribution of recurring collapses and landslides (Bistacchi & *alii*, 2013; Francese & *alii*, 2013).

Today, the processes of slope degradation are mainly governed by water, frost weathering, and gravity-related forces, which are primarily responsible for shaping the landscape, whereas glaciers have been relegated to the status of a very rare morphological element with correspondingly limited morphogenetic capacity. The most striking aspects of the recent activities of small glaciers, which are consigned to the higher cirques, materialize in the well-preserved moraines of the Little Ice Age, a brief phase of climatic cooling that triggered the advance of glacial bodies at the beginning of the 16th century and lasted until the middle of the 19th century (Carturan & *alii*, 2013).

Until a few years ago, many cirque glaciers occupied higher elevations, were less exposed to sunlight, and were fed by recurring avalanches. Today, the conditions needed for the preservation of glaciers have deteriorated, including the decline of permanent snowpack at higher elevations. As a result, these glaciers have demonstrated a marked reduction in volume and appear almost completely covered by a continuous layer of debris; although such local topographic effects offer shelter to glacierets, they also contribute to their ephemeral existence (Baroni & *alii*, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020).

Finally, karst processes deserve to be mentioned, although they exert far less of an impact. These processes act on carbonate rocks, dolomites, and evaporites (the chalk of the Bellerophon Formation), and they are mostly superficial, occurring in karst canyons, in small sinkholes, and on the karrens that pit the rock surfaces freed from Pleistocene glaciers.

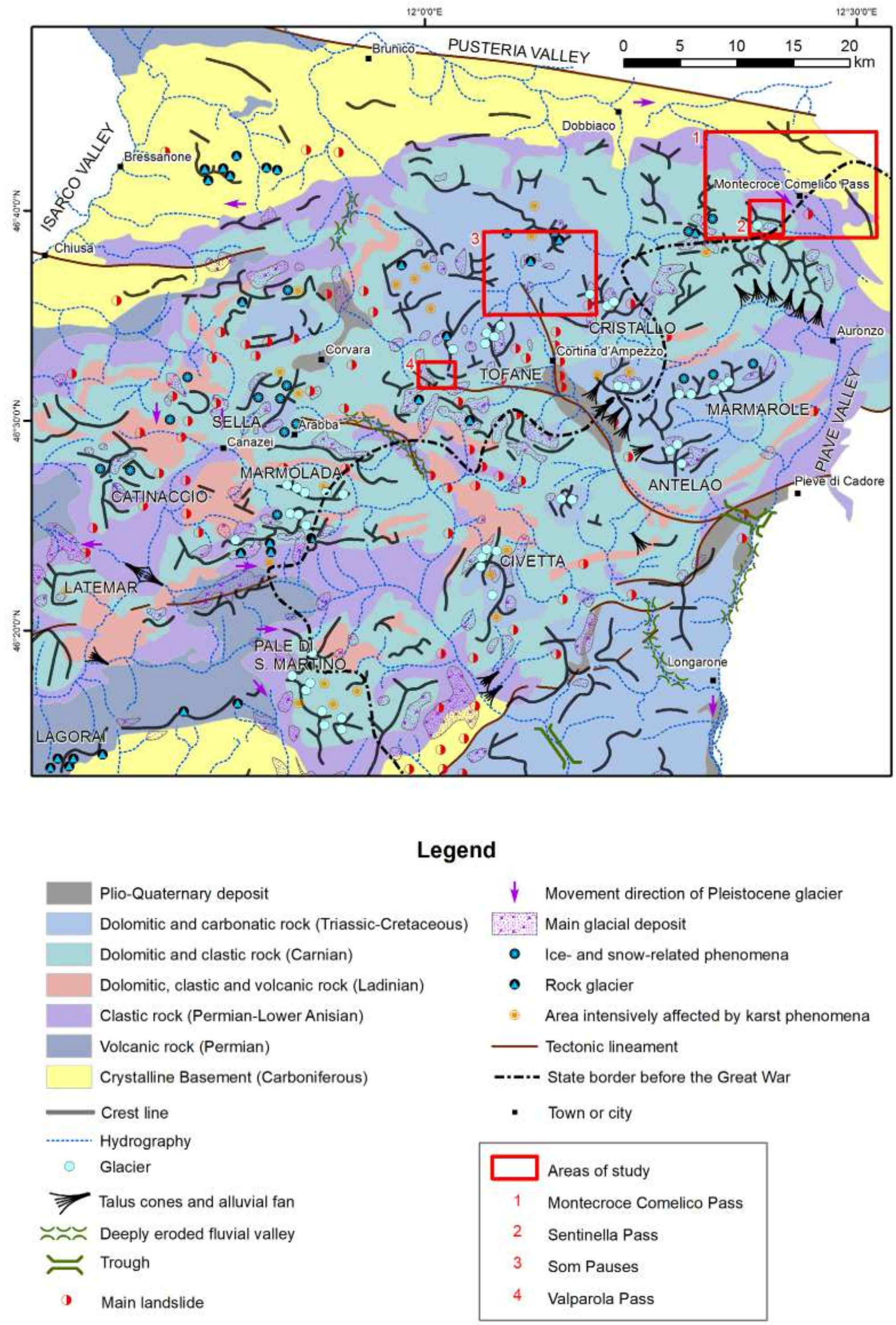

FIG. 1 - Geomorphologic schematic map of the Dolomites and the areas of study.

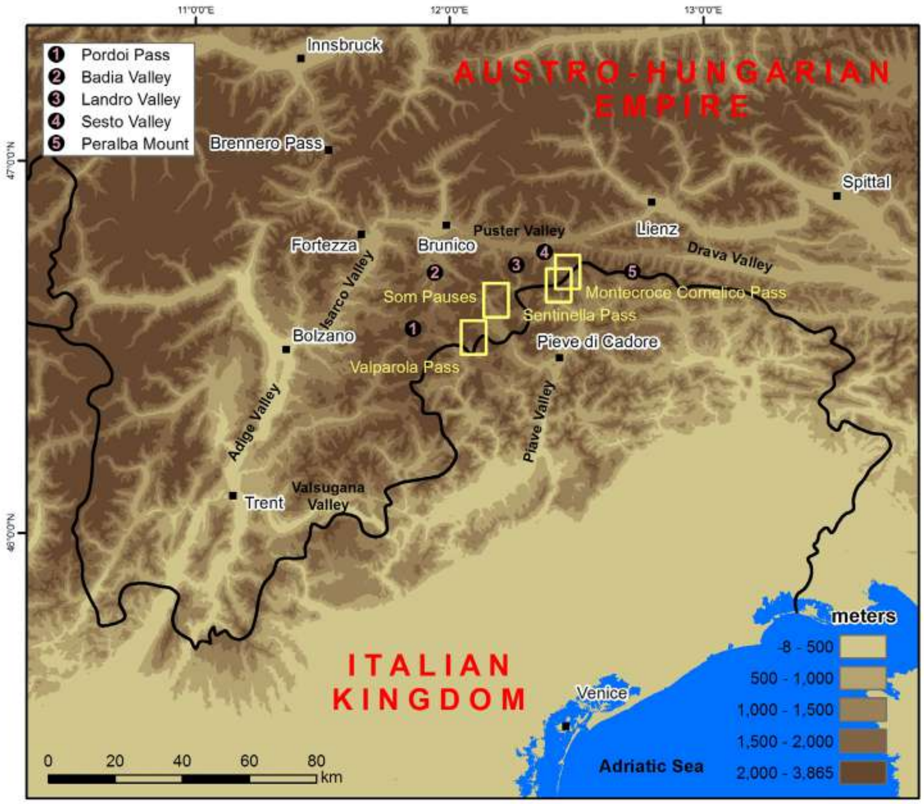

FIG. 2 - The theater of war between Italy and Austria-Hungary. The yellow squares indicate the areas of study, while the numbers inside the black circles pinpoint the valleys and passes cited in the text. The black continuous line marks the national border before WWI.

THE FIRST WORLD WAR IN THE DOLOMITES

In the document *Variations to the directives of 1st September* (SME-US, 1927-88, vol. 2 bis), issued on April 1, 1915, whose instructions were implemented at the beginning of the First World War, General Cadorna, Chief of Staff of the Royal Italian Army, assigned what would have been the first objective of the 4th Army: to reach the Puster Valley. For the Austro-Hungarian Army, the Puster Valley represented an important interior-lateral line (Vergara & Bondesan, 2020) and thus had to be defended in order to avoid being breached by the Italians (see Appendix 1).

The Puster Valley was linked in its southern part with three north-south valleys: the Badia, Landro, and Sesto Valleys (n. 2, 3, and 4 in fig. 2). It was through these valleys that the Italian invasion was forced to pass. Beyond the tactical and logistical difficulties that topography and communication infrastructures in the Dolomites represented for the Italian campaign, access to the three north-south valleys was prevented by Austro-Hungarian defensive infrastructures (Vergara & Bondesan, 2020). After the Napoleonic wars, many forts had been built in several valleys of the Eastern Alps to thwart the advance of armies (Ruffo, 1998). During WWI, many of the Austro-Hungarian forts inside the main valleys were further reinforced with field fortifications, thereby garrisoning the first defensive line. In the Italian literature, the Austro-Hungarian blockade of mountain passes and valleys has been identified by the term *sbarramento* (pl. *sbarramenti*) or "barrage"(see D'Ayala, 1841).

It was against these *sbarramenti* that the Italian campaign collided. Three of the four case studies discussed in this paper are focused on some of these *sbarramenti*: the *sbarramento* of the Montecroce Comelico Pass, which prevented access to the Sesto Valley; the *sbarramento* of the Som Pauses, which blocked one of the access points to the Landro Valley; and the *sbarramento* of Valparola Pass, which blocked one of the access routes to the Badia Valley.

Once war was declared, despite General Cadorna's disposition to immediately reach the Puster Valley, the 4th Army was not able to launch important attacks in the Dolomites, thus giving the Austro-Hungarians sufficient time to reinforce their defensive positions and to deploy their troops. The first important Italian attack in the Dolomites, which was aimed at overcoming the Austro-Hungarian *sbarramenti*, took place in the second week of June 1915. In other areas, as in the Montecroce Comelico Pass, no attacks occurred before the first week of August.

As supplies continued flowing to this front throughout the summer of 1915, battles grew bloodier. The aim was to outflank the *sbarramenti*, thereby bypassing the crests and securing better observation posts from which to enhance the precision of artillery; this objective drove the fighting from the field fortifications in the valleys to the mountainsides, cliffs, glaciers, and peak summits. Due to this strategy, the Dolomite Front is still considered one of the most important instances of mountain warfare in military history.

By the beginning of autumn 1915, General Cadorna realized that attrition warfare had clearly commenced in the area assigned to the 4th Army for reaching the Puster Valley, and therefore no breakthrough was possible in this part of the front. This reality dashed the general's hopes of reaching the Puster Valley and compelled him to instead redirect the 4th Army to implement a mainly defensive strategy. Offensive action was consequently designated exclusively to the great mass of troops concentrated in the Julian Alps and the Carso.

Although both armies had decided upon a strategic defense for the Dolomite Front from the autumn of 1915, military activities never ceased, even during the extremely cold and snowy winters of 1915-16 and 1916-17. The main military actions, however, were limited to the summer season and were usually intended to divert a main attack from elsewhere, thereby confining enemy troops to a secondary front (SME-US, 1927-88).

No important changes occurred after the autumn of 1915 on the Dolomite Front. Indeed, it remained almost entirely unaltered until October 1917, when the Austro-Hungarians, no longer engaged against the Russians, spread out with German help from Caporetto, in the Julian Alps, onto the Venetian Plain. This forced a quick and total withdrawal of the majority of the Italian units, including the 4th Army from the Dolomites, to the plain. The new Italian defensive line was placed on the Piave River; thus, the forces of the Central Empires were no farther than 35 km from Venice. The Piave River Front held until October 1918, when the last Italian offensive started. This offensive ended on November 4, 1918, with the declaration of the armistice between Italy and Austria-Hungary.

MATERIALS AND METHODS

The present research was developed through three main steps: a geomorphological study, a military history study, and a military geography study. The main result was a geomorphological map and a military history map for each area of study. The scale of the maps for the study of the interest areas falls within the scale of the sketches of military history available in the military literature as well as within the typical scale used for studies of military opera-

TABLE 1 - Main topographic, geologic, and geomorphologic base maps consulted for this study.

Topographic maps			
Name	*Scale*	*Institution*	
Carta Topografica d'Italia	1:25 000	Istituto Geografico Militare	
Carta Tecnica regionale	1:10 000	Regione Veneto	
Carta Tecnica regionale	1:10 000	Provincia Autonoma di Bolzano - Alto Adige	
Geologic maps			
Name	*Scale*	*Institution/Author*	*Year*
Carta Geologica d'Italia	1:100 000	Servizio Geologico d'Italia	
Carta Geologica d'Italia	1:50 000	Servizio Geologico d'Italia	
Piano di Assetto del Territorio. Carta litologica	1:10 000	Comune di Cortina d'Ampezzo	
Carta geologico-escursionistica. Parco Naturale Dolomiti di Sesto	1:25 000	Provincia Autonoma di Bolzano-Alto Adige	2004
Carta geologica della Valle del F. Ansiei e dei Gruppi M. Popera-Tre Cime di Lavaredo (Dolomiti orientali)	1:25 000	Università degli Studi di Milano and CNR	1982
Carta geologica. Dolomiti occidentali	1:25 000	Provincia Autonoma di Bolzano-Alto Adige	2007
Geological Schematic Map of the Dolomites. In: Geomorphological features of the Dolomites (Italy)	= =	A. Carton & M. Soldati	1993
Geomorphologic maps			
Name	*Scale*	*Institution/Author*	*Year*
Carta geomorfologica. Piano di Assetto del Territorio	1:10 000	Comune di Cortina d'Ampezzo	=
Geomorphological Map of the Surroundings of Cortina d'Ampezzo (Dolomites, Italy)	1:20 000	Università di Modena e Reggio Emilia and CNR	2005
Geomorphological Map of the Alta Badia Valley (Dolomites, Italy)	1:20 000	CE, MIUR, CARG Bolzano, CNR	2009
Saggio di carta geomorfologica dell'Italia nord-orientale	1:1 000 000	CNR - G.B. Castiglioni	1969
Carte geomorfologiche delle fronti dei ghiacciai appartenenti ai gruppi montuosi: Antelao, Civetta, Cristallo, Croda Rossa, Marmarole, Pale di S. Martino, Pelmo, Popera, Sorapiss, Tofane	Different scales	Università di Padova - Thesis' degree of Luigi Cristiana	1990-1991
Carta delle morene stadiali della regione dolomitica	1:125 000	Università di Padova and CNR - G.B. Castiglioni	1964
Geomorphological Schematic Map of the Dolomites. In: Geomorphological Features of the Dolomites (Italy)	= =	A. Carton & M. Soldati	1993

tions at a tactical level of warfare, from 1:5000 to 1:100 000. These scales are suitable for obtaining very detailed geomorphological maps that represent major military features and events. Some of the studied areas belong to the Alto Adige-Südtirol (South Tyrol), which is an autonomous and bilingual Italian province, as well as to Austria. For reasons of simplicity, the toponyms in both the text and the maps are reported only in Italian.

Geomorphologic study

The geomorphological study was devoted to the analysis of former topographic, geologic, and geomorphologic maps (table 1), as well as to the interpretation of orthophotos and satellite images and field surveys. A GIS project collected all the georeferenced data and different digital terrain models (DTMs), processing geographical information and producing different outputs.

As former maps did not cover some of the parts of the study areas, or the scales of these maps were too small for this study, remote sensing interpretation and field validation were conducted. The images used included orthophotos and Google Earth™ imagery. The orthophotos were provided by the Provincia Autonoma di Bolzano-Alto Adige (2011, color, ground sample distance: 0.5 m) and by the Regione Veneto (2006-2007, color, ground sample distance: 0.5 m).

A digital terrain model (DTM), with a cell size of 5 m, was used for geomorphological interpretation. The DTM was obtained by rasterization through kriging of the digital cartography provided by the Provincia Autonoma di Bolzano-Alto Adige and the Regione Veneto. Further steps to complete the DTM included resampling, transforming the geographic coordinate system, and merging the raster images. The visualization of all the material previously mentioned and the creation of the geomorphologic maps were accomplished by ArcGis™ 10.1. This software allowed some spatial elaboration based on the DTM and was aimed at achieving better comprehension of the territories' morphology (e.g., hillshade and slope calculation).

The geomorphologic map of each area of study was developed on the basis of a common legend. This legend was structured according to the geomorphologic processes that produced the main geomorphologic forms and deposits present in the Dolomites and in the bedrock, with the latter classified on a lithological basis. Additional information included main hydrography, settlements, and driveways. The base maps were derived from official national and regional cartography (table 1) and from DTMs.

Military history study

The military history study reviewed the extant research contained in the military history literature and the creation of a specific GIS. The main military history literature that was consulted comprised narrative texts and focused on local events. Some of these texts yielded accurate descriptions as they mainly pertained to direct experiences. For instance, works by Berti (1982, 1985) were essential to the present research for examining military events in the Montecroce Comelico Pass, the Sentinella Pass, and the Som Pauses. With regard to the Valparola Pass, the main consulted works were those of Pieri (1996) and Viazzi and Mattioli (1997). Another useful monograph on the military events that took place in the Sentinella Pass was that composed by Zandonella Callegher (2008).

Inside these sources, original sketches of the military events that transpired in these different areas of study were of particular importance. However, the accuracy of military geographical information, such as the direction of the attacking lines or the position of emplacements, varied widely, depending on the author, the original scale, the symbology, the quality of the base maps used, and the purpose of the document.

All military historic information was implemented into the GIS project. On the basis of the topographic maps listed in Table 1, the original sketches of military history were geolocalized. The information from the sketches was digitalized into a vector format, stored into a geodatabase, and ultimately portrayed in a final map of each area. In order to control and improve the precision of the information from the sketches in the historiographic sources, toponyms and geographical reference features extracted from the texts were compared and eventually introduced into the final maps. Furthermore, in the case of the defensive lines, their positions, when still preserved today, were controlled by the interpretation of the orthophotos and Google Earth™ imagery.

Further integrated analysis between historic and geographic data was supported by specific GIS tools for spatial analysis on the DTM as viewshed analysis and topographic profile tracing. The GIS also permitted the creation of a geodatabase with military history information. This database contained the following records for each feature:

– the area of study;
– localization: toponyms or topographical information from the literature;
– position check: whether or not the localization of the feature has been validated by remote sensing;
– information: detailed information of the feature (i.e., military units deployed, fighting, military relevance, type of emplacement, etc.); and
– bibliographical references;

The final military history maps reveal the main positions of the units in the field and the major military events. The maps contain a simplified topography that comprises contour maps from DTM processing, the main river course, roads, and main toponyms.

A common legend for all the military history maps was developed. This legend contains simplified information regarding the abovementioned geodatabase. In particular, the feature "defense line" represents the outer line of defense positions (which corresponds to the "line of contact" for an attacking enemy). Thus, it refers to field works as trenches, lines of barbed wire, *chevaux de frise*, and so forth. The term "general emplacement" includes observatories, firing emplacements, recovery emplacements, and shelters and huts in the rear lines. Furthermore, every map contains specific symbols, each of which are indicated inside the frame of each map (e.g., lines of attack that correspond to the main battles).

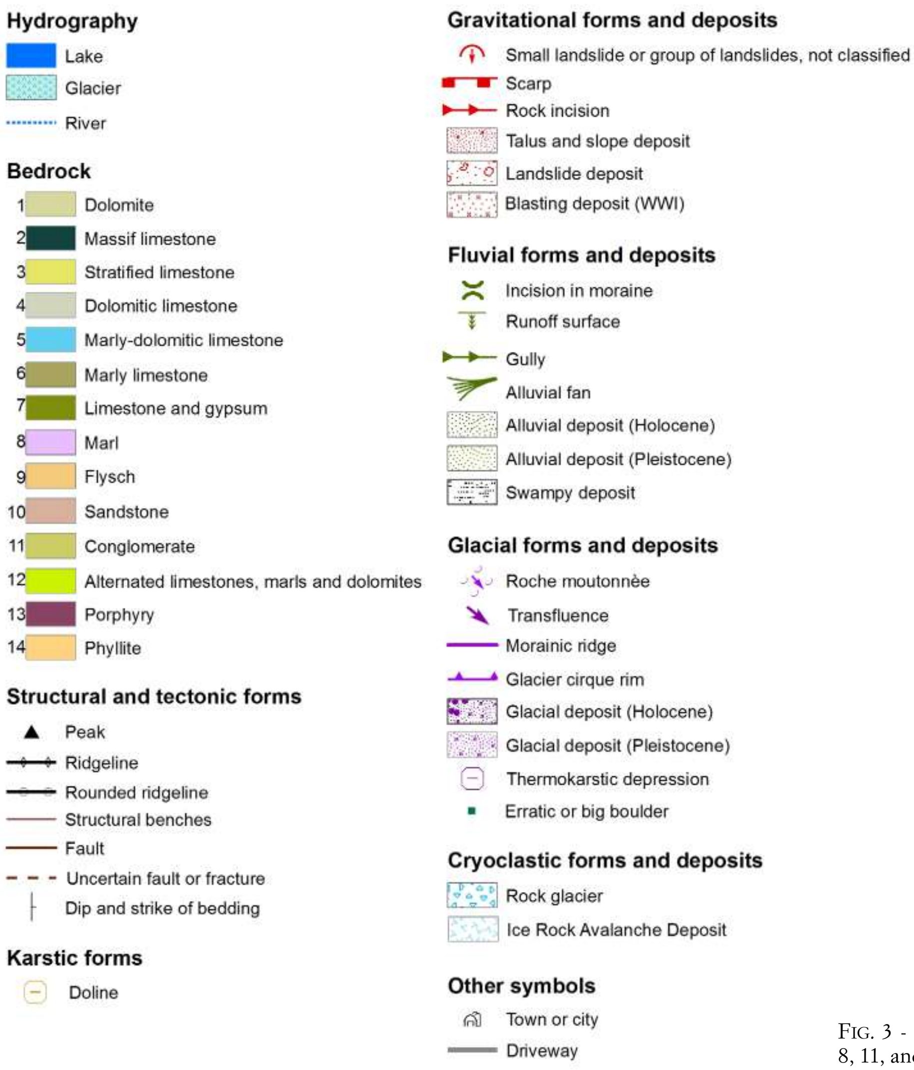

FIG. 3 - Legend for the geomorphologic maps (figs. 5, 8, 11, and 13).

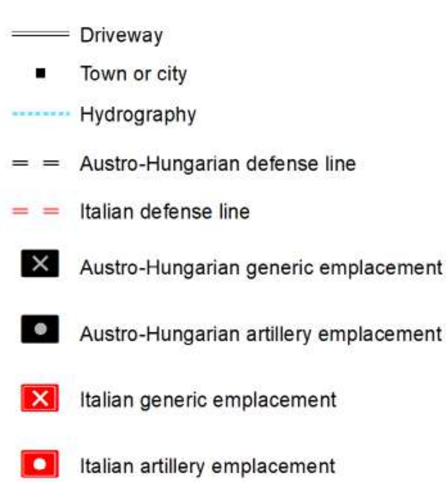

FIG. 4 - Legend for the military history maps (figs. 6, 9, 12, and 14).

FOUR CASE STUDIES OF THE DOLOMITE FRONT

Montecroce Comelico Pass - Geomorphologic settings

The Montecroce Comelico Pass is arguably one of the wider passes of the Dolomites, where the heads of two wide glacial valleys meet. The valley slopes are asymmetric with a well-defined metamorphic ridge on the eastern sectors, along the current border with Austria. Deeply carved glacial cirques, formed on the eastern valley side, generate spurs perpendicularly oriented toward the Sesto Valley. A central ridge, Mount Covolo, has been shaped by glacial erosion and dominates the surrounding terrain, even though it does not have a high elevation.

The dolomitic and limestone summits, outcropping on the western side, form jagged slopes and peaks: the main peaks are Mount Popera, Cima Undici, and Croda Rossa, where glacial erosion has formed coalescent wide cirques. The buttresses of Cima Colesei and Mount Castelliere constitute the lower ramparts facing the Sesto Valley thalweg.

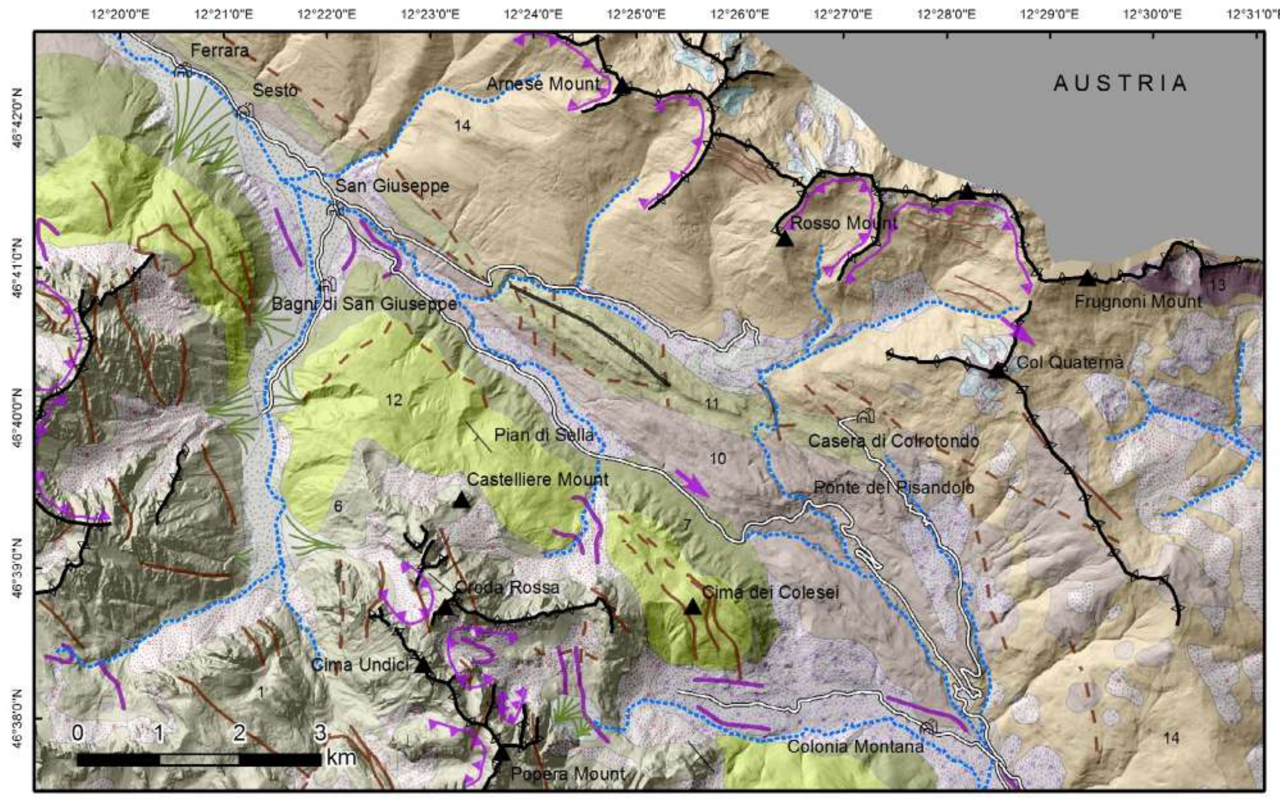

FIG. 5 - Geomorphologic map of the Montecroce Comelico Pass (see fig. 3 for legend).

Extensive glacial deposits are located in the Popera Valley. On the eastern side, some rock glaciers are clear evidence of a periglacial environment. The main watershed divide splits the head of the Sesto and Padola valleys with the formation of an embryonic dendritic drainage network. The evolution of the main valleys occurred due to erosive processes controlled by a coincident tectonic line.

Military events. The Montecroce Comelico Pass served as one of the best possible ways to enter Puster Valley, mainly because of its width and its proximity to the valley itself. When Italy declared war on the Austro-Hungarian Empire, the latter decided to defend the pass, which stands nearly atop the old state boundary. In the Italian literature, this Austro-Hungarian defensive line was called the "sbarramento of Sesto."

During the first months of the war, the Italian 10th Division, which was deployed in this area, did not conduct significant attacks, thereby permitting the Imperial 56th Mountain Brigade not only to reinforce their defensive position but also to gain, at the beginning of June, all of the Carnic Crest in this sector. The Austro-Hungarian defensive line was stable until the end of the war, connecting Mount Castelliere, Piano Sella, the road at the Montecroce Comelico Pass, Mount Covolo, Pullbach, Mount Rosso, Demut, Schöntalhöhe, Mount Ferro, and Frugnoni.

The Italians launched two major attacks in this zone. The first, on August 4, 1915, was preceded by four days of artillery bombardment. The main targets were Mount Castelliere, Mount Covolo, and Mount Rosso, but in the meantime, three diversionary attacks were conducted: against Mount Ferro, from the Col Quaternà against the Frugnoni, and in Val Fiscalina (outside the study area). This bloody effort allowed the Italians to advance their first defensive line, especially to the southern side of Mount Covolo and to the north of the Rio Bianco, east of Mount Castelliere.

The second attack was conducted by 33 Italian companies against 19 Austro-Hungarian and Bavarian companies on September 6, 1915. This offensive was developed mainly to target the Mount Castelliere-Mount Covolo sector and from the Valorea Crest to the Mount Rosso-Vanscuro sector. In some areas, the Italians were able to conquer some enemy positions, but they could not hold them for long; in other areas, they could not break through the barbed wire. The slope was a slaughter factor for the Italian infantry, leading to more than 600 deaths. The Austro-Hungarians counted only six deaths. After these attacks, there were no other relevant military actions in this sector until the withdrawal from Caporetto.

Comments about the relation between geomorphology and military events

At the beginning of the war, the front stabilized along the administrative border, which followed the watershed line. The two factions deployed along the crests on the valley sides and over the spurs, which were transversed by the main valley slopes the valley sides and over the spurs, which were transversed by the main valley slopes.

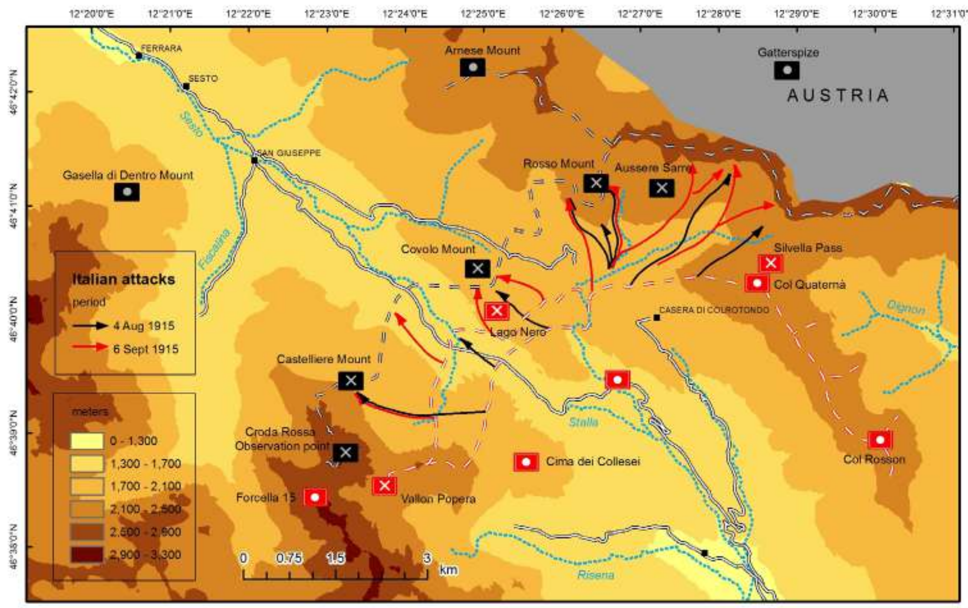

FIG. 6 - Military history map of the Montecroce Comelico Pass (see fig. 4 for legend).

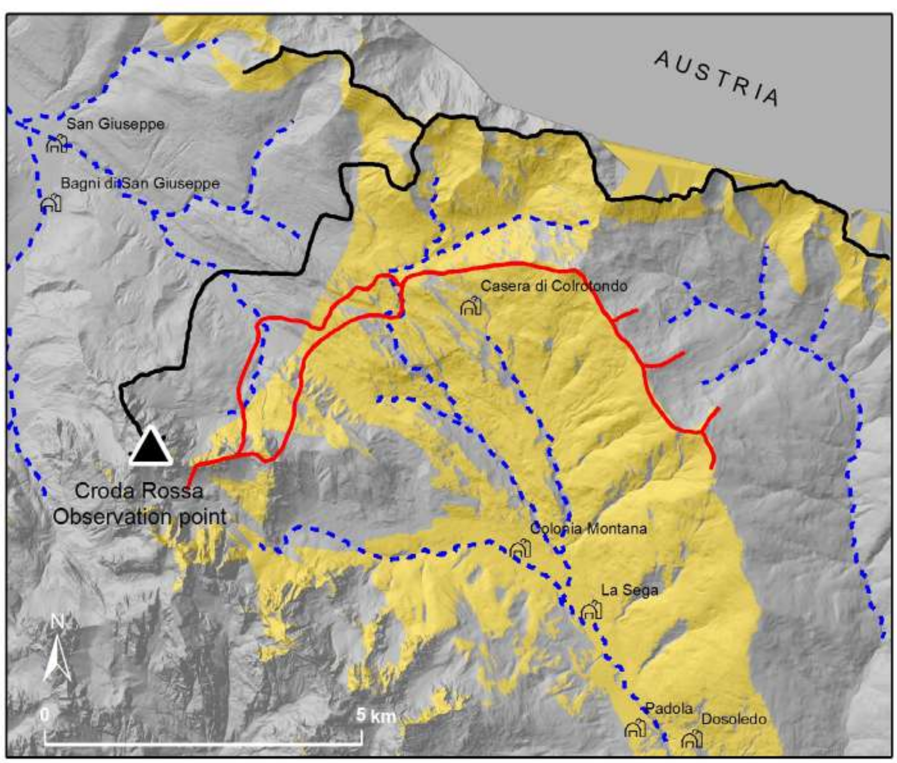

FIG. 7 - Viewshed from the observation point at Croda Rossa (black triangle). This sketch shows the area that could been seen from the observatory (yellow color). It also shows the Italian line of defense (red), the Austro-Hungarian line of defense (black), the nearby villages, and the hydrography (blue dashed line).

The imperial troops dug trenches on the ridge lines, which were served by connecting trails on the back, and were partially protected from Italian crossfire and artillery.

On the valley floor, the Italian line of defense developed from Vallon Popera to Col Quaternà and Col Roson, occupying the tops of the ridges whenever possible.

The Austro-Hungarian line was organized on the ridges of the eastern foothills over two crossing spurs overlooking the Rio Cor and the Klammbach. The line crossed to Mount Covolo and gained a dominant position on which both Italian attacks were concentrated; while on the western side, the line joined Mount Castelliere.

Holding the summit points was particularly important, as they were used by both adversaries as observatories for fundamental tactical employment. The Italians took possession of Forcella 15, which ensured the accuracy of artillery toward the Puster Valley, 12 km away from the front. The Austro-Hungarians occupied the crest of the Croda Rossa, on which they established an observatory overlooking a large part of the Italian Front, including the rear lines of the upper Padola Valley (fig. 7).

The differences in the lithological nature of the two valley flanks were instrumental, allowing easier movements in the eastern sector, which featured metamorphic rock outcrops, as opposed to the indented morphology of the dolomitic summits of Croda Rossa-Mount Popera, which rendered troop movements far more difficult. The domain of the main summits held by both armies permitted easy defense against enemy attacks under conditions of clear visibility. Additionally, attacks had to be launched mainly uphill, and in the open field (only a few small hollows provided temporary shelter for the Italians during attacks).

Italian attacks were concentrated on the dominant points (Mount Rosso, Mount Covolo, and Mount Castelliere) where the approach and deployment of forces on a broader front were easier.

In particular, as is apparent in fig. 7, in which the viewshed from the observation point is represented, the dominance of Croda Rossa by the Austro-Hungarians was particularly important, because it allowed almost complete control of the Italian lines.

It can therefore be concluded that the dominance of summits and valley sides were key to the success of the Austro-Hungarian defense.

Sentinella Pass - Geomorphologic settings

The Sentinella Pass is a typical dolomitic formation with steep sides and mountain peaks bordered at the base by slope and glacial deposits. The genesis of these forms is strongly related to tectonic and glacial action with the formation of a set of coalescing cirques that isolate horns and

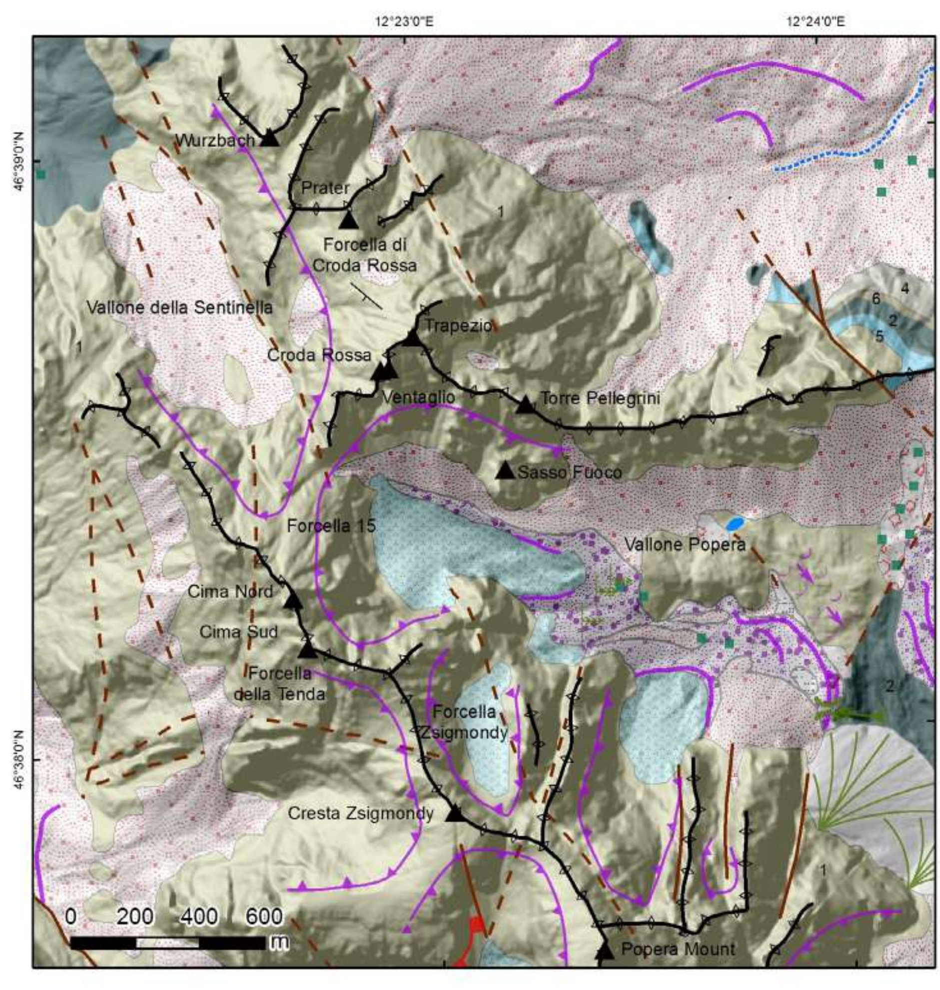

FIG. 8 - Geomorphologic map of the Sentinella Pass (see fig. 3 for legend).

arête. The two main cirques form two elongated valleys: the Vallon della Sentinella in the Austro-Hungarian territory, and the Vallon Popera in the Italian territory.

The tectonic lines are mainly oriented in a NNW-SSE direction, controlling the formation of the main valley gorges, cliffs, and orographic depressions. The ridge lines are strongly displaced by fractures that, together with the periglacial phenomena, generate an uneven morphology with forks and saddles (especially in Zsigmondy Crest).

Some glaciers facing north and west are still active, although they are currently undergoing significant withdrawal, and they generate well-formed morainic arcs.

At the lowest points, at the Montecroce Comelico Pass, some small alluvial fans are present, collecting water from the largest stream cuttings.

Military events. Before the war started, the boundary between the two countries was along the ridge of Croda Sora i Colesei and south to Croda Rossa; from there, it turned southward along the Sentinella Pass and continued along the crest line of Cima Undici-Zsigmondy Crest-Mount Popera-Mount Giralba. From Mount Giralba, the boundary turned westward along the Forcella Giralba.

During the first month of the war, the Austro-Hungarian 56th Mountain Brigade occupied the Croda Rossa and the Sentinella Pass. The Italian 10th Division took possession of Mount Popera and the Zsigmondy Crest. On Mount Popera, the Italians raised two 65-mm guns, one of which was settled at 3000 m ASL (known as "the cannon that shoots from the stars") and was directed against the Austro-Hungarian observation point in Croda Rossa.

The importance of the Sentinella Pass is well evidenced by Berti (1985), who declared that it "is a window that watches, by one side to half of Padola Valley, and by the other side, almost half of the Sesto Valley."

The first relevant military event in this sector was the Italian attack on the pass on August 7, 1915. Italians mounted a frontal attack from Vallone Popera, which was preceded by an artillery bombardment (mainly by the three cannons on the Creston Popera). The frontal attack was intended to be supported by a contemporary encirclement through the right side of the pass, from the Pianoro del Dito, and through the left side from Cima Undici. Due to poor organization and lack of communication, encirclement by the left side failed.

During the attack, some platoons took possession of Sasso Fuoco, which was important because it served as a basis from which shots could be fired at some distance and it had some small saddles in Croda Sora i Colesei, which provided protection for the main attacking column as it was climbing. When the column arrived around 150 m

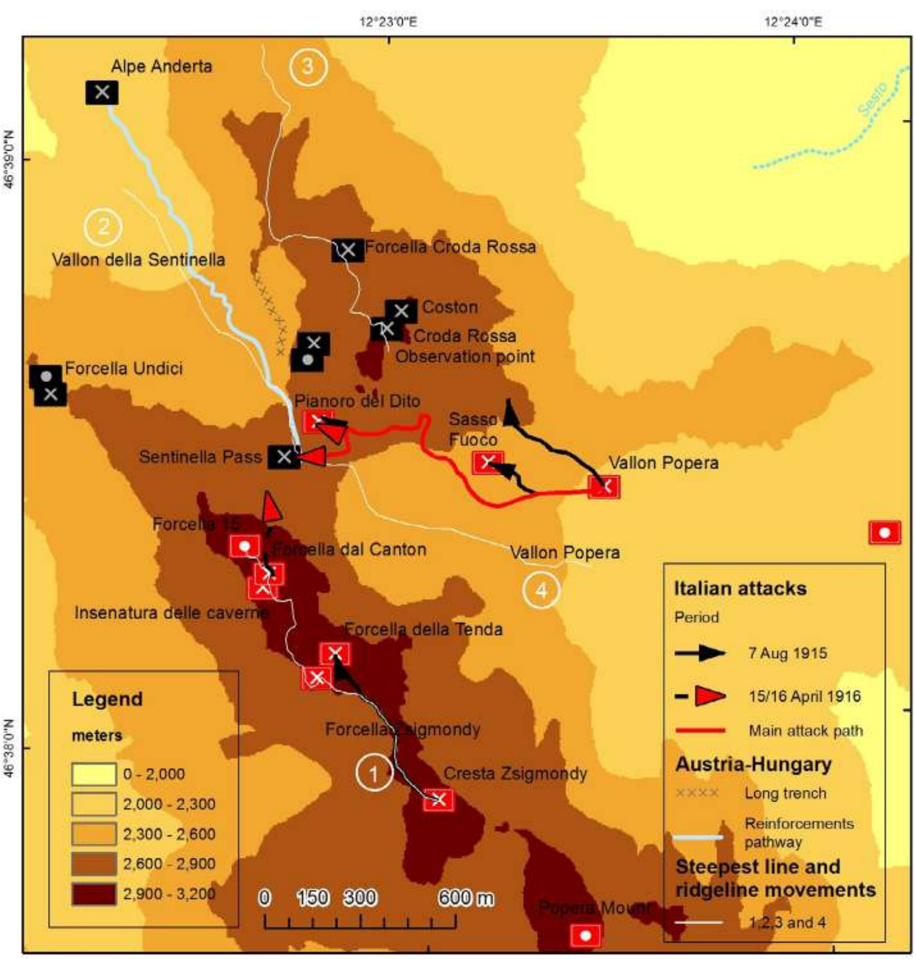

FIG. 9 - Military history map of the Sentinella Pass (see fig. 4 for legend).

from the pass, some troops hid behind the rocks of Il Dito and some climbed the Pianoro del Dito. From Pianoro del Dito, it was possible to only shoot at the Austro-Hungarian reinforcements arriving from Alpe Anderta, but not to descend to the pass as they had planned, due to the steep cliffs. The main column attack was then cancelled due to the presence of two Austro-Hungarian machine guns placed at the Sentinella Pass, which blocked the advance.

On August 14 and September 2, 1915, the Italians accomplished two similar actions, both of which were again aborted in the final part of the advance.

Another Italian attack started on April 14, 1916. This attack followed the same plan with the exception of two key differences, both of which were decisive in conquering the pass. The first difference was the surprise factor: an attack in April was not anticipated by the defenders and, due to the amount of snow and ice covering Vallon Popera, the troop column was able to ascend silently, unnoticed by the defenders (as had happened before). The second difference was the occupation of several positions on the Cima Undici massif, which permitted relentless suppressive fire on the defenders entrenched on the pass and allowed for the descent of some Italians, who were able to assume a defensive emplacement on the pass by the back. The occupation of the positions on Cima Undici was made possible by a difficult movement of supplies and troops, hidden from the enemy, along the crests (starting from Zsigmondy Crest) during the winter of 1916. After the conquest of the pass, the Italians failed in several further attacks, mounted from the south side of the massif, against the Austro-Hungarian positions on Croda Rossa. The Italian occupation of the pass forced the Austro-Hungarians to change their transport route to positions on Croda Rossa.

Comments about the relation between geomorphology and military events

The conquest of Croda Rossa, Cima Undici, and Mount Popera was fundamental to the domination of the Montecroce Comelico Pass and to providing the opportunity to bypass the pass to the north, toward the Val Fiscalina. The pass, between Cima Undici and Croda Rossa, was the hinge point of the Italian-Austro-Hungarian Front. Both sides, for this reason, tried to conquer the pass and the nearby ridges.

The movement of troops was protected along the summits, which were quickly occupied from the beginning of the war. The valley floor was trafficable only when the enemy did not occupy a dominant position. For this reason, the Italians did not transit through the valley bottom of Mount Popera (the Austro-Hungarians were occupying the Sentinella Pass) and the Austro-Hungarian troops climbed the northern part of the Vallon della Sentinella, as doing so allowed them to remain hidden from Italian observation.

The main pathway for the Italian attack avoided the steepest line (table 2) and permitted near horizontal movement, at approximately the same height as the Sentinella Pass, when reaching the pass (fig. 10). Following this line, the Italians moved, along some sections, on the upper part of the talus slope, where transit was easier due to the finer particle size of deposits.

The attack of April 1916 developed in part along the crest of Cresta Zgimondy-Cima Undici, from which, once the dominant position on the pass had been obtained, permitted the Italians to defend against the main attack that took place on the left side of the Vallon Popera, unseen from the Sentinella Pass. The conquest of the Sentinella Pass by the Italians determined the dominance over the Austro-Hungarian supply lines, which were no longer sheltered and had to move along the ridge to the east. Transporting supplies thus became more difficult for the Austro-Hungarians.

Subsequent attacks carried out by the Italians on the Croda Rossa failed because of the steep slopes, the cragged morphology, and the presence of highly precipitous narrow ravines in the rocks, which were hardly passable but easily defensible by the Austro-Hungarians. The front remained stable in these positions for the rest of the war, until the withdrawal from Caporetto.

TABLE 2 - Mean slopes. This table compares the average slopes of the paths to reach the highest summits. The numbers inside the brackets indicate to which line they correspond in fig. 9 and fig. 10.

Main Italian attack pathway	32%
Austro-Hungarian reinforcement pathway	42%
Steepest line in Vallon della Sentinella (2)	58%
Steepest line in Vallon Popera (4)	44%

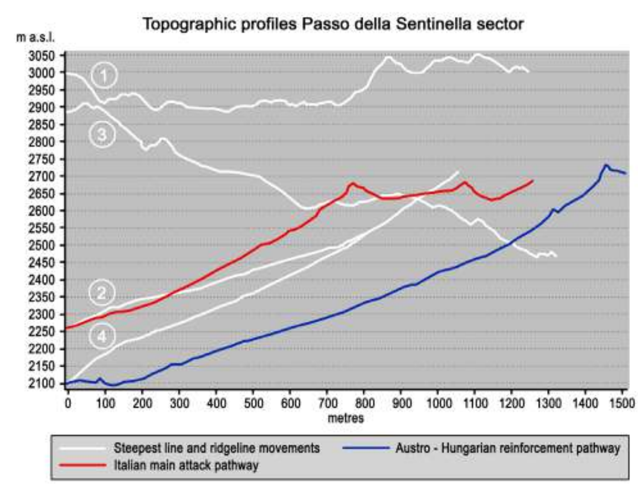

FIG. 10 - Topographic profiles for the Sentinella Pass area. The numbers inside the white circles indicate to which line these profiles correspond in fig. 9 and to which mean slope they correspond in Table 2.

Som Pauses - Geomorphologic settings

The main crest lines of the southern quadrants converge on the area of Podestagno-Pian di Loa; while in the northern quadrant, a preferential alignment of rocky ridges in an east-west direction can be observed. The southerly direction of the ridges, as well as the valley furrows, are closely controlled by tectonics, whose preferential directions are NS and NNW-SSE. The valleys follow the direction of the crest lines and converge toward the star node of Podestagno-Pian di Loa, from which they branch off from the Boite Valley and emerge from the node with a meridian

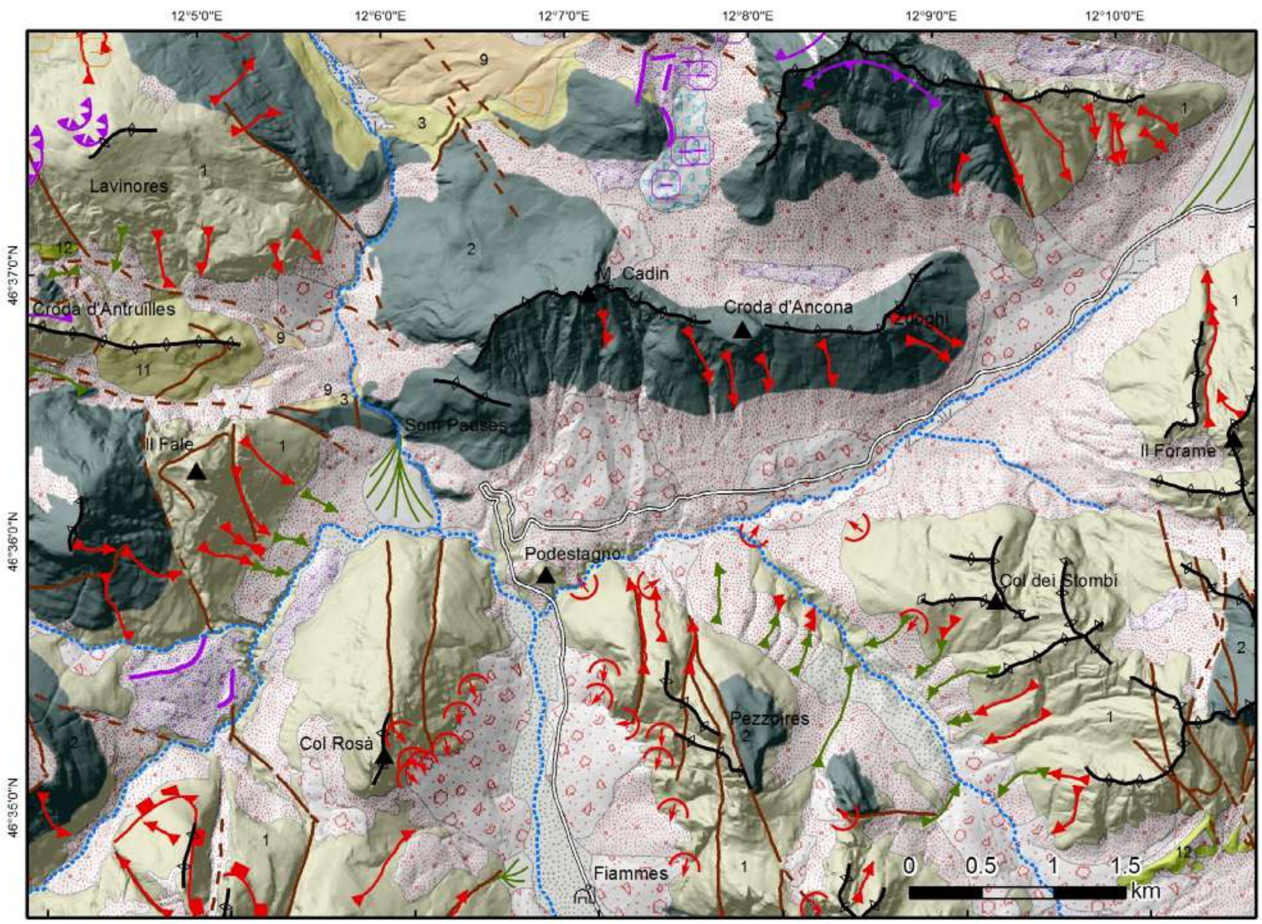

FIG. 11 - Geomorphologic map of the Som Pauses (see fig. 3 for legend).

direction. The valleys are mostly narrow, with bedrock outcroppings at their floor – except for the Boite Valley, which has a wider bottom filled with abundant alluvial deposits.

The vergence of the layer is to the north, forming a typical monocline. The inclination of the layers is about 10°-20° with a structural control on the Col Rosà, on the Tofane (outside the study area), and in the small Pomagagnon areas. The structure is part of the great syncline of Altopiani Ampezzani, the core of which is just north of the study area.

The rock slopes are mostly steep and strongly dissected depending upon the lithologies that constitute the bedrock, which are mainly dolomites and limestones belonging to the Upper Triassic and Early Jurassic. When covered by slope debris, the morphologies are more regular, with typical angles of the most abundant size classes. The foot of the summits is covered with slope deposits that reach the valley floor, often of considerable thickness. The debris is predominantly gravitational, forming talus and landslide bodies, and only in limited areas is the debris morainic (stadial deposits of the Val Travenanzes and small morainic ridges at the foot of the Croda Rossa d'Ampezzo).

Morphogenesis occurs through the denudation of the slopes (both gravitational phenomena and stream incision) and the fluvial erosion of valley floors. Downstream of the hydraulic junction of Podestagno, a number of debris flows are active both in the right and in the left slopes, determining the etching of deep canyons at higher elevations and associated accumulations that often reach the valley floor.

Military events. On May 20, 1915, the Imperial forces left Cortina d'Ampezzo and organized their defensive line in the Som Pauses. This barrage mainly prevented the Italian use of the road connecting Cortina d'Ampezzo to Carbonin, which was garrisoned by the 51st Mountain Brigade.

From August 7 to 15, 1915, the first Italian attack occurred, mounted by the Second Division: three columns, mainly supported by the bombardment of artillery installations north of Cortina d'Ampezzo.

The left column occupied Ponte Alto, interrupting the direct connection between the Austro-Hungarian positions in the Fanes Valley and those at Som Pauses. The center column took the Austro-Hungarian position of Podestagno but was then stopped by the defensive position of the Som Pauses, leaving many to die on the field. The right column was directed against Forcella Lerosa in order to encircle the positions of the Som Pauses, but the enemy entrenchments in the highest parts of the valley halted this incursion.

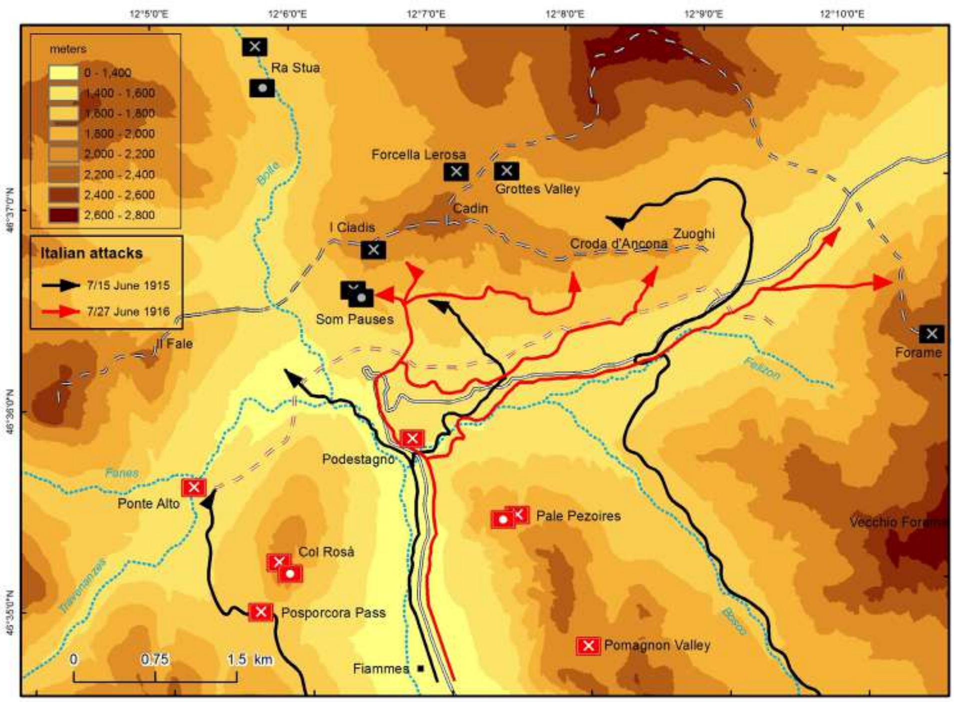

FIG. 12 - Som Pauses military history map (see fig. 4 for legend).

The failure of this operation was a consequence of insufficient artillery support – indispensable in breaking the excellent Austro-Hungarian defense system – and an inadequate number of troops, as well as extremely unfavorable topography. Nevertheless, these attacks allowed the Italians to move their first defensive line forward, thus consolidating their presence in Cortina d'Ampezzo.

During the autumn of 1916, other military actions occurred in this sector, mainly under the Italian initiative. These actions, however, were ultimately futile, as they caused many casualties without yielding any significant results.

The second important event in this sector was the Italian attack that occurred from June 7 to 27, 1916, in which four infantry regiments and two battalions of "Alpini" (Italian alpine units) participated. One column marched along the Felizon Valley, while the other climbed up the slopes of the Croda dell'Ancona and attacked the positions of Selletta di Som Pauses, I Ciadis, Croda dell'Ancona, and the Zuoghe. Even though, during the attacks, the Italians achieved some temporary successes, on the 10th day of the battle, they were forced to withdraw to their former positions. Tragically, the Italian forces suffered 324 deaths, 2826 injured, and 85 missing. No other relevant military event was registered in this sector until the Italian withdrawal after the defeat at Caporetto.

Comments about the relation between geomorphology and military events

The morphology of this area seriously affected the tactics of the Austro-Hungarian army, which sought to take advantage of summits and narrow valleys, occupying the Val Travenanzes-Som Pauses-Croda dell'Ancona.

The ridge of the Som Pauses is likely a tectonic-gravitational lowered block and forms a rampart from which the underlying narrow valley can be easily controlled (even with individual weapons), blocking access to the area of Ra Stua and to the upper Valley of Rio Felizon.

Croda dell'Ancona, adjacent to the Som Pauses, albeit less incumbent on the valley floor, forms a extremely elongated defensive barrier that follows the crests of Mount Taè and Mount Taburlo to the west. The gradient of the slopes is such that a frontal attack would be very unlikely to succeed. Indeed, the Italians failed to do just that in both 1915 and 1916; the Austro-Hungarians, garrisoning the mountain summits, prevented the circumvention attempted at Forcella Lerosa in 1916. The Forcella Lerosa constitutes a *cul-de-sac* that permitted a direct line of sight to attack Italian troops through crossfire from the northern face of Croda dell'Ancona and the southern slope of Croda Rossa d'Ampezzo.

Valparola Pass - Geomorphologic settings

The investigated area lies between the two passes of Falzarego, in the lower topographical position, and Valparola. The main focus of the study was the corridor stretching in a northwest-southeast direction between the Sass di Stria and the Lagazuoi (known as Ntra I Sass). The geomorphological setting is typical of the Dolomites. The main lithology is genetically related to carbonate platforms and depositional basins of the Middle and Upper Triassic formations, lifted and tilted by north-vergent thrust systems. There are significant summits (Sass di Stria and Lagazuoi), and the two passes themselves were generated by the great line of the Falzarego Thrust. The thrust forms two main hogbacks (Sass di Stria and the more elevated Lagazuoi) with impressive vertical

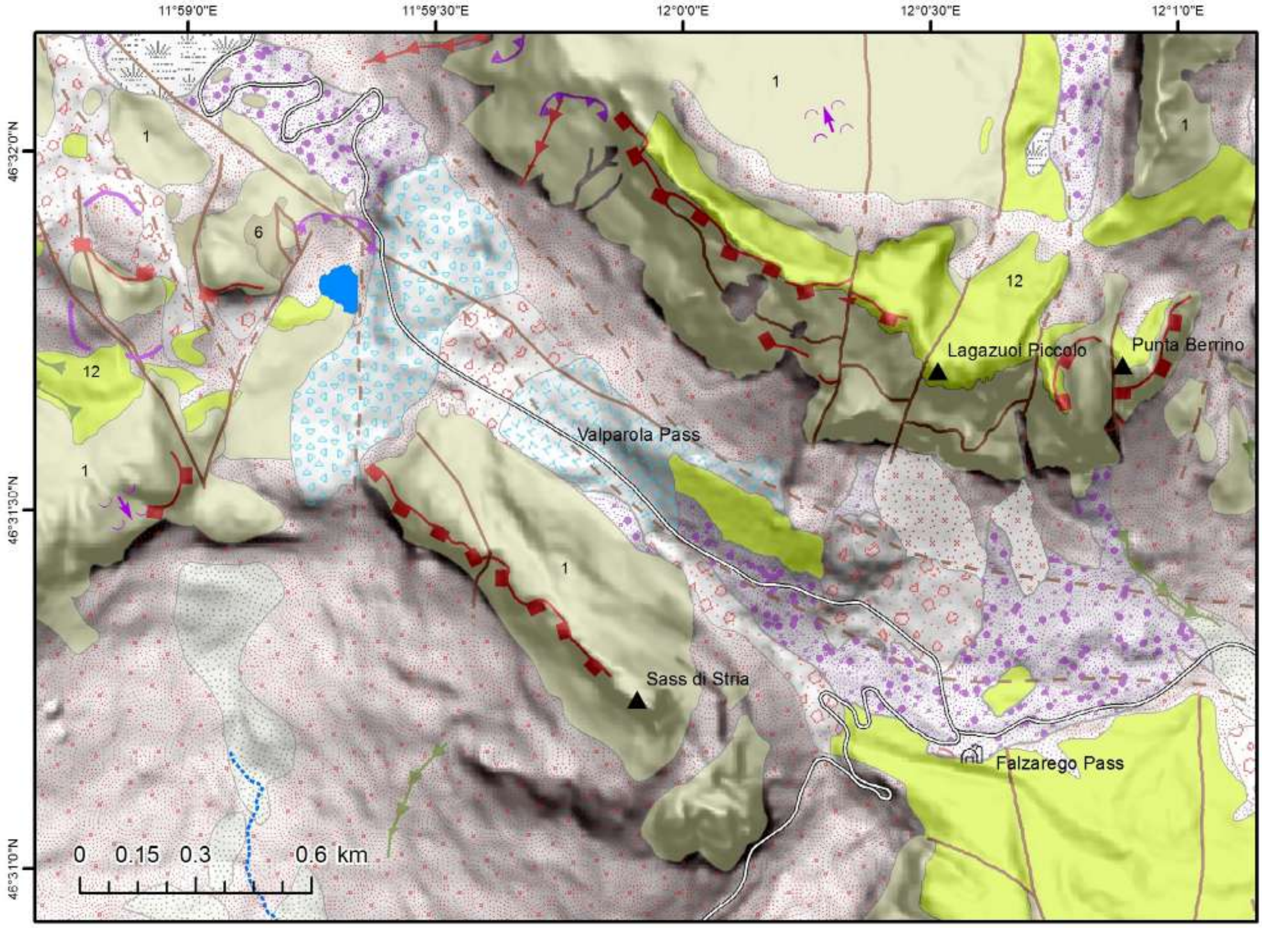

FIG. 13 - Geomorphologic map of the Valparola Pass (see fig. 3 for legend).

walls facing south, forming steep rocky gullies, pinnacles, and spurs; the entire area is also crossed by a subvertical fault system. Tectonic structural elements form ledges and escarpments. In particular, the ledge called Cengia Martini played a key role in the battle. It extends along a plane of thrust in correspondence with a cataclastic band where the Italian "Alpini" could more smoothly dig tunnels and shelters. The Cengia Martini constitutes a secondary structure associated with the Falzarego Thrust.

Talus deposits form at the foot of the rocky walls. On the valley floor, landslides and glacial deposits (mainly on the western side, belonging to the Last Glacial Maximum) reveal the action of the periglacial process, the most important being some large rock glaciers. The distinction between glacial and gravitational deposits is not easy to determine, and these deposits were likely generated by ice-rock avalanche deposits (Ghinoi & Soldati, 2017; Panizza & *alii*, 2011).

The glacial morphogenesis is widespread over the entire area of Falzarego-Valparola; some glacial cirques are present on the southern slope of Lagazuoi. Karstic forms are also present on limestones and dolomite formations.

Military events. The Valparola Pass represented one of the two main access points from the south to the Badia Valley, the other being the Campolongo Pass. The Italians did not launch important attacks during the first month of the war against the defenses of the Austro-Hungarian 51st Mountain Brigade. The Italian 17th Division moved forward from June 3, 1915, along the road to Andraz and occupied the areas that the Austro-Hungarians had abandoned voluntarily.

The most remarkable action accomplished by the Italians during this time was the June 15 conquest of the Goiginger position, an important observatory on the saddle of the Sass di Stria, which, however, was quickly reoccupied by the Imperial forces.

The Italian offensive became more determined after July 5, when the artillery bombardment intensified. The Tre Sassi Fort on the Valparola Pass was heavily bombarded. On July 9, simultaneously with other operations stemming from the conquest of Cima Falzarego and Col dei Bos, both east and next to the Lagazuoi Piccolo, two Italian columns moved forward from their departure lines. One column (fig. 14, A) emerged from the forests, which were south of the Sass di Stria, toward the Vonbank position, but the advance was quickly stopped by heavy fire from the defenders, who were distributed along the side of the two rocky reliefs, Sass di Stria and Lagazuoi. The other column (fig. 14, B), on the day after, once again surprised the Imperial forces on the saddle of Sass di Stria, but their occupation was brief, and the Italians were quickly driven out.

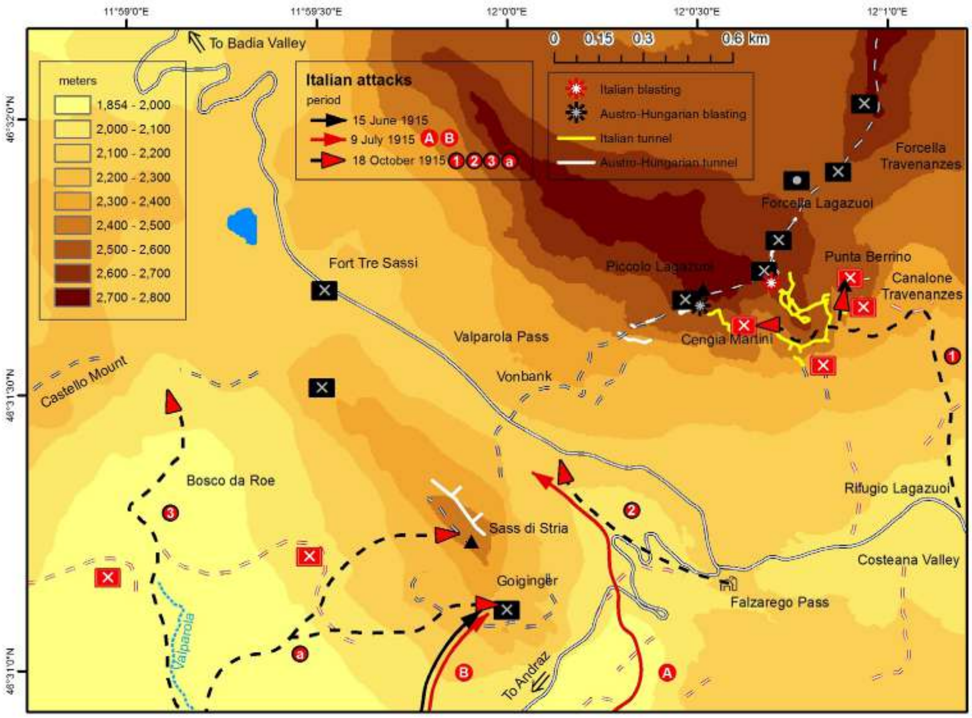

FIG. 14 - Military history map of the Valparola Pass (see fig. 4 for legend).

After these failures, the Italians started a systematic bombardment of all Imperial positions, and a small blitz was conducted until the second half of July, when the Italians launched offensives against the near reliefs (Col di Lana and Tofane). The attack against the *sbarramento* of Valparola was not carried out, as it depended on the result of the attack on Col di Lana and Tofane, which had failed.

On October 16, General Etna (commander of the 17th Division), in order to avoid the movement of the Imperial troops from this front to the Isonzo Front, ordered an attack on the Valparola Pass and the Imperial defensive works between the Settsass and Mount Sief (on the west side of the Rio Valparola). General Etna planned to attack with four columns, three of which appear in our area of study:

– Column 1 (fig. 14, 1): through the Cima Falzarego and Forcella Travenanzes toward the Lagazuoi Piccolo
– Column 2 (fig. 14, 2): from the head of the Costeana Valley toward the Valparola Pass
– Column 3 (fig. 14, 3): up to the Rio Valparola, from the forest, it would be steered toward the northeast side of Mount Castello and the western heights of Lake Valparola.

These attacks were preceded by another blitz against the Sass di Stria (fig. 14, A). This time, the Italians were able to take the peak, but only for a short time. On October 18, a major artillery bombardment started and, in the afternoon, the four columns advanced. The first column was able to take possession of the Punta Berrino and the Cengia Martini. From the Cengia Martini, the Italians controlled the left part of the Vonbank position and the paths that connected the Sass di Stria emplacements to the north (Mariotti, 1964).

The second column was stopped in front of the barbed wire by crossfire from the Sass di Stria and the Vonbank position. Likewise, the third column was stopped in front of the barbed wire. Both resumed offensive actions until the end of the month, but no progress was made.

Two other Italian attacks were launched in the sector of Sass di Stria-Valparola on the evenings of November 8 and 9, but without any significant results. After these last attacks, the Italians did not again attempt to break through the *sbarramento* of Valparola. The stalemate that consequently arose gave rise to "mine warfare," in which both parties sought to dig tunnels to reach the enemy positions and destroy them with explosives. At the end of October 1917, as in the other parts of the Dolomite Front, the Austro-Hungarians advanced with little resistance up to the new Italian defensive line on the Fiume Piave, facilitating the abandonment of the Dolomite Front.

Comments about the relation between geomorphology and military events

The Valparola Pass was particularly important in the context of the military operations in the Dolomites because it provided the most direct access to the Badia Valley. It constituted a bottleneck that could be easily controlled from the summit of the Lagazuoi to the northeast and to the crest of the Sass di Stria to the southwest.

At the beginning of the war, the Austro-Hungarians occupied the highest summits (Grande Lagazuoi, Piccolo Lagazuoi, Sass di Stria, and the higher sector of the Valparola Pass). The line of defense followed the juncture between the peaks along the change of the slope, where it was easier to dominate the attackers in the area of horizontal movement and where the slope at the foot of the defenders was steeper. The defensive line was elongated in this way and proved to be much more effective. Where the trenches and defenses were particularly exposed to the enemy or where there was no ground to provide suitable locations, soldiers from both sides dug galleries on the mountainsides. The same tunnels were also used for the "mine warfare" discussed earlier. The trenches were built with stone walls (sangars) using blocks from the landslides and slope deposits; when on bare rock, they were excavated, such as at Sass di Stria.

The goal of the fighting was twofold: first, to gain dominant positions from which access corridors could be controlled; and second, to conquer the passes.

The Italian attacks on the higher positions occurred in two phases: first, advances toward the top, especially along rocky gullies that allowed soldiers to take shelter; and second, close fighting at higher elevations. In all cases in which the Italians fought in the open field and started from the bottom, they were rejected. Invariably, the attack failed when the defender exploited its elevated position to dominate the space of movement of the attacker.

The attacks on the Sass di Stria occurred following the minimum slope and along stretches that were repaired as quickly as possible. The Sass di Stria was occupied by the Austro-Hungarians, who dominated the Valparola and Falzarego passes, as well as a stretch of the "Road of the Dolomites." The inclined profile of the crest dipping northeast and the favorable inclination of the layers provided easy access only to the Austro-Hungarians, while the Italians had to climb very steep cliffs. The steep sides of the Sass di Stria were a sort of natural bulwark.

The arrangement of the Austro-Hungarian defense was fully controlled by the geomorphological setting. Also, the location of the trenches that cut the valley transversally was conditioned by the longitudinal gradient changes that placed the Austro-Hungarians in a dominant position.

Considering the Italian attacks on the Lagazuoi, the presence of the typical dolomitic morphology given by steep walls, with ravines and spurs, allowed a slight, but sufficient, shelter to the Alpini's attack. They could climb the wall and effectively occupy the Cengia Martini, arriving just 150 m from the Austro-Hungarian line. The Cengia Martini, formed along a secondary thrust, allowed the Italians to occupy approximately 200 m of wall at about 2500 m ASL, away from Austro-Hungarian gunfire, roll bombs thrown from above, and mines.

The Piccolo Lagazuoi was particularly affected by the "mine warfare," which altered the morphology of the area by creating deep scars on the slopes as well as craters and debris cones generated by the explosions. Actions at high altitude became mountain warfare in which training and the movement capability of the soldiers in extreme conditions prevailed. The movement was no longer of great masses of men horizontally, but of small groups vertically.

Today, the area of the Lagazuoi presents its trenches, tunnels, huts, signs of collapse and explosions, and accumulations of debris at the foot of the slopes. The blasts of the five mines that took place from January 1, 1916 to September 16, 1917 generated two large debris cones at the foot of the south face of the Lagazuoi. The explosions also created large craters in the summit walls and opened deep fractures on the vertical side. On the northern side of the Sass di Stria, a 500 m-long tunnel dug by the Austro-Hungarians and used as warehouses, kitchens, dining rooms, depots, garrisons, and accommodations is still preserved. It presents a dozen louvers open on the sidewalls. The Italians dug an 1100-m-long helical tunnel under the Piccolo Lagazuoi that is remarkably still passable today.

CONCLUSIONS

The border between Italy and Austria follows main crest lines according to the geomorphological alignment with a sinusoidal geometry. At the onset of the First World War, the Austro-Hungarians retreated for many kilometers in several tracts (Vergara & *alii*, 2018), aiming to shorten the front line and to establish a more favorable defensive line, particularly in the Som Pauses area.

Italian efforts in the Dolomites were focused on controlling the mountain passes so as to quickly open the gate to Val Pusteria and South Tyrol. The particular geomorphology of the Dolomites includes several peaks, each of which is over 3000 m.a.s.l., with steep or vertical walls, usually hundreds of meters high, mainly in the form of cuestas morphology. The invasion of the Austro-Hungarian territory with a traditional army would have been possible only by moving along the major valleys and crossing the Alpine passes.

These passes were all dominated by high summits, which allowed the Austro-Hungarians to easily hold defensive positions and thereby control movements along the valleys (usually narrow, apart from the Montecroce Comelico Pass). The high elevations and the limited space for maneuvering led to the systematic failure of the Italian attacks. The Italian forces were forced to move uphill on slopes whose inclinations were prohibitive even for Alpine troops. Without the opportunity to deploy troops along a wide front, Italian superiority was thwarted.

Only the attacks carried out by small Italian units with alpine experience were able to achieve limited tactical goals (winning the Sentinella Pass, the Piccolo Lagazuoi, and the Cengia Martini). Denivelation and slope steepness allowed the Austro-Hungarians to easily defend the summits. Combat continued unabated for two and a half years without the achievement of significant results.

When the war turned to "mine warfare," the dolomitic formations permitted the digging of long tunnels in the mountains, which in turn allowed soldiers to live more comfortably in the hard alpine climate, effectively protect themselves against artillery fire, and occupy the summits in a protected position. Debris accumulations provided stones and blocks useful for the construction of sangars, trenches, and shelters, thereby facilitating the construction of trench networks very different from those erected along the Western Front.

While the presence of vertical walls constituted a natural defense against Italian attacks, the slopes facing Austro-Hungarian territory were usually protected from direct artillery fire from Italians and provided cover from enemy observers, who could not effectively direct their artillery and other weapons. The slope gradients were generally favorable to the Austro-Hungarians, being lower on the northern quadrants.

Dolomite is a compact rock amenable to the construction of self-sustaining tunnels (and with a limited danger of collapse). This facilitated the "mine warfare" (among the case studies in this research, we considered only the Lagazuoi, but it is worth noting that similar tunnels were realized at more than 30 sites along the Dolomite Front). The compactness of the rock and the logistics needed to drill tunnels required many months of hard work, often resulting in marginal tactical advantages.

In conclusion, the characteristic landscape of the Dolomites created unique morphologies with high asymmetric peaks, steep slopes, and narrow valleys. The battles that occurred here during the First World War were primarily concerned with summit positions, the possession of which ensured the defense of the Austro-Hungarian territory during the entirety of the war. Holding these summits was also essential for directing artillery fire so that the Austro-Hungarian supply lines, placed in a tight angle, would be relatively unaffected by Italian batteries.

Geomorphology played a fundamental role, altering the balance of forces, military training, and the number of supplies, which, in the open field, played an equally fundamental role.

Finally, the organization of Austro-Hungarian defenses and the plans of attack devised by the Italians seemed to have followed the same scheme everywhere and without exception, mostly because the terrain in which warfare between these two factions took place gave no reasonable alternatives to the combatants.

APPENDIX 1 - HISTORICAL SETTINGS

Italy declared war on Austria-Hungary and joined the Allied forces on May 23, 1915, approximately one year after the assassination of Archduke Franz Ferdinand of Austria. The theater of war between the Italian Kingdom and the Austro-Hungarian Empire was determined by the state border that had existed between the two countries since the Treaty of Vienna in 1866. When offensives began, a large part of the state border became the war front. This front mainly extended through the Eastern Alps, from the Swiss border to the Adriatic Sea (fig. 2). The Dolomites occupied the central part of this front.

Due to Italy's military alliance, as well as political, economic, and irredentist national interests, the Italian military was forced to take an offensive stance. The operational design of General Cadorna, Chief of Staff of the Royal Italian Army, identified the country's key strategic objectives beyond the Julian Alps and the "Carso" (the "Classic Karst" area at the Italian border with modern-day Slovenia). The bulk of the Italian forces were therefore deployed in these directions.

Despite this fundamental operational design, on the eve of their entrance into the war, and after a careful reassessment of the strategic and organizational situation of the two armies, the Italian Kingdom and its Chief of Staff, General Cadorna, established a defensive stance for the entire front during the army's mobilization. The only exception concerned the Italian 4th Army, deployed in the central sector of the war front, which included the Dolomite region. In the document *Variations to the directives of 1st September* (SME-US, 1927-88, vol. 2 bis), issued on April 1, 1915, whose instructions were implemented at the beginning of the war, General Cadorna assigned what would have been the first objective of the 4th Army: to reach the Puster Valley. Therefore, the 4th Army became the only major unit that, from the beginning of the war, was assigned a task beyond the state border that was of strategic, not just tactical, importance.

The initial operational plans of the Austro-Hungarian Empire against Italy were strictly defensive. From August 1914, the Empire was heavily engaged on both the Russian and Serbian fronts. In fact, when Italy declared war, Austria-Hungary was forced to rely mainly upon local militia for the new Alpine war front until other forces could be moved to the region from the other fronts (SME-US, 1927-88; Langes, 1981; Berti, 1982, 1985; Del Negro, 1994; Lichem, 1995; Pieri, 1998; Thompson, 2008; Mondini, 2015; Pozzato, 2015a, 2015b; Scroccaro & Bondesan, 2016).

Despite the difficulties faced in the Carpathian and Balkan fronts, from the autumn of 1914, the Austro-Hungarian General Staff carefully initiated preparations in case of an Italian front. At the beginning of March 1915, at Bolzano, the Command of the "Pustertal" Division was established. This division, basically comprising two brigades, was deployed from the Passo Pordoi to the zone of Mount Peralba n. 1 and 5 in fig. 2) and was appointed to the defense of the Puster Valley. The *Alpenkorps* contingent, a valuable reinforcement for the Austro-Hungarian forces in the Dolomites, arrived from the German Empire two days after hostilities with Italy began (Berti, 1985).

APPENDIX 2 - MILITARY GEOGRAPHY

Military geography, the science that studies the influence of geographical elements on military operations (Porro, 1898), presents two main areas of interest: "in one respect [military geography] is of an applied nature, employing the knowledge, methods, techniques, and concepts of the discipline [geography] to military affairs, places, and regions. In another sense, military geography can be approached from an historical perspective" (Palka & Galgano, 2005).

Although the first treatises on military geography were published in the first half of the 19th century, the applied nature of military geography emerged in Europe in the second half of the century (Porro, 1898) by focusing mainly on geology and its influence on military operations. Among the forerunners of this new military applied study, Sonklar (1869, 1873) stood out in Austria, while Fervel (1873, 1875), Clerc (1876, 1880a, 1880b, 1883, 1888), Niox (1880), and Marga (1885) distinguished themselves in France.

After WWI, interest in geology continued to increase within armies, and "the advent of the Second World War brought about the proliferation of applied geology on a scale hitherto unimagined" (Kiersch & Underwood, 1998;

Rose & *alii*, 2019a; Laterza & *alii*, 2019; Galgano & Rose, 2020). This was particularly true in Germany (Häusler & Willig, 2000), the UK (Rose & Rosenbaum, 1998) and the US (Terman, 1998).

The application of geology to the solution of military problems was definitely strengthened and tested during the Second World War, when many geologists were employed in national armies (Rose & *alii*, 2019b). During this conflict, the tasks of geologists were predominately in the areas of water supply, military mining, dugout construction, locating construction materials, and terrain classification for the mobility of troops and vehicles (Kiersch & Underwood, 1998; Kress, 2002). For instance, geologists made significant contributions to the Allied armies, particularly in the UK (Brooks, 1920; Rose & Rosenbaum, 1998; Rose & *alii*, 2000; Rose & Pareyn, 2003), the US (Brooks, 1920; Pittman, 1998), and France (Brooks, 1920). The armies of the Central Powers also paid significant attention to military geology. Indeed, by 1918, some 100 German geologists were contributing to the solution of military problems on the Western Front (Brooks, 1920).

During the Cold War, the synergy between geology and the military continued to grow under the guidance of technology and quantitative analysis (Barnes, 2008). The application of geology to military operations, as developed in the European and Pacific regions, was the most important advancement in engineering geology during the 1940s and 1950s (Kiersch, 1955; Leith, 1997). Furthermore, many important textbooks and publications that advanced the principles of engineering geology practice and military geology were issued after the Second World War, including those by Trefethen (1949), Paige (1950), Eckel (1951), Keil (1954), Kiersch (1955), and Schultz and Cleaves (1955).

In the present day, applied military geography is developed within military organizations, such as national and international defense institutions, and it is linked to various activities, such as cartographic production or searching for underground water resources. However, this approach also attracts the interest of academic scholars, as evidenced by studies regarding some of the most recent wars, such as those in Kosovo, Afghanistan, and Iraq (e.g., Beck, 2003; Palka & Galgano, 2005; Palka & *alii*, 2005; Palka, 2008; Willig, 2012; Gellasch, 2014; Rose, 2014; and Vlachopoulos & Skordaki, 2016).

The other major area of interest for military geography, which concerns historical studies, has a longer tradition than applied military geography. In fact, Porro (1898) stated that "military geography was the branch of geography that for longer and more tightly was related to the history, because it represented an essential complement for the knowledge of the theaters of war."

Over time, the relationship between military geography and military history developed in two main directions. One way, the most recent one, is considering the impact of past war events on geography, particularly on natural environments. The majority of those interested in studies that relate military geography and military history are geographers. Some recent examples of this approach include Collins (1998), Hupy (2006), Hupy and Schaetzl (2008), Hupy and Koehler (2012), Smit (2018), and Galgano (2019).

The other way, the classical one, considers military geography as a key aspect in understanding past military events and views geography as a main factor constraining military operations and the outcomes of battles, campaigns, or wars. The results obtained by this approach represent an interest in historiography.

Currently, however, only a few scholars, the majority of which are Anglophones, are interested in considering the influence of geography on warfare. Some of these scholars are represented by the International Association of Military Geosciences (Rose, 2018), which holds the International Conference of Military Geosciences every two years and publishes the proceedings of each conference (Underwood & Guth, 1998; Rose & Nathanail, 2000; Ehlen & Harmon, 2001; Doyle & Bennett, 2002; Caldwell & *alii*, 2004; Nathanail & *alii*, 2008; Häusler & Mang, 2009; Rose & Mather, 2012; McDonald, 2014; McDonald & Bullard, 2016; Rose & *alii*, 2019a; Guth, 2020). In this context, military geographic analysis of past events is carried out mainly by geographers and geologists who apply tools, methodologies, and materials typical of their disciplines. Studies supported by digital technologies, such as GIS and remote sensing, have thus been published in recent years (Zacharova & Elznicova, 2014; Dykes & Hancock, 2002). GIS, in particular, produces results suitable for the integrated analysis of spatial and historical data (e.g., Koch & El-Baz, 1998; Beck, 2003; Bondesan & *alii*, 2013, 2015; Smith & Cochrane, 2011; Magnini & *alii*, 2017; Vergara & *alii*, 2018).

Particularly with respect to WWI, the majority of the studies that concerned military geography followed the classical approach, which considers military geography as a key aspect of understanding past military events. These kinds of studies were developed even from the first moments of the war (e.g., Leaf, 1916; Sacco, 1916; Gortani, 1920; Bryan, 1920; Brooks, 1920; Anselmi, 1921; Martonne, 1925; Fossa-Mancini, 1926). Among the studies regarding the Italian Front, Johnson's (1917, 1921) books, which focus mainly on strategic aspects, stand out.

Examples of scholars recently interested in the geologic influence on the military events that occurred on the Western Front include Doyle and Bennet (2002) and Willig (2011). Barrett and Badoi (2011) have published research on the Transylvanian Front, while Schramm (2011), Bondesan & *alii* (2015) and Vergara & *alii* (2018) considered the Alpine Front.

With respect to the bibliography specifically focused on the influence of geography on the Dolomite Front during WWI, it can be considered sparse, even though almost every author who has considered the military events on that front has highlighted the importance of geography. Beyond the texts that were published during or just after the war, the only references found that apply a military geography reading to the events that occurred in the Dolomites are part of the proceedings of the VIII International Conference of Military Geosciences (Häusler & Mang, 2009), the conference "In guerra con le aquile" (Argentieri & *alii*, 2015), and the XIII International Conference of Military Geosciences (Bondesan & *alii*, 2019).

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