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WWI MILITARY USE OF CAVES IN THE CLASSICAL KARST OF NORTHEASTERN ITALY

Abstract: Bondesan A., Fioraso M. & Preto N., *WWI Military Use of Caves in the Classical Karst of Northeastern Italy.* (IT ISSN 0391-9838, 2022).

The area of the Classical Karst in Northeastern Italy was involved during the Great War by a series of military actions known as "the Twelve Battles of the Isonzo". The knowledge of the karstic landscape and its features clearly represented an advantage in military operations. A well-consolidated theoretic military geological preparation led armies to exploit for warfare purposes natural morphologies, such as caves, sinkholes, fault scarps and dry valleys; many artificial modifications were apported to the hypogean and epigean landscapes to adapt landforms to military purposes. Human-made tunnels, walls, stairs, floors, built with concrete and/or rocks found onsite, served to the realization of complex defensive systems, whose strategical importance was newly re-discovered in recent times. Two hundred and twenty natural caves have been mapped in the Italian Classical Karst that were used in wartime, to analyze their utilizations and geographical distribution. Most caves were used by soldiers as shelters, representing a safe natural environment during enemy artillery bombings. Several other purposes reveal the complexity of artificial adaptations and planning in construction works. Water reserves, electrical stations, command posts, ammunition depots are only few examples of the natural exploitation offered by caves. We investigate six Austro-Hungarian military caves from various locations along the frontline, describing their different artificial modifications and geological features. The Classical Karst not only represents a globally known key site for the study of karst geomorphology, but is also one of the most iconic traits of warfare on the Austro-Hungarian front during WWI.

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Key Words: War caves, Military geosciences, Italian Classical Karst.

Riassunto: Bondesan A., Fioraso M. & Preto N., *Grotte ad uso bellico durante la Prima Guerra Mondiale nel Carso Classico dell'Italia nord-orientale.* (IT ISSN 0391-9838, 2022).

Durante la Grande Guerra le dodici Battaglie dell'Isonzo furono combattute sul fronte del Carso. La profonda conoscenza del territorio carsico e delle sue caratteristiche ha rappresentato un vantaggio nel corso della guerra. La preparazione e la pianificazione teorica nell'ambito della geologia militare ha portato gli eserciti contrapposti a sfruttare le morfologie naturali tipiche dell'area. Numerose modifiche antropiche sono state apportate sia nel sottosuolo carsico che in superficie, così che elementi quali: tunnel, muri di sostegno, scale e pavimentazioni, costruiti facendo uso sia di materiali cementizi che pietra locale, hanno consentito la realizzazione di una complesso sistema difensivo cruciale per la sua importanza strategica. Duecentoventi cavità naturali sono state inserite in un database per analizzarne la loro distribuzione geografica e l'utilizzo. La maggior parte delle grotte sono state impiegate come rifugio dai soldati, grazie al riparo che naturalmente fornivano dal fuoco dell'artiglieria nemica, ma numerosi altri utilizzi delineano un quadro certamente complesso nella pianificazione dei lavori apportati nel contesto carsico. Alcuni esempi di utilizzo: riserve di acqua, stazioni elettriche, posti di comando e depositi di munizioni. In questo studio sono state investigate 6 grotte poste in diverse località rispetto ai fronti, e differenti anche per scopo, per descrivere l'utilizzo antropico e le tipologie di caratteristiche geologiche sfruttate a supporto dell'esercito Austro-Ungarico. Il Carso Classico non rappresenta solo una sito di importanza mondiale per lo studio del fenomeno carsico, ma al contrario, è anche un ottimo *case study* per osservare le interferenze delle attività antropiche e militari in un contesto naturale. Lo sfruttamento umano del paesaggio epigeo e del sottosuolo rappresenta uno dei tratti più iconici della campagna bellica Austro-Ungarica sul fronte della Grande Guerra che si pone in diretto confronto con numerosi altri simili paesaggi in tutto il mondo.

Termini Chiave: Grotte di guerra, Geoscienze Militari, Carso Classico Italiano.

INTRODUCTION

Wars and karsts represent two important elements of the complex relationship between human existence and natural resources. If a modern point of view of conflicts between nations can be compared to a science (Pogue, 1917) or to an extensive application of multidisciplinary scientific knowledge, it is apparent that geosciences may be one crucial applied science capable of modifying war achievements. Analyzing geological applications to warfare in WWI, Pogue (1917) highlighted three main aims: (a) the use of geological knowledge, such as engineering geology and geomorphology (selection of campsites, construction of drainage systems, excavation of trenches and tunnels, mine warfare, etc.), (b) the employment of geologists in operations (especially for cartography), and (c) the exploitation of resources (water supply for troops and animals, crushed stones and gravel for concrete, terrain trafficability, etc.).

A much more detailed and modern analysis appears in Bondesan & Ehlen (2022) and Guth (1998), who consider military geoscience applications to engineering, intelligence, logistics, and, likely most important, the education of soldiers in peacetime, promoting important roles in civil protection. In Galgano & Rose (2021), strong emphasis is placed on georesources, such as raw materials and water supply, engineering geology (the application of geotechnical problems to wartime construction works), and terrain analysis. From quantitative analysis of photographs in WW1 (Collier, 2018), and large-scale projects such as the Pacific geological mapping program (Corwin, 1998), to recent geographic information systems (GIS), significant breakthroughs occurred in military decisions thanks to what can be called "geologic intelligence." Such technologies have been fundamental to activities undertaken not only in wartime, but also in peacetime, contributing to a precise evaluation of military impact on territory (e.g., bomb cratering; Kiernan, 2010a).

Since the beginning of the 19^{th} century, military geology achieved a fundamental role in conflicts and their outcomes (Kiersch & Underwood, 1998). With the major technological advances in weaponry, the capability to know exactly where to strike an enemy and where to protect one's own forces has become the only way to gain and maintain an advantage during military operations. With large-scale trench excavation during WWI, especially on the Western front, the geological substrate played a major role in the structuring of defense lines (Kiersch, 1998). On the Southern front, between the Austro-Hungarian and Italian armies, the landscape and subsurface early on became iconic in the imaginary of WWI battles. As one Austrian slogan stated after Italian artillery bombing in the fourth Isonzo battle: "We have but to retain possession of a terrain fortified by nature to win" (Kiersch, 1998). The "fortified terrain" to which the Austrian was referring was the Classical Karst.

A karst (Ford & Williams, 2007) is a landscape marked by caves and extensive underground water systems that occur in particular types of rocks that are soluble by water-based solutions, such as carbonates and evaporites. It has been roughly estimated that more than 20% of the human population lives in karstic territories. Ever familiar to Europeans, the term "karst" can be traced back to pre-Indo-European languages, referring to "stone" (Gams, 1993; Ford & Williams, 2007). The state of the art on karst studies and related geomorphological features was refined in the Classical Karst, in the northern portion of the Dinaric Mountain chain, which encompasses a wide plateau spanning Italy, Slovenia, and Croatia.

The exploitation of natural caves for war purposes may have originated long ago, initially as underground refuges for "Paleolithic humans" (Guth, 1998) to protect them from external environmental forces and other human beings. Later, the opportunity to exploit large and complex natural underground facilities shielded by several meters of solid limestone and dolostone (two of the most diffuse lithologies in karstic areas) became a valuable advantage during the large-scale development of artillery and aerial bombing.

Most of the best-known utilizations of caves during wartime occurred in Indochina and in the Pacific archipelagos. During WWII, the best-documented examples of such utilizations were the Japanese defense of tactically important sites such as Palau Island, Bismarck Island, and the Mariana Islands. Peleliu Island (Palau Archipelago) was fortified with at least 118 caves and tunnels (Price & Knecht, 2012) which were systematically located along a reef-limestone ridge. These caves were used as small-scale refuges, similarly to caves found in the Karst, and were crucial to defending against the US naval bombings that usually occurred before landing operations. In some cases, the facilities were large enough to host a hospital and a headquarters, from which nocturnal attacks could be launched (Price & Knecht, 2012). Guam (Mariana Islands) differs from small-sized coralline atolls due to the presence of a well-developed and extensive karst (48 km long, 6 to 19 km wide), with wide karst aquifer structures serving as a deep freshwater lens. Glacio-eustatic sea-level variations and active tectonics resulted in a complex karst system, with allochthonous water inputs from the volcanic substrate (Mylroie, 2001; Taborosi & *alii*, 2005). This karstic landscape shares many similarities with the Classical Karst and Italian south-alpine plateau, which also includes several caves that differ in terms of origin: pits, collapse dolines, vadose and phreatic caves, and pervasive fractures (Taborosi & *alii*, 2014). In Indochina, the widespread wartime use of caves is recorded in Cambodia and Laos, where tropical-type karst features are present, with ancient caves dominated by planarly developed large rooms and typical towers or pinnacles. In this case, in addition to cave modifications, capable of altering the natural integrity of the karst system (Kiernan, 2012), surficial alterations and destruction related to bombings and military operations affected the substrate and impacted soil erosion (Kiernan, 2010a, 2010b).

In WWI, the Austro-Hungarian and Italian armies along the front settled into peculiar karst areas located in the Pre-Alps and Dinarides and along their foothills, such as the Asiago Plateau, Montello Hill, and the Italian Classical Karst Plateau. Considering the spatial distribution of caves and geological structure in the karstic landscapes involved in military operations during WWI and the importance of underground facilities in the conflict, this work aims to analyse the role of the so-called "war caves" and the transformations they have undergone. We focused on the wartime uses of natural caves, looking at artificial modification and exploitation of natural resources, to address their value and the magnitude of impact played during the defense of the Classical Karst territory. This will give the chance to understand this new, integrated defensive system made by artificial constructions and natural morphologies, which involved various sorts of military (and civilian) activities during WW1.

In the following section, a set of case studies detailing artificial modifications of natural caves in the Classical Karst and the exploitation of geological features of karst terrain will be analyzed and discussed. The plateau of the Classical Karst was of high strategic importance (Gherlizza & Radacich, 2005) for both the Italian Royal Army, as a corridor leading directly to Ljubljana, the current capital of Slovenia, and the Imperial Austro-Hungarian Army, as a natural defense of the city of Trieste.

METHODS

This study aimed to analyze military adaptations of cave interiors in the Italian Classical Karst during WWI, considering their positions along the frontline and the surrounding main morphological structure. Geological mapping was performed through the digitalization of lithological boundaries and tectonic lines, mainly derived from Jurkovšek & *alii* (2016) and Cucchi & Piano (2013b), via the use of ARCGIS™.

Three Digital Elevation Models (DEMs) were created. A 90-meter resolution DEM derived from open-access data from the TanDEM-X mission (German Aerospace Center) (Rizzoli & *alii*, 2017; Wessel & *alii*, 2018) provided a general framework of the Classical Karst, one which allowed for the reconnaissance of larger structures. A further detailed morphological analysis focused on the Italian Classical Karst area was performed through 10-meter and 1-meter DEMs and hillshade models. Digital orthophotos and numerical maps at 1:10,000 scale were available and downloadable from the cartographic websites of the Friuli-Venezia Giulia and Veneto regions.

Descriptions and geographical coordinates of the caves considered in this study were collected from the online regional inventory of caves of the Friuli-Venezia Giulia (Servizio Geologico Friuli-Venezia Giulia, 2022) and Veneto (Federazione Speleologica Veneta & Società Speleologica Italiana, 2019) regions as well as from Gherlizza & Radacich (2005), who published the most detailed and complete paper on war caves.

Six caves were chosen as case studies of cave modification for military purposes during WWI. These six caves reflect different modification features in various geological and geomorphological contexts. All of the caves have been explored, photographed, and described through speleological and geological surveys.

A statistical analysis based on the war cave inventory in Gherlizza & Radacich (2005) was carried out, considering their military use and spatial distribution in relation to frontlines and karstic features.

STUDY AREA AND HISTORICAL BACKGROUND

Geological Background

The Classical Karst is a carbonate plateau located between Italy and Slovenia and facing the Gulf of Trieste, in the northern part of the Adriatic Sea. The term "*kras*" in the Slovenian language refers to a sterile, rocky territory without water capabilities (Gams, 1993). The stratigraphy of the area is marked primarily by a succession of carbonate units deposited from the Lower Cretaceous to the Eocene in the Friulian sector of the Adriatic carbonate platform (Vlahovic & *alii*, 2005) and a flysch unit deposited after the drowning of the platform as a consequence of intense tectonic activity (fig. 1). The Classical Karst is characterized by two primary orientations of geological structures: NW-SE and NE-SW (Jurkovšek & *alii*, 2016; Placer, 2015; Tentor & *alii*, 1994).

The NW-SE orientation is aligned with some of the largest structures in the area, such as the Trieste-Komen anticline (which runs along the Italian-Slovenian border) and the Karst Thrust, which superimposes the plateau over flysch and Quaternary deposits on the present marine shelf, as well as some major faults, including the Brestovica Fault, the Rasa Fault, and the Divaca Fault, dissecting the plateau. The NE-SW orientation is marked by many minor strike-slip lineaments sectioning the plateau, especially in the Italian part (Cucchi & Piano, 2013a; Cucchi & Piano, 2013b; Jurkovšek & *alii*, 2016).

All of these features are part of a complex structural setting linked to two main directions of tectonic stress: the first of the Dinaric type (NW-SE), especially in the northern part of the Karst, and the second of the Alpine type (NW-SE). Tectonic structures played a fundamental role in speleogenesis in the region. In the northern part of the Karst, there is also evidence of interference of the two main directions of lithospheric stress, causing the structures to rotate from the original NW-SE Dinaric orientation to a WNW-ESE orientation due to alpine compression. Bedding on the southwestern part of the main anticline dips to the SW with moderate inclination while, in the northern part (Doberdò Karst), some beddings rotate to the north, creating a sort of dome structure perpendiculary dipping to the Karst border (Cucchi & Piano, 2013a; Cucchi & Piano, 2013b; Jurkovšek & *alii*, 2016).

In the area considered in this study, nine lithostratigraphic units (Jurkovšek & *alii*, 2016) have been recognized. Typical calcareous and dolomitized facies of carbonate platform were deposited from the Barremian to Thanetian Age, and a flysch made of syn-orogenetic turbiditic siltstone, claystone, sandstone, and marls was deposited during the Ypresian (Eocene) Age and has been associated with the formation of the Dinaric foredeep (Lenaz & Princivalle, 1996).

Today, the flysch surrounds the plateau from the southern part of the Classical Karst to the North-Istrian Karst along the Adriatic coast. On the plateau, the most important Quaternary deposits are Terra Rossa, a typical residual deposit or soil of the Mediterranean Karst, alluvial-colluvial deposits, and cemented talus deposits (Cucchi & Piano, 2013a).

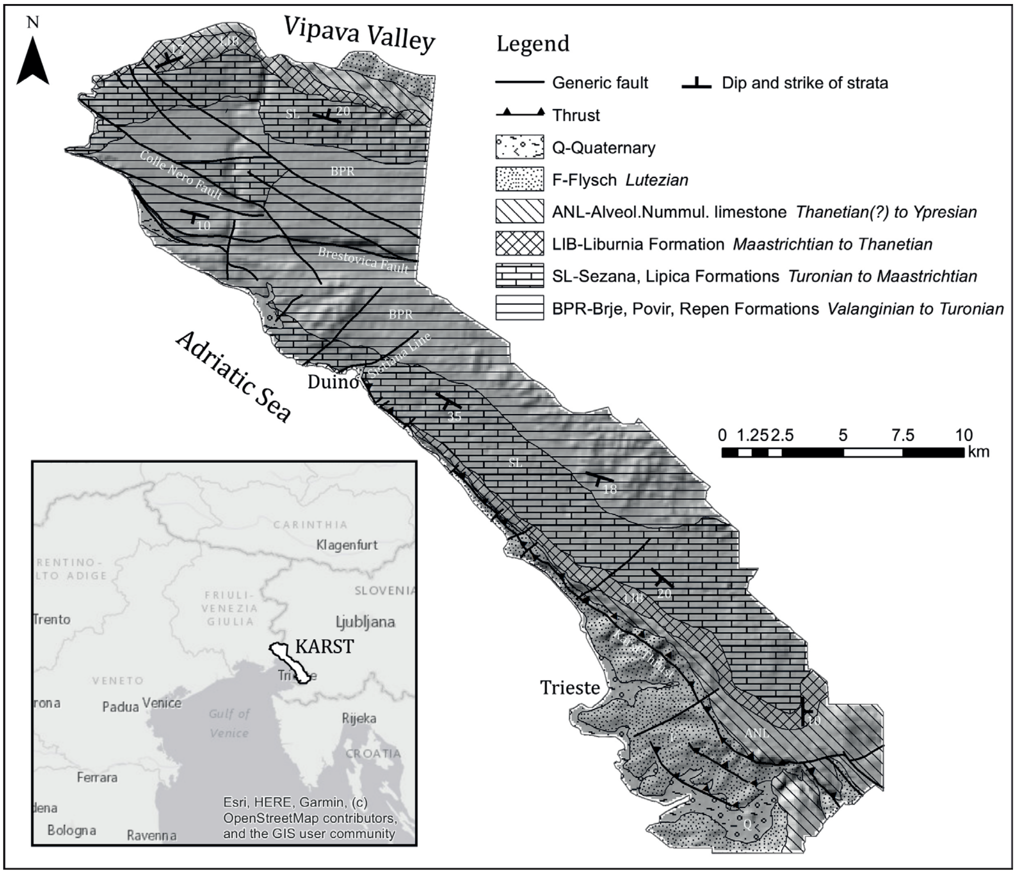

FIG. 1 - Geographical framework and geological sketch map of the study area, based on Jurkovšek & *alii* (2016). The area encompasses the entire Italian Classical Karst and the uppermost sector of the Slovenian Karst (Kostanjevica Karst).

Geomorphology of the Classical Karst

A karstic environment like that of the Classical Karst is composed of carbonates such as limestone and dolostone, which are affected by water dissolution processes, and a rocky massif characterized by high secondary porosity (faults and joints). On the surface, there are epikarst features such as watercourses absorbed by sinkholes, caves, depressions (dolines and uvala), karren fields, and springs. In the Classical Karst, a territory formed in an area with two different tectonic stresses with different orientations, the presence of a large structure (such as the Trieste-Komen anticline) and a net of faults were fundamental in the formation of a huge underground cave network.

The Karst Plateau extends from the Adriatic Sea to the south to Vipava Valley to the north (fig. 1), and from the alluvial plain of Isonzo River to the west to Brkini Hills to the east. On the Karst Plateau, several planation surfaces and paleo-valleys, which developed as corrosion plains (dammed karst condition) and were shaped by fluvial erosion (Gams, 1998), are found. Two main watercourses once flowed from the SE to the NW (D'Ambrosi, 1966; Gams, 1998) following the ridges and the anticlinal structure along the Italian-Slovenian border. One of these two main rivers can be identified as a paleo-Timavo/Reka river, and numerous other rivers could have flowed from Vipava Valley over the Karst Plateau before tectonic uplift deflected flow directions.

On the Classical Karst, morphological elements are located on two main elevation levels, one made of hills and ridges that surround and divide the plateau into smaller parts, and another made of karst plains. These morphologies are divided into different units as drawn in the geomorphological map (fig. 2). Especially in the Italian area of the Classical Karst, the central ridge that runs along the state border between Medeazza and Sezana is formed by the most ancient calcareous units, despite rocks on the plain between Basovizza and Sistiana being more recent. Karst plains can preserve small differences in elevation and small scarps formed by tectonic displacement between adjacent structural blocks. In the map, the karst plain in the northern sector is divided into upper and lower units (upper karst plain and lower karst plain of fig. 2) to highlight the changing topography.

Other important features are border ridges located on the extremes of the Classical Karst that are preferentially related to lithological boundaries. Dry valleys such as those of the Isonzo or Vipava rivers are impressive morphological elements.

On the surface, but especially on the Karst Plateau, numerous caves have been inventoried. These caves commonly exhibit, in the upper sectors, horizontal or sub-vertical morphologies that can be associated with bathyphreatic or phreatic speleogenesis, which itself can be related to a tectonically stable period in which the carbonate plateau was

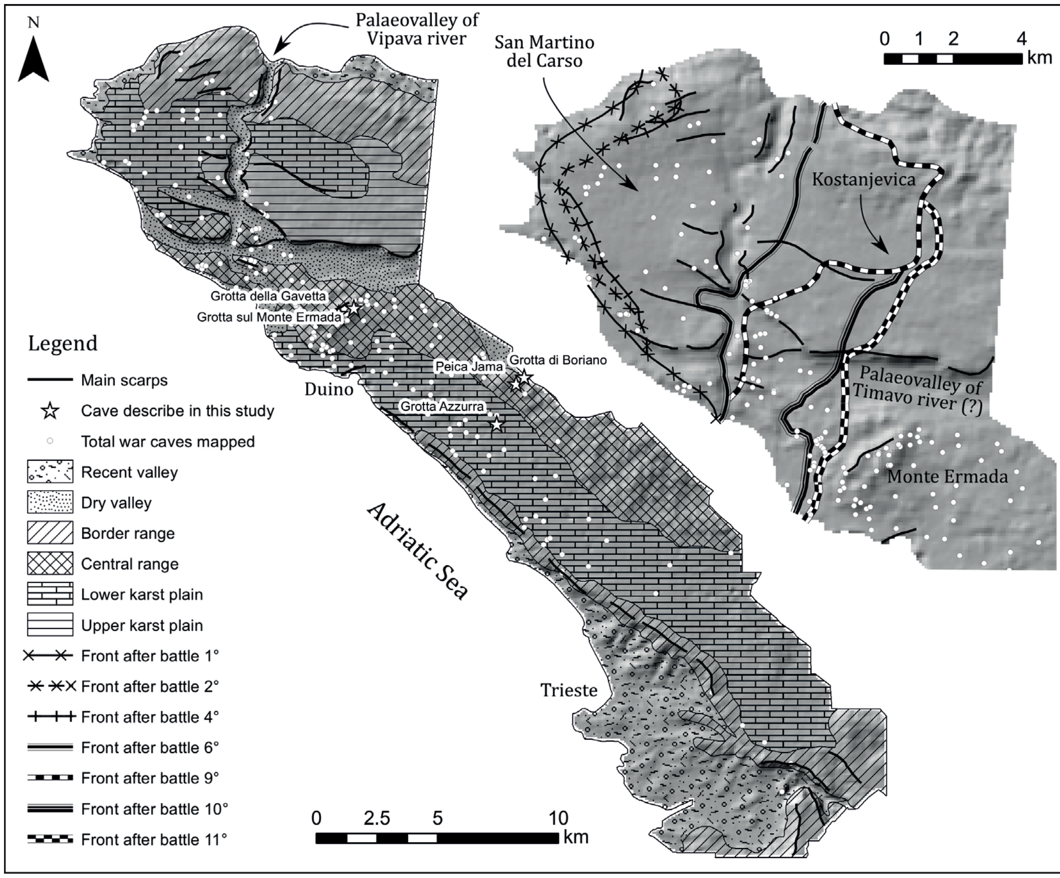

FIG. 2 - Geomorphological map and a close-up of fronts of the 12 Isonzo Battles (the 12th battle, known as "Caporetto Battle", was fought outside of the study area). Geomorphological units are based on Gams (1998) classification.

partially covered by flysch lithologies, and the water table surface was close to the topographic surface. Later, drawdown vadose cave (Ford & Williams, 2007) morphologies developed due to the rising tectonic-driven uplift of the plateau and the consequent deepening of the water table surface until the actual minimum gradient to the karstic springs was reached. As a result, multiphase caves with different cave levels (Palmer, 2007), frequently close to the surface, may be found in the Karst area, as in other sites with a multistage lowering of the water table, due to tectonic uplift and/or valley entrenchment (e.g., as in Piccini, 2011; Piccini & Iandelli, 2010; Columbu & *alii*, 2017). The planimetric development of caves in the areas of Duino, Aurisina, and Monrupino followed, as preferential orientation, the S and W quadrants, coinciding with dips of strata on the left side of Trieste-Komen anticline (Cucchi & *alii*, 2000).

Collapse dolines are typical of the Karst Plateau and are formed by both rockfalls inside cavities (due to a lack of buoyant support after the lowering of the water table and the formation of excessive stress on the walls and roofs of caves) and dissolution processes exhuming horizontal conduits in unroofed caves.

A simple hydrogeological model of the Classical Karst permits the division of the entire territory into three sectors (Cucchi & Zini, 2007). In the first sector, epigean waters from allochthonous rivers flow in valleys with flysch and Quaternary deposits as substrate (as in the case of Timavo River) and enter the underground network. In the second sector, meteoric water flows in vadose cave conduits. In the third sector, karstic springs (such as the Timavo River springs) prevail. Adsorption points are localized in both the southern (Timavo gorge in San Canziano) and northern parts of the Classical Karst, where the Isonzo and Vipava rivers disperse water along their riverbeds due to the nature of bedrock lithologies. According to the hydraulic gradient, underground water flows along the left side of the Trieste-Komen anticline following the dip of strata and through one large karst resurgence (Timavo springs) and many other springs with a smaller discharge.

The Timavo River is a well-known allogenic subterranean karstic river, about 50 km long (Gabrovsek & Peric, 2006), that crosses the Classical Karst from NE to SW. It is intercepted by caves all along the plateau (Gabrovsek & Peric, 2006), and its course, which is allegedly quite complex, has not yet been completely mapped.

Historical Background

The Classical Karst area was affected during the First World War by a series of great military operations named "Battaglie dell'Isonzo" (Battles of the Isonzo), a term invented by the Austro-Hungarian press. The term does not sufficiently describe the real dynamic of conflict in the region. All 12 battles were assigned the same name, and no stalemates occurred along the riverbanks of the Isonzo River, which demarcated the border between the Astro-Hungarian Empire and the Italian Kingdom. In fact, these battles were extremely dynamic on the Karst Plateau (see the front evolution in fig. 2). In the period following the rupture of the Triple Alliance (May 4, 1915), Italian strategy was directed by General Cadorna and consisted of a rapid offensive operation intended to reach, in the shortest possible amount of time, the cities of Ljubljana and Vienna, given the knowledge that a major portion of the Austro-Hungarian army would be occupied on the Eastern front and in the Balkans (even though the Russian army was defeated by an Austro-Hungarian offensive operation, and the Serbian army did not help its Italian allies). During the first operation along the course of the Isonzo River and among the first natural bulwarks of Doberdò Karst (a name for the north-western part of the Classical Karst), the Austro-Hungarian defensive system was prepared in a few days on the border of the plateau, and a controlled overflow of the Isonzo River was created along the watercourse to ward off the Italian army. In the summer of 1915, Austro-Hungarian troops were holed up in natural cavities modified as shelters, while their Italian opponents were completely exposed to artillery on the plateau surface.

Until the summer of 1916 (during the fifth Isonzo battle), the front remained static on the Karst despite changes to the frontline in the Friulian plain between the cities of Monfalcone and Gorizia. The sixth battle represented a turning point, as the Italian army launched a massive offensive preceded by the analysis of warfare terrain (also using aerial reconnaissance of the enemy's defensive system) and an intelligence operation aimed at distracting the enemy from the Karst front with a fake offensive in Valsugana Valley in Veneto and Trentino. Once the valley between Doberdò Karst and Kostanjevica Karst (located in Slovenia) was overcome by Italians in September 1916, Austro-Hungarian troops retreated to the Jamiano area to the north and occupied Mount Ermada fortifications (Hausler, 2013). For the Italian army, the objective was to overwhelm the defenses of remaining enemy forces in hilly areas and to reach Trieste. The frigid winter of 1916 and 1917 prevented the Italians from advancing, giving sufficient time to the Austro-Hungarians to adapt a huge number of caves for military purposes. Despite the Italian offensive in Vipava Valley on the northern Karst border and the conquest of Kostanjevica during the summer (after the defeat at Mount Ortigara in the Altipiano dei Sette Comuni in Veneto), the Italians prepared another offensive designed to reach the valley of Brestovizza. The Austro-Hungarian army fiercely resisted on the Mount Ermada front and, in October 1917, launched an offensive along the extreme northern section of Isonzo River in Caporetto. This operation permitted the Austro-Hungarian army to rapidly cross the alluvial plain between Veneto and Friuli, ultimately reaching the Piave River.

RESULTS

The term "war caves" denotes all natural caves of speleological importance – i.e., whose geometrical extension is large enough (at least a few meters) for a person to enter and remain inside – that have been used for any military purpose, with or without anthropic modification. A huge number of these caves were adapted for defense during the Battles of the Isonzo. In the first attacks on the Classical Karst area, trenches were built using stone walls ("sangars") or were excavated at a small scale in the bedrock. However, new trench warfare developments forced both the Italians and the Austro-Hungarians to excavate deeper into the ground (Tavagnutti, 1997), which ultimately led to the exploitation of natural caves as a much more efficient way of fortifying the frontline. The Austro-Hungarian army were prepared for this task, deploying a special sappers unit, guided by speleologists and engineers, to search for new caves and plan internal modifications. In 1917, two practical manuals written by Rudolf Wilner (Gherlizza & Radacich, 2005) were distributed throughout the Austro-Hungarian Empire. Engineer and speleologist Lieutenant H. Bock (whose name is engraved in concrete in the Azzurra Cave of Samartorza, fig. 4C), a member of the Fifth Army, which was, at the time, deployed on the Karst Plateau, launched a project to search, map, and explore caves in the area.

Consequent modifications of cave morphology were extremely variable – some caves served to simply house soldiers and were not internally altered at all, whereas others were substantially modified, excavated, and morphologically altered by concrete work. In some cases, these caves were also interconnected by artificial tunnels. In this work, we did not consider completely artificial tunnels that were unrelated to the karst environment, such as tunnels in ice, quite common during the "white war," i.e., battles fought at high altitude, often on glaciers (Carton & *alii*, 2017; Carturan & *alii*, 2020; Bondesan & *alii*, 2015; Francese & *alii*, 2015a; 2005b; 2019; Laterza & *alii*, 2018).

Caves were classified according to their level of artificial modification, distinguishing (a) natural, (b) mixed, and (c) artificial caves. Considering a database of 64 caves on Doberdò Karst, 49% of them were artificial (with less than 10% of natural development) (Tavagnutti, 1997). The first documentation of wartime use of caves in the Classical Karst dates to the 1920s (Gariboldi, 1924; Gariboldi, 1925; Bertarelli & Boegan, 1926) with a simple but refined description of caves, attributable to the fact that, at the time, many modifications and internal wood or iron-steel structures were still preserved. For the first time, the great defensive system of the Austro-Hungarian army, which was underestimated during the conflict, was depicted.

Typically, many adaptations were made to cave entrances to seal off the interior (even hermetically in the event of a gas attack) or either reduce the size of access points or secure them from rockfalls. The likely most important, and one of the most frequent, cave modifications was the excavation of multiple entrances. Natural caves with multiple access points are quite uncommon, but different entrances are preferable when the caves are militarily occupied. Consequently, artificial tunnels were often dug to reach the external surface at multiple points or to connect adjacent dolines. Multiple entrances afforded better safety in the event of direct attacks by the enemy and, in the case of artillery shelling, which could cause an access point to collapse, created an alternate escape route. Multiple access points, when located at different altitudes, also generated natural air flux due to the barometric pressure gradient – this was essential, as proper air circulation is particularly important in underground warfare (Bondesan & *alii*, 2015), especially in overcrowded caves. Modern underground military facilities are always linked to the surface by several manmade entrances and conduits designed for air circulation purposes, in both large, concrete tunnels and earth excavation. Even in the Afghanistan wars between 1979 and 2004, natural and artificial cave complexes, which arguably comprised the core of Mujahideen, Taliban, and Al-Qaeda fortifications (Zečević & Jungwirth, 2007), provided multiple exits, especially as US forces focused mainly on "search and clear" operations underground because attempts to directly destroy tunnels by bombing did not succeed (Bahmanyar, 2004).

In inner conduits and halls of caves, some of the most frequent works were the construction of terraces, especially in sloping floors, sustained by stone or cement retaining walls built using rockfall deposits commonly found on the floor of large natural caves. Horizontal terraces were specifically designed to hold a precise number of soldiers, as described in the Austrian army military handbook (Gherlizza & Radacich, 2005). Another typical modification was the construction of walking paths on leveled cave floors, and stairs.

Caves were not solely used as fortified shelters or barracks, but also as a water resource. As the Classical Karst Plateau completely lacked a superficial hydrographic network, caves became a precious source of water. Soldiers collected water in gours (known also as "rimstone dams" or "rimstone barrage", they are wall-shaped calcitic deposits that form dams and enclose pools of water in caves) or in apposite concrete tanks positioned to collect water directly from dripping speleothems or from outside. Since a large number of caves, at least in the central part of the Italian Karst Plateau, dip to the SW, according to the general orientation of limestone layers (Cucchi & *alii*, 2000), Austro-Hungarian soldiers canalized and stored water by taking advantage of the inclination of cave floors. By digging artificial wells near Timavo River springs, the soldiers could also extract water from this subterranean river.

Other karstic landforms besides caves underwent artificial modifications during WWI. For instance, numerous sinkholes were exploited to create concrete shelters and barracks on their bottom or flanks. It is also worth mentioning the adaptation of "unroofed caves" (Mihevic, 1998) and "intersection sinkholes" (Ferrarese & Sauro, 2001). These are a form of irregularly shaped natural depressions, generally elongated, partially filled by sediments and with speleothems on walls, generally due to the intersection of the cave with the topographic surface. Although many of these features are located close to some war caves -and, from a tactical point of view, appear quite useful- their military use has as of yet remained undocumented.

In the following section, we describe the different case studies. Numbers in brackets in the title of each case study are the official codes of the Friuli-Venezia Giulia cave inventory (Servizio Geologico Friuli-Venezia Giulia, 2022).

Grotta di Ternovizza - Ternovizza Cave (n° 78)

This cave comprises two natural cavities – the real Ternovizza Cave and the Peica Jama cavern – joined by an artificial tunnel excavated during WWI. Two access points occur through two different sinkholes, one facing directly toward the main pit (35 m deep) of Ternovizza Cave, and the other, bigger entrance of Peica Jama Cave facing a large wall of well-bedded Monte Coste limestone (Povir Formation) (fig. 3). This last access point was modified by a concrete stairway that started at the sinkhole border and a concrete wall that partially sealed off the natural entrance (fig. 3A-3B). The first room (fig. 3B) has an area of about 15 x 20 m and features a concrete terrace that leads to a short artificial tunnel (fig. 3A). At the bottom of this room, a junction between the initial part of Ternovizza Cave and the pit was constructed. Nearby, another tunnel was dug (fig. 3C), oriented in the same direction as the main shaft. This may have been an attempt to reach the bottom, where large rooms with many gours occur. In fact, the cave and the bottom rooms had been identified as early as the second half of the 19th century. The connection between the two caves permits a notable air flux, useful for overcrowding conditions. It has been assumed that this cave was used as a hospital.

Grotta Azzurra - Azzurra Cave (n° 34)

This cave opens at the bottom of a small rocky wall that forms the flank of a large collapsed sinkhole, with nearby depressions, considered unroofed caves (due to the presence of speleothems), and many other small sinkholes, aligned along a small valley parallel to the main orientation of the cave (fig. 4). A massive entrance, developed horizontally in Aurisina limestone (Sezana Formation), leads to an enormous collapsed room, about 100 m long and 20 to 40 m wide, with a characteristic vault shape. At the end of the main room, the cave develops eastward with a tighter, cylindrically shaped meander, with evidence of formation under phreatic conditions. This cave features a second entrance through an artificial tunnel that connects the main room with a small sinkhole opening on the top. Three concrete (fig. 4A-B-C) tanks were built here to collect water dripping off of large associations of speleothems or interbed discontinuities. One tank (fig. 4A) surrounds a stalagmite, furnishing a water flux that flows on the muddy floor of the cave until being intercepted by a bigger concrete tank (fig. 4C), which can contain 40 m^3 of freshwater (Gherlizza, 2011).

Grotta sul Monte Ermada - Cave on Mount Ermada (n° 1621)

This cave, located on the summit of Mount Ermada, was an integral part of the Austro-Hungarian defensive system, as testified by the huge number of nearby fortifi-

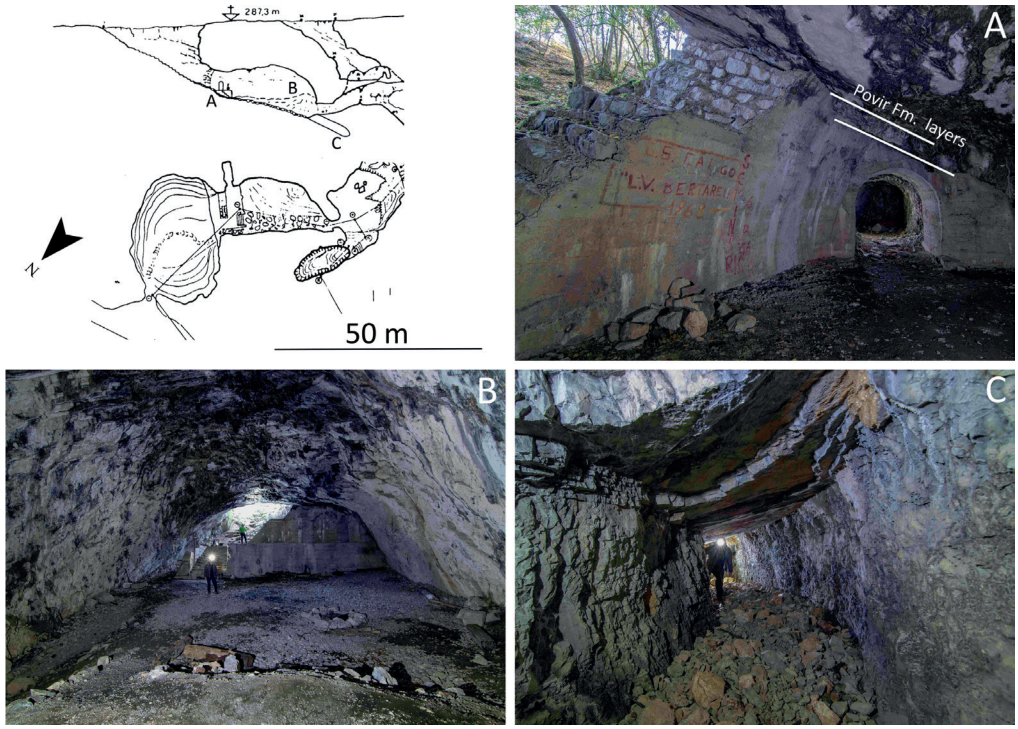

FIG. 3 - Ternovizza Cave map modified from Commissione Grotte Eugenio Boegan (1992). Photos: (A) the entrance wall and the first artificial tunnel; (B) a view of the first room; (C) the second artificial tunnel.

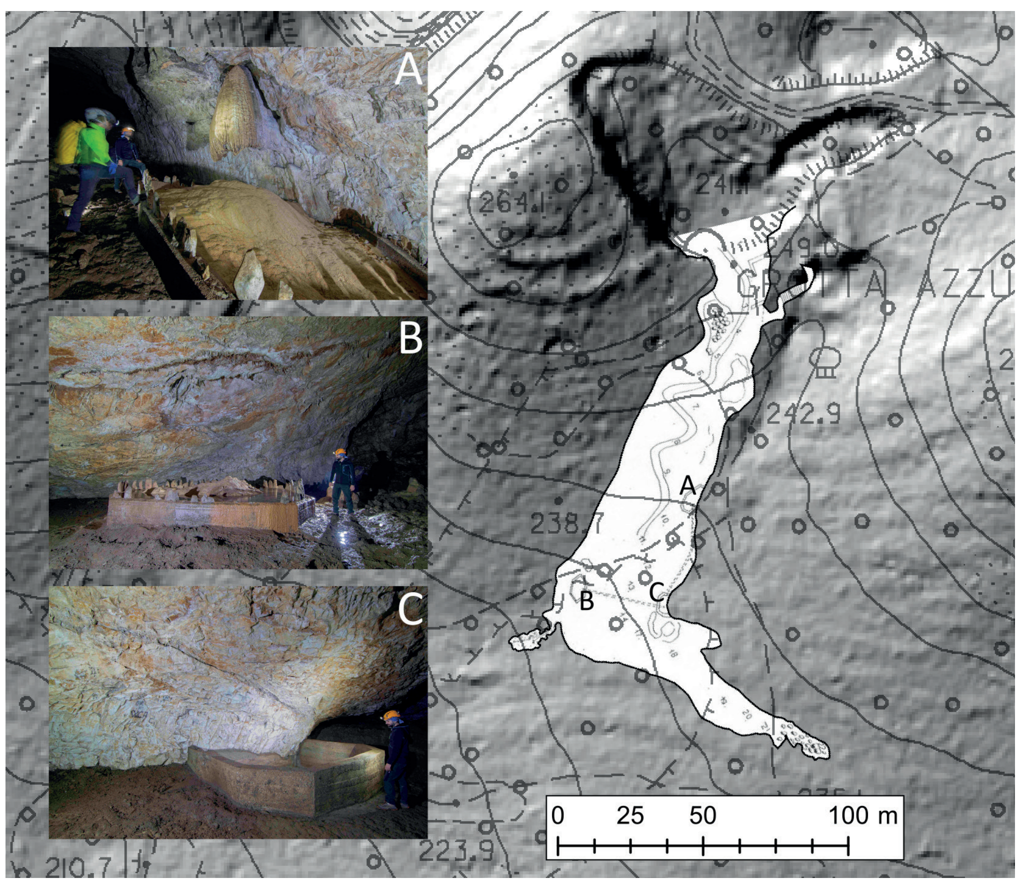

FIG. 4 - Azzurra Cave map modified from Commissione Grotte Eugenio Boegan (1993), projected on LiDAR-based hillshade image. Photos: (A) tank under a big calcite speleothem; (B) tank under a series of small stalactites; (C) tank built under a discontinuity in the rockmass.

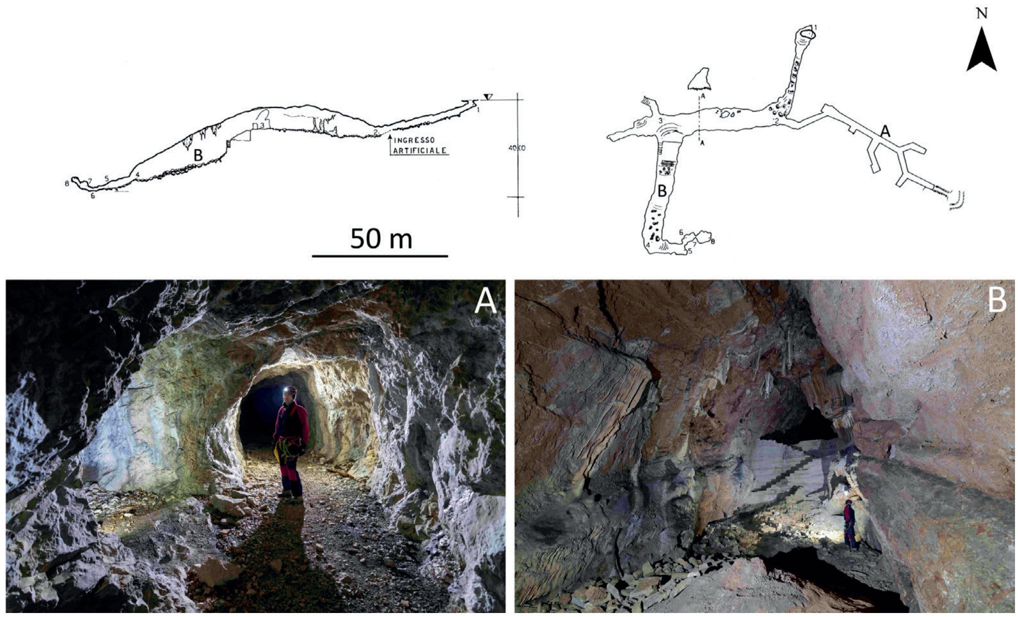

Fig. 5 - Mount Ermada Cave map (Commissione Grotte Eugenio Boegan, 1968). Photos: (A) artificial tunnel; (B) concrete stairs and terraces in the great hall at the end of the cave.

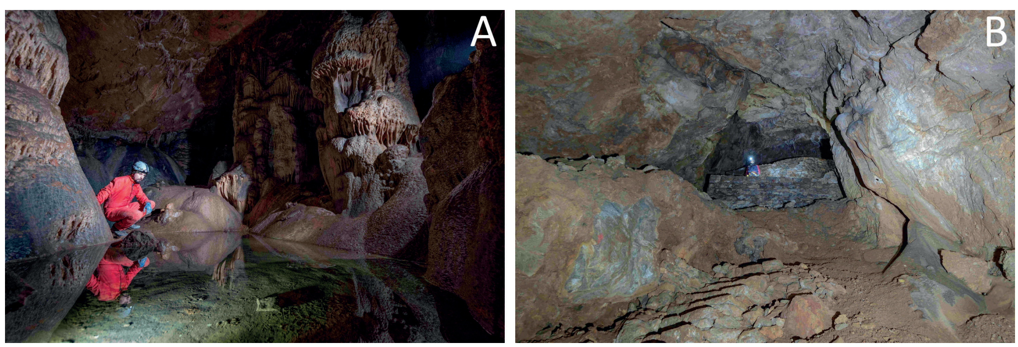

Fig. 6 - (A) a gour filled with water inside Boriano Cave; (B) terraces and staircases made by loose rocks partially cemented in the Gavetta Cave.

cations that were developed on all of the surrounding reliefs. These fortifications include trenches, concrete bunkers, artillery positions, dugouts excavated on the bottom of trenches, and stone constructions close to the bottom of sinkholes. The cave is composed of two parts (fig. 5): an artificial section (fig. 5A) comprising the main tunnel, with secondary tunnels radiating from it, and a naturally formed section. The development is sub-horizontal on two main axes. One has a N-S orientation that is inclined and covered by colluvial and rockfall deposits and represents the conduit from the entrance. It continues until the final section of the cave, which includes some of the biggest and most interesting visible adaptations of war caves. The second axis, which is very large and full of speleothems, is oriented W-E and constitutes the central conduit. The inner part of the cave has a large stairway completely made of concrete (fig. 5B) that allows access to the bottom part of the cave, concrete terraces, and interesting traces of an electrical system. Moreover, this cave was used as a hospital (its alternate name is "Hospital Cave"). Two cave entrances open on two different sides of a path that leads to a small village on the SE side of Mount Ermada, within 100 m from each other (a safety disposition in the event of direct attack). Due to this and other caves, Mount Ermada was the most defended, technologically advanced, and complex fortification system in the area.

Grotta di Boriano - Boriano Cave (n° 125)

This cave opens along a limestone outcrop of the Brje Formation, starting with a large room that connects to the outside surface – a sort of collapsed doline that exposes the inner cave, with many weathered fossil speleothems. An inscription dated to 1917 suggests that this cave was used as a refuge for Austro-Hungarian soldiers. The cave has a sub-horizontal development along the bedding direction of limestone layers; all of the cave sections have large zones covered by rockfall deposits and, in the second half of the cave, there are abundant speleothems and concretions. In some rooms, the floors are entirely covered by gours whose depth is sometimes over 1 m. Water drips all year round from natural calcite formations (fig. 6A), and as such the cave was probably used for centuries as a source of freshwater by the inhabitants of Boriano/Brje in Slovenia (the entrance is located only a few meters from the national border). For this reason, the cave is also known as *Vodnica Jama* (Water's Cave) (Gherlizza, 2011).

Grotta del Pilone and Grotta della Gavetta - Pilone Cave and Gavetta Cave (n° 3092 and n° 4482)

These two caves are considered together because they share the same structures and are both joined by an artificial tunnel. The main entrance of this complex is artificial, excavated as a trench, and gives access to the first room of Grotta del Pilone. Natural entrances are less practical because Grotta del Pilone is partially obstructed by the concrete used for the construction of an electricity pylon; while, for Grotta della Gavetta, they are represented by two close, parallel, 4-m-long shafts. Inside these two caves, there are adaptations such as terraces in rocky blocks partially filled by concrete, stairs constructed from concrete (fig. 6B), and, in general, a leveling of walking paths created by removing rockfall deposits.

Air circulation in the caves is evident, especially at the junction between them. These caves were also part of the defensive system located on the upper part of Mount Ermada, very close to the line of trenches, and are characterized by a particular fragmented development and the presence of typical, entirely artificial cavities excavated for protection.

DISCUSSION

To relate the location of caves and their importance in military operations and wartime practices, 223 entrances from a total of 220 caves have been mapped on the Classical Karst Plateau (fig. 2). Furthermore, using data from Gherlizza & Radacich (2005), all of the caves considered in this study were classified by use and by their main modifications (fig. 7). From the analysis of their employment (fig. 7A), as expected, "shelter use" was the most frequent (~75%), for both military and civilian purposes. Other minor uses, such as "water reservoir", "ammunition depot", or "hospital" were rare, but they had specific military importance related to war fronts. Besides, every natural and artificial cavity on the Classical Karst Plateau could have been used as a shelter – however, statistical data are less representative in this respect because of the difficulty of searching and exploring every cave, especially since many caves described in the past have not yet been found. Due to these potentially misleading analytical interpretations, only the main use of these caves was considered in the present work.

The analysis of cave modifications (fig. 7B) is sometimes more crucial because, for example, "adaptation works" are related only to caves whose natural features have been modified. Such analyses employed qualitative data and, as such, their results could change with more accurate documentation. In most war caves, artificial works consisting of tunneling (~45%) and construction of walls and stairs (~30%) highlight the ability of armies to modify the karst landscape and his features, promoting human activities and usability of natural resources.

As described in Gariboldi (1924; 1925), many caves had complex interior structures made of wood or steel beams that permitted them to have inner hut-like constructions for more comfortable occupation. These structures have now disappeared due to the extensive collection of scrap metal after WWI. For this reason, it is more difficult to determine whether some caves had unique functions as evidence needed to support such investigations, such as electrical and hydraulic facilities, may not have been preserved.

A geographical analysis of the 220 cave positions related to the morphological features of the Classical Karst Plateau discovered a close relationship between the development of fronts and karstic reliefs. The Italian Royal Army strategy was designed to capture the city of Trieste by rapidly crossing the Classical Karst Plateau between Basovizza and Sistiana. In 1917, offensive military operations by the Italian army stopped near Duino, very close to the major relief in the area. In particular, the area with the majority of war caves is Mount Ermada, which served as a sort of natural fortress thanks to the many sinkholes opening atop the mountain, which were cleverly used by Austro-Hungarian troops. Furthermore, in the valley just north of Mount Ermada, a graben-like depression and a dry valley (probably of the paleo-Timavo River) (fig. 2) represented one of the major obstacles for the Italian army because the morphology of the terrain and the orientation imposed by faults in the area were exploited by the Austro-Hungarian army to create a powerful defensive line on the plateau: the Hermada-Kostanjevica line of defense (Comando III Armata, 1917).

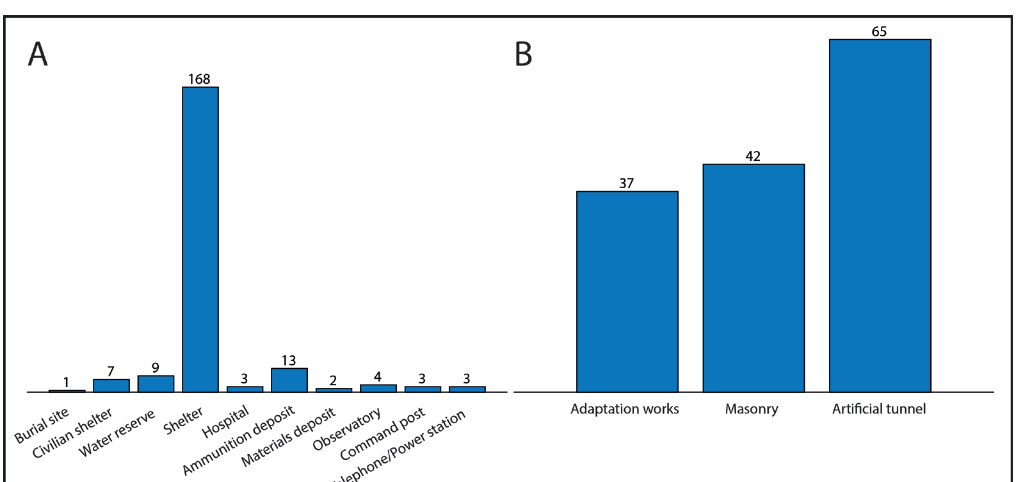

Fig. 7 - Analysis of cave wartime uses (213 caves in total) (A) and typologies of cave modifications (144 cave in total) (B) based on the database from Gherlizza & Radacich (2005).

To better understand the strategic superiority provided by karstic territory it is useful to compare it with two other "classical" karst landscapes that were involved in WWI. At the same time as the 12 Battles of the Isonzo were occurring, the northern front ran along the Venetian pre-Alps and the Dolomites (the current border between the Veneto and Trentino Alto-Adige regions; Vergara & *alii*, 2019; Vergara & *alii*, 2020a; 2020b).

The so-called "Battaglia degli Altipiani" were the military operations carried out along the W-E axis between the Adige Valley and the Brenta Valley (Valsugana). In the northern part of the Asiago Plateau, which has a huge low-sloping terrain whose surface is dominated by limestone and dolomitized limestone of the Calcari Grigi Group (Barbieri & Grandesso, 2007), one of the deadliest battles of the entire war was fought: the Battle of Mount Ortigara. Today, the area is well-known, from a speleological point of view, for its many deep abysses (Federazione Speleologica Veneta, Società Speleologica Italiana, 2019) and epikarst features, such as highly developed karren fields and glacial-karst sinkholes.

The other important location of karst warfare in the region is Montello Hill, which was involved at the end of the Isonzo Battles during the rapid Austro-Hungarian advance on the Venetian-Friulian alluvial plain (Ferrarese & Bondesan, 2018; 2022). The hill is located on the western side of the Piave River and was used by the Italians as a natural barrier, one which was crossed during the "Battaglia del Solstizio" in June 1918. Montello Hill has a unique morphogenesis: the hill, shaped by both karst and fluvial processes, comprises an anticlinal fold emerging from the Quaternary covers and positioned on the hanging wall of the Montebelluna-Monreale Line (DISS Working Group, 2021), the most advanced active thrust of the Southeastern Alps. Furthermore, Montello Hill is not a "classical" karst landscape because its lithologies constitute a thick series of alluvial fan conglomerates, channel fillings, and lacustrine fine-sediments (Massari & *alii*, 1986) in which deep sinkholes have been carved by solution processes and hundreds of caves (up to 8 km long), many of which are hydrologically active, creating a dense underground network of pits and meanders. The key to the chemical dissolution is the carbonate cement in the conglomerate matrix and the dominance of limestone/dolostone pebbles.

When considering the territory between Mount Ortigara and Mount Chiesa in the northern portion of Asiago Plateau, karst warfare in the area may be likened to that previously described on the Classical Karst Plateau, but with more complex structural constraints. Three main structural deformations are known (Barbieri & Grandesso, 2007): Norian-Early Jurassic rifting, Paleogene rifting, and Neogene contraction. An array of normal faults, locally re-activated as strike-slip faults, striking between NNE-SSW and NNO-SSE, defined a pattern of fractures that deeply conditioned karst features (sinkholes, trenches, karren fields, caves). Mount Chiesa is part of a wedge-shaped domain between two strike-slip faults (fig. 8) and was an important Austro-Hungarian military fortress, with an artificial tunnel excavated on the N-S trending summit ridge that led to protected openings on the top. In the adjacent area, several military facilities were constructed on rocky walls or in sinkholes on the sheltered side with respect to the battlefront; trench lines were usually excavated near natural man-sized fractures, which could represent an additional defensive advantage, exploiting the natural trend of tectonic discontinuities in the limestone (fig. 8). Many entrances open in or near to the trenches and were also a source of water due to permanent snow and ice deposits inside the first sections of the caves. The entire front of the Battle of Mount Ortigara ran N-S, following the alignment of ridges.

The military operations conducted on both the Asiago Plateau and Classical Karst Plateau involved the exploitation of karst features almost solely by the Austro-Hungarian army, with the converse characterizing military operations on Montello Hill, carried out almost exclusively by the Italian army. The northern side of Montello Hill, facing directly at the braided channel of the Piave River, was fortified by the Italians using paleo-karst cavities and the remains of ancient caves on blocks detached on the main scarp (Gasparetto, 2002; Dalla Libera, 2013) to build artillery and machine-gun positions and refuges. The vertical fluvial scarp, called "Coston," also presented a trench line excavated on the upper part; while the first line, the so-called "Trincea Sommitale," was well-defended by the slope and gave a complete view of all of the fronts (Dalla Libera, 2013). The second and third lines were functionally designed based on the topography. The second line was built in the area with the greatest number of sinkholes, and here the portions of trenches constructed inside the sinkholes increased directly proportional to the abundance of dolines (Dalla Libera, 2013), confirming the general advantage of using karstic features.

The military exploitation of karst areas and, more generally, mountainous regions with specific geomorphological features can offer numerous advantages to the defender army, especially one with a well-prepared strategy based on the use of territory, as in the case of the Austro-Hungarian army during WWI (Zečević & Jungwirth, 2007) – conversely, this creates significant disadvantages for attacking forces. The Italian army underestimated the defensive system of the enemy and was consequently tempted by the lure of a rapid war in the crossing of Slovenia. The absence of intelligence on how best to prepare to face the problem of warfare in a rocky plateau worsened the situation for the Italian army.

The use of caves by Austro-Hungarian forces was frequent along both the front, with simple modifications made to create small shelters or positions for artillery and observation, and sidelines. War caves are distributed all over the plateau and were likely created in the event of an advance by the Italian army. Cave exploitation also varied with their geographical position, especially in relation to the front and to the morphology of the caves – for example, telephone exchanges or hospitals were typically constructed on sideline positions and in large rooms.

When analyzing the impact of war in karst areas, even anthropic impacts on comprehensive karst landscapes in general, including both the geosphere and biosphere, must

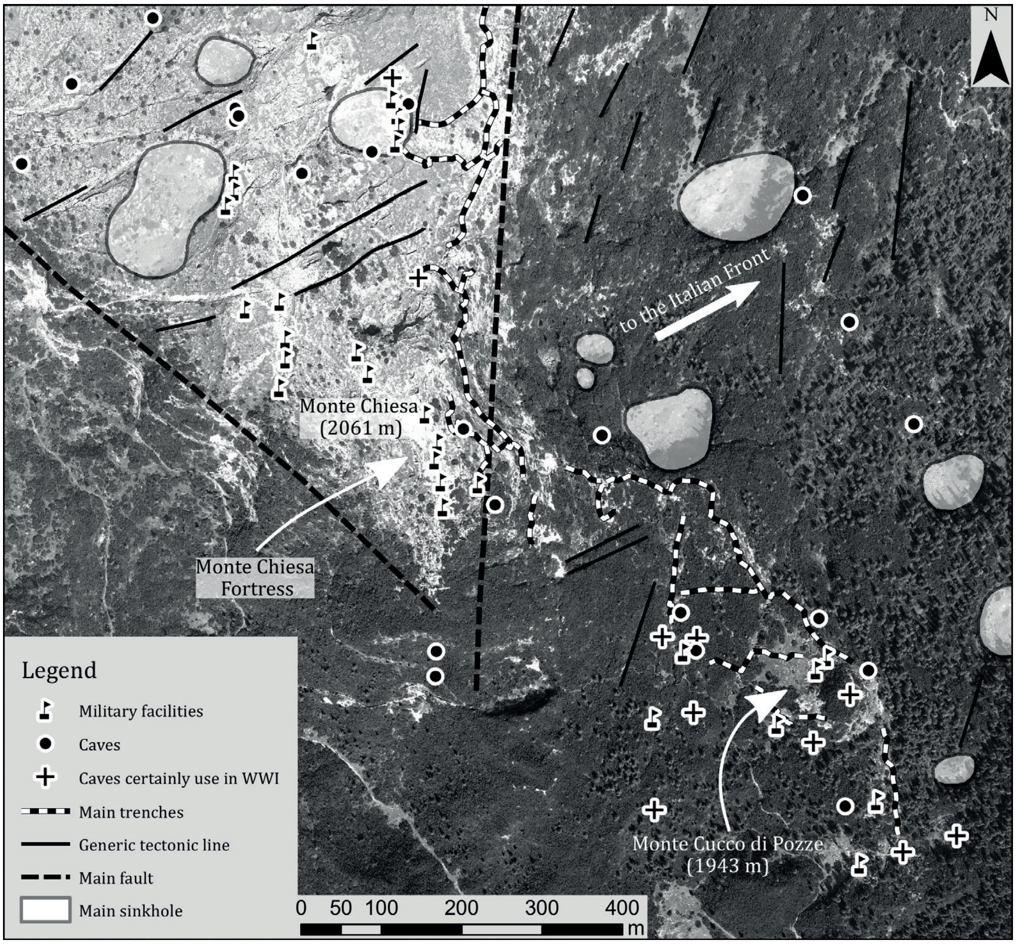

Fig. 8 - Example of karst warfare on northern part the of the Asiago Plateau where structural constraints played an important role in the building of military facilities and trenches. Cave positions according to Federazione Speleologica Veneta Società Speleologica Italiana (2019); information on wartime use during WWI according to Busellato & Gruppo Grotte Schio (1991).

be considered. A typical example is the pervasive deforestation necessary to open a viewshed on enemy positions and provide wood for constructions and heating, as well as that induced by extensive artillery shelling. Changes in vegetation cover and soil erosion interferences (Kiernan, 2021) are important factors to consider with regard to the hydrogeochemical cycle.

All cave modifications previously discussed can entail permanent anthropic landscape degradation and modification. Although agriculture, forestry, and pasture practices in the last century have partially restored pre-conflict conditions, similar to the restoration of the Slovenian Dinaric karst after WWII as described by Gams (1999), the underground landscape remains substantially and permanently compromised, affecting karst processes.

CONCLUSION

From a geological point of view, the Classical Karst exemplifies the military exploitation of geology, which may be described as "karst warfare." The evolution of the entire plateau under hydrological conditions that varied over time, first with a piezometric level close to the surface during dammed karst conditions, and second with the general deepening of the water table (Gams, 1998) and an active tectonic regime, allowed for the formation of many caves by phreatic speleogenetical processes, with mostly horizontal conduits, even close to the surface, where human exploitation is easier, courtesy of the denudation produced by fluvial erosion and tectonics. At the same time, there are also many caves with vadose morphologies and small shafts or deep sinkholes at the entrance, which can be easily adapted during military operations for safe use.

Multiple generations of planation surfaces and corrosion plains carved with sinkholes, frequently bounded by fluvial and tectonic scarps, made the karstic landscape a critical area for military operations.

Karst processes were a crucial factor on many war fronts, especially during WWI in northeastern Italy. In the other two important Italian–Austro-Hungarian fronts, the presence of sinkholes, rocky surfaces, and caves favored the armies that made use of these features.

In many other war zones, karstic features were properly used for purposes requiring underground operations, and modern technological developments (Zečević & Jungwirth, 2007) can help armies identify underground structures due to remote sensing and applied geophysical techniques.

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