Geoheritage (2023) 15:53
https://doi.org/10.1007/s12371-023-00816-x

ORIGINAL ARTICLE

The Debated Discovery of Dolomite and the Proposal of a New Geosite at Borcola Pass (Eastern Italian Pre-Alps) in Honor of Giovanni Arduino

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Received: 22 November 2022 / Accepted: 6 March 2023

Abstract
Within the Venetian Pre-Alps, the Borcola Pass connects the Posina (Vicenza province) and the Terragnolo (Trento province) valleys. The Posina valley is located north of Schio (Vicenza) within the Italian Southern Alps structural unit. In this area, the injection of Paleogene basaltic dykes along fault/fractures in the late Triassic Dolomia Principale unit has produced a local metamorphism of the dolomite rock into a marble characterized by the presence of brucite veins. This marble was studied in the eighteenth century by the famous Italian scientist Giovanni Arduino, who understood its metamorphic origin. In fact, the marble is always associated with sub-vertical basaltic dykes intruded into the carbonate rocks of the Pre-Alps. Arduino performed also chemical experiments on the marble. The reading of the description of the experiments induced later authors (e.g., Maraschini, von Morlot, Mc Kenzie) to infer that Arduino unknowingly discovered the mineral called dolomite. In this work, we propose that the abandoned Borcola Quarry should be nominated as a geosite, to allow its conservation and popularization and to preserve the memory of a probably minor, yet informative step in the long-lived history of the discovery of dolomite. In addition, this site presents other reasons of interest, such as petrography, mineralogy, structural geology, industrial archeology, and eco-geotourism. The proposed geosite is therefore of great importance in terms of its multidisciplinary scientific value, aesthetic appeal, and educational value.

Keywords Geoheritage · Venetian Pre-Alps · Giovanni Arduino · Dolomite · Marble · Schio-Vicenza fault

Introduction

In the eighteenth century, from 1740 to 1747, the Italian geologist Giovanni Arduino (1714–1795) (Fig. 1) was commissioned by the Republic of Venice to improve the performance of the Schio (Vicenza) silver mines. Arduino is worldwide famous for his subdivision of the Earth's surface and rocks into four orders, which included primary, secondary, and tertiary mountains, as well as the plains (Vaccari 2006). During his stay in Schio, he visited the Venetian Pre-Alps making observations on the nature of the different rocks, from the basement schists, which he attributed to the first order, to the alluvial sediments that were attributed to the fourth order. Particular attention was paid to the intrusions of basalts in the limestone rocks, which by comparison to the Vesuvian rocks were interpreted of volcanic origin (Arduino 1775, 1779).

Related to the volcanism of the area was the study of some marble lenses with subvertical attitude embodied within the sub-horizontal calcareous rocks and in close association with dykes of magmatic rocks. From careful field observations, Arduino understood that the marble originated from the transformation of the carbonate rock through the action of the volcanic magma (Arduino 1779). He also performed chemical experiments on the marble by using sulfuric acid, from which he obtained anhydrite plus a bitter salt. From this salt, after complex treatments, some crystals later originated. The description of those experiments induced some authors to infer that Arduino unknowingly discovered the mineral called dolomite, which would have gained his name only 12 years later by Nicolas Théodore de Saussure, who baptized it in honor of Déodat Gratet de Dolomieu (de Saussure NT 1792; Carozzi and Zenger 1991). This birthright of the new mineral discovery has been reported firstly by the Italian geologist Pietro Maraschini (1828) and later

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Published online: 12 April 2023

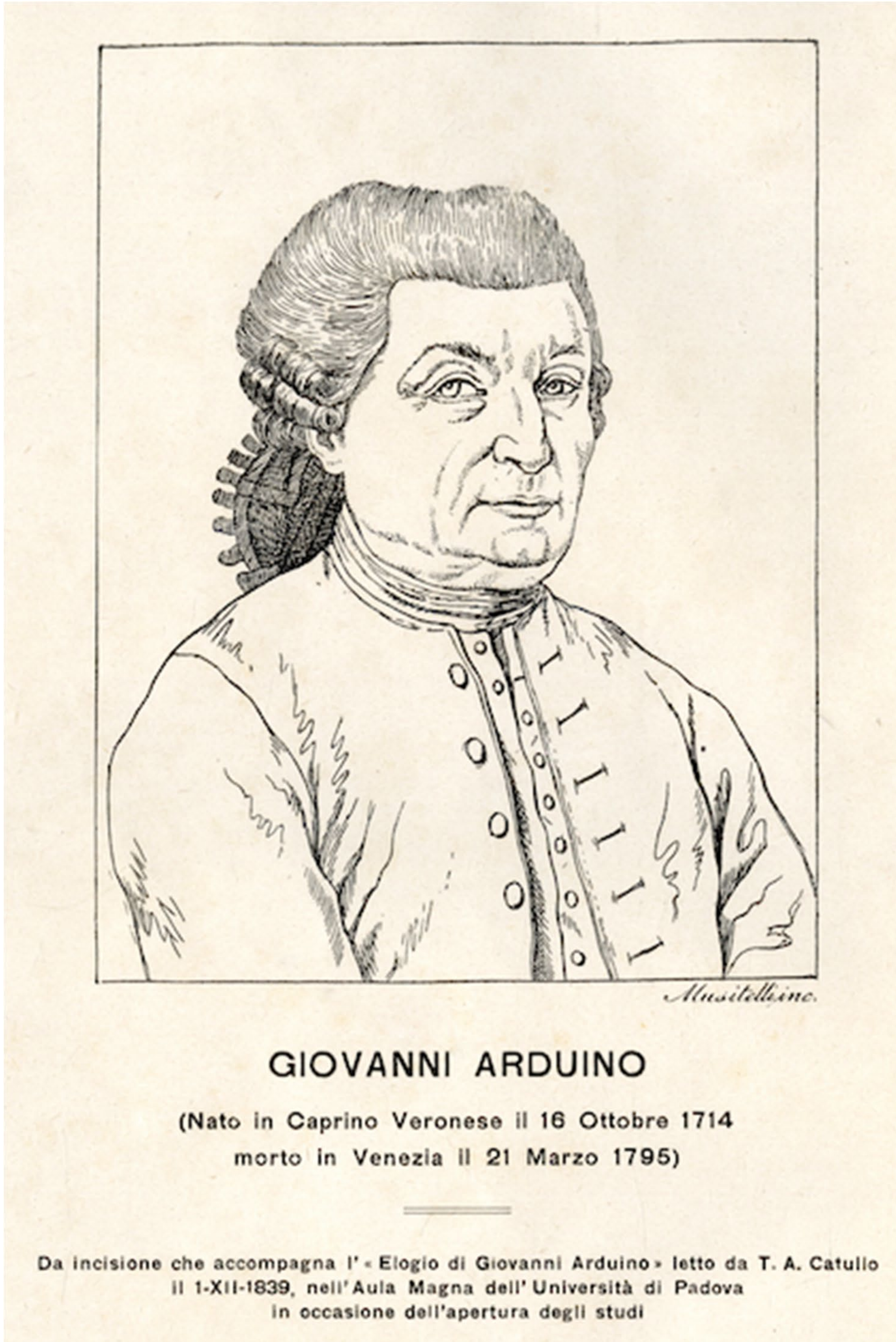

Fig. 1 The Italian scientist Giovanni Arduino (1714–1795) (drawn from Stegagno 1929)

by other authors (e.g., von Morlot 1847; McKenzie 1991; Meister et al. 2013). Marble quarries of the Vicenza Pre-Alps thus became, for a short while, one of the stages of the history of geology, and of the discovery of dolomite, an achievement of geological sciences which triggered a debate on the origin of sedimentary minerals, the so-called "dolomite problem" (e.g., Meister et al. 2013), still an open question of sedimentary geology.

The marble studied by Arduino was extracted and used in the eighteenth century for local church altars and columns. Most of the currently inactive quarries, including those visited by Arduino, are located in steep and rough slopes of the Vicenza Pre-Alps (Zampieri 2022).

Close to the Borcola Pass (1207 m asl), at the head of the Posina valley (Fig. 2), the largest inactive quarry of these marbles is easily accessible from the main road and presents

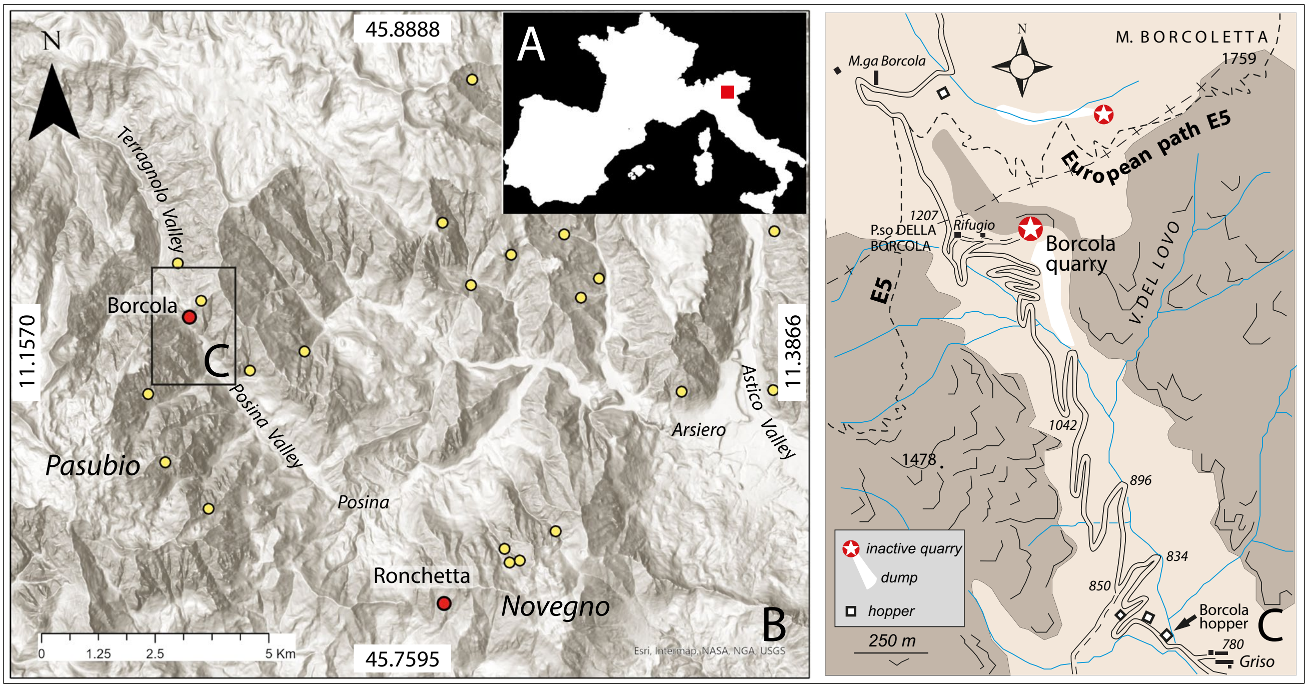

Fig. 2 **A** Study area (red square) in the context of Southwestern Europe. **B** Map of the Posina valley: the yellow circles are brucite marbles quarries active in the twentieth century, and the red circles are the Borcola quarry proposed geosite and the Ronchetta quarry visited by Arduino. **C** Map of the Borcola Pass area

several reasons of interest. Although this quarry was not in the outcrops cited by Arduino, its accessibility and the presence of different geological features make this site a suitable candidate for a geosite (Zampieri and Roghi 2022).

In this work, we propose that the Borcola Quarry should be nominated as a geosite, to allow its conservation and popularization and to preserve the memory of a probably minor, yet informative step in the long-lived history of the discovery of dolomite and of the understanding of natural processes underlying its formation.

Geological Setting

Stratigraphy

The study area is located within the eastern Italian Southern Alps, which are part of the Jurassic passive margin of the Adria microplate. The oldest exposed rocks (Recoaro Phyllites) belong to the pre-Permian Variscan crystalline basement. The overlying sedimentary cover has a thickness of 2.5–3 km. The complex Permian-Middle Triassic stratigraphy includes several siliciclastic and carbonate units intruded and capped by Ladinian volcanics. However, the surface geology is dominated by Upper Triassic to Lower Cretaceous carbonates. Within this interval, the thickest unit is the Upper Triassic Dolomia Principale (~ 600 m), a dolomitic peritidal succession with a wide regional distribution. The overlying Calcari Grigi Group (Early Jurassic) is a carbonate platform unit characteristic of the horst of the passive margin known as the Trento Platform, and it is mostly made of limestone. The Calcari Grigi Group includes three formations: from the bottom, they are the Mt. Zugna Formation, made of mostly fine-grained limestones organized into meter-scale peritidal cycles; the Loppio oolitic limestone, a massive 20-m thick layer of oolitic grainstones; and the Rotzo Formation, which is composed of lime mudstone beds, marls, black shales, and biostromes of oyster-like bivalves of the "Lithiotis group," deposited in a dominantly subtidal shallow water environment (Masetti et al. 2012). Above, the St. Vigilio oolitic limestone is the youngest shallow water unit of the Trento Platform. The overlying Middle-Upper Jurassic Ammonitico Rosso formation is composed of a condensed pelagic red nodular limestone. The Lower Cretaceous is represented by pelagic thinly bedded limestones (Maiolica Formation). All Paleozoic–Mesozoic rocks were then intruded by Paleogene mafic to ultramafic dykes and explosion necks (De Vecchi 1966). Marbles with brucite formed at the contact between the Upper Triassic dolomite of the Dolomia Principale and the largest Paleogene dykes.

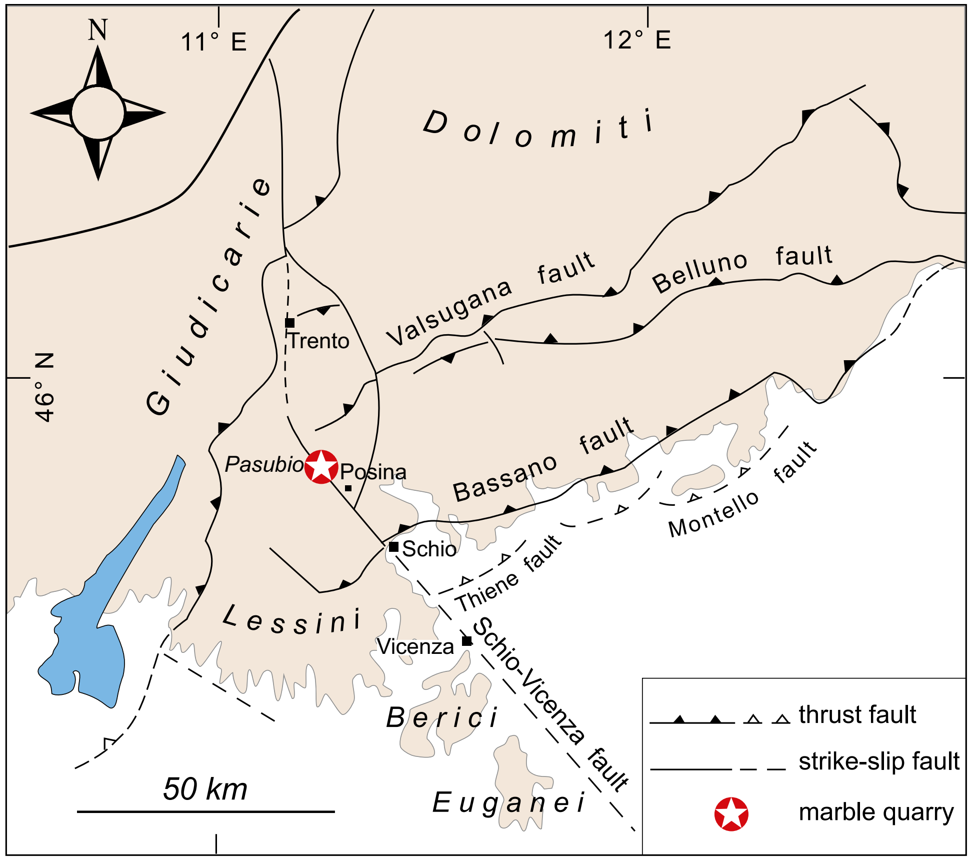

Fig. 3 Structural sketch of the eastern Southern Alps

Structural Setting

Borcola Pass is located in the eastern Southern Alps, which are an SSE-vergent mountain belt (Fig. 3) mainly developed during the Neogene by contraction and oblique inversion of the Mesozoic passive margin of the Adria plate (e.g., Masetti et al. 2012). They are arranged in an imbricate fan of thrust sheets involving the crystalline basement (e.g., Castellarin et al. 2006). In plan-view, the thrusts show several undulations controlled by inherited features, mainly N-S trending normal faults developed during several extensional phases in the framework of the thinning of the Adria margin from Norian to Early Cretaceous (Masetti et al. 2012) and during the Paleogene magmatic event (De Vecchi et al. 1976; Zampieri 1995).

The subsequent Neogene (Alpine) contraction had maximum principal stress axis trending NNW and reactivated the steep N to NNE trending normal faults with sinistral strike-slip kinematics (Zampieri and Massironi 2007). The foreland of the eastern Southern Alps mountain belt is limited to the west by a regional structure known as the Schio-Vicenza fault system (SVFS), of which the main fault is the Schio-Vicenza fault (SVF) (e.g., Zampieri et al. 2021). Its knowledge is deeply rooted in the geological literature and spans more than a century and a half, having been firstly recognized by the Austrian author Schauroth (1855). Since then, the SVF has been the subject of many scientific works and was frequently used in regional tectonic models as a key feature accommodating the indentation of the northern Adria plate margin (e.g. Semenza 1974; Mantovani et al. 2020). The seismotectonics of Italy is the result of the relative motions between Africa and Eurasia. In the eastern Southern Alps, the shallow crustal seismicity is located on south-verging thrust faults within the Adriatic cover (Chiarabba et al. 2005).

The SVF is a steep fault trending NW–SE, i.e., transverse to the mean trend of the fold-and-thrust belt. South of Schio, the SVF is the westernmost strand of a set of buried faults which lies in the subsurface of the Quaternary Veneto plain. Bittner (1879) firstly suggested that the SVF does not end at Schio (Fig. 3) but was instead extending within the chain until at least the Borcola pass, 18 km northwestwards. Von Klebelsberg (1918) extended the fault until the Adige Valley, further to the north. Near Posina the SVF joins with a set of N-trending conjugate faults (Zampieri and Massironi 2007).

Given its geometry and orientation, the most recent activity of the SVFS during the shortening of the Southern Alps was dominated by strike-slip movements. Most papers recognize a sinistral activity but in contrast, few instrumental data of the northern part of the area point to a dextral strike-slip activity (e.g., Pondrelli et al. 2006). This contrast has been reconciled separating two segments of the fault in a sinistral opening "zipper" model (Zampieri et al. 2021).

Another puzzling character of the SVF is its weak seismic activity, which would be expected to be more important given the regional role of the fault delimiting the eastern Southern Alps active and seismogenic thrust fronts (Zanferrari et al. 1982; Galadini et al. 2005; Burrato et al. 2008).

Geoheritage of the Borcola Quarry

We identify an easily accessible and abandoned marble quarry near Borcola Pass as a potential geosite, which should have national or regional standing and which best illustrates the missed discovery of dolomite by Arduino in 1779.

Features of the Borcola quarry that collectively contribute to its unique geoheritage are organized into six categories: (1) history of geology, (2) petrography, (3) mineralogy, (4) structural geology, (5) industrial archeology, and (6) eco-geotourism.

History of Geology

The host rock most close to the volcanic rocks is the white brucite marble which, in the nearby Ronchetta quarry (8 km to the southeast on the western slope of the Mount Novegno, Fig. 2), attracted the curiosity of Arduino (1779, pag. 6). He wrote the following:

> Ho già detto nella Memoria medesima [of the Raccolta di Memorie Chimico-Mineralogiche, Metallurgiche, e Orittografiche, B. Milocco, Venezia] che questo marmo è situato nella gran frana della montagna testé nominata, che nel volgare idioma deli paese chiamasi la Lavina di Ena, dove vedesi disposto in grosso e lungo filone; ma qui aggiungo che il filone istesso apparisce al giorno, e s'interna nel monte incassato tra pietre calcarie comuni e rozze, delle quali essa montagna non solo, ma anche tutte l'altre di quella Provincia, che hanno vene, o sivvero filoni di tal sorta di marmi, sono stratificatamente formate: ad eccezione di vari materiali apparentemente vulcanici, che in parecchie situazioni vi si osservano dei quali i marmi medesimi, dove più dove meno, trovansi misti, donde sovente hanno forme diversamente e vagamente brecciate.[1]

The "Lavina di Ena" (the Enna landslide) is on the western slope of the Mount Novegno (Fig. 2), called by Arduino "Montagna di Lovègno." The long sentence underlines these concepts: (i) the marble forms a large and long dyke cashed into the bedded calcareous rocks, of which the mountains of the region are made; (ii) in the area, the marble is associated and mixed with materials seemingly volcanic and a vaguely brecciated appearance.

The Ronchetta Quarry is substantially similar to the Borcola Quarry, but it is far from main roads and hardly accessible. The importance of brucite marbles quarried at Borcola and Ronchetta lies in the presumed early discovery of dolomite by Arduino. He performed chemical experiments on the marble by using vitriolic (sulfuric) acid, from which he obtained selenite plus a bitter salt from which, after complex treatments, some crystals later originated. These had the shape of tetrahedron pyramids, quite different from that of the dolomite, and could be tentatively referred to as potassium alum (Zampieri 2022). In addition, it is worth considering that the sulfuric acid dissolves the dolomite, and eventually, crystals of dolomite included in the marble or in the brucite veins would be destroyed. It is probable that Arduino experiments on the brucite marble have produced calcium sulfate plus magnesium sulfate (the bitter salt). The latter is not equivalent to the Ca-Mg carbonate, i.e., to the dolomite. However, it is worth reporting that Arduino and De Dolomieu met in Venice on the 17th of August 1789, and inevitably, they exchanged information on the respective researches (Vaccari 1993). Therefore, it is possible to infer that, if not unwitting discoverer of the dolomite mineral, Arduino contributed to that discovery.

Petrography

The western Veneto region was the site of mafic to ultramafic magmatism during the Paleogene (Veneto Volcanic province of De Vecchi and Sedea 1995). The volcanic nature of dark rocks interlayered and intruded within the sedimentary succession of the Veneto Pre-Alps was firstly suggested by Arduino, who in the second half of the eighteenth century theorized the equally important role of water and fire within lithogenetic and orogenetic processes. He compared rocks collected in the Mount Vesuvio with rocks of the Vicenza mountains concluding that an ancient volcanic activity developed in Veneto. The German translation (Arduino 1778) of the volume "Raccolta di Memorie Chimico-Mineralogiche, Metallurgiche, e Orittografiche" (Arduino 1775) strongly influenced the German scientific community (Vaccari 1993). By means of several letters to the Italian and Mitteleuropean scientists, Arduino's ideas

[1] I have already said in the same memory (of the Raccolta di Memorie Chimico-Orittologiche, B. Milocco, Venezia) that this marble is located in the just cited great landslide of the mountain, that in the vulgar idiom of the country is called Lavina of Ena, where a large and long dyke can be seen, but here, I add that the same dyke outcrops dipping into the mountain in between common and rough limestones, of which not only this mountain, but also all the others of that province, having veins, or dykes of this sort of marbles, are stratifically organized: with the exception of various apparently volcanic materials, that in several situations are more or less mixed to the same marbles from which they often have differently and vaguely breached forms.

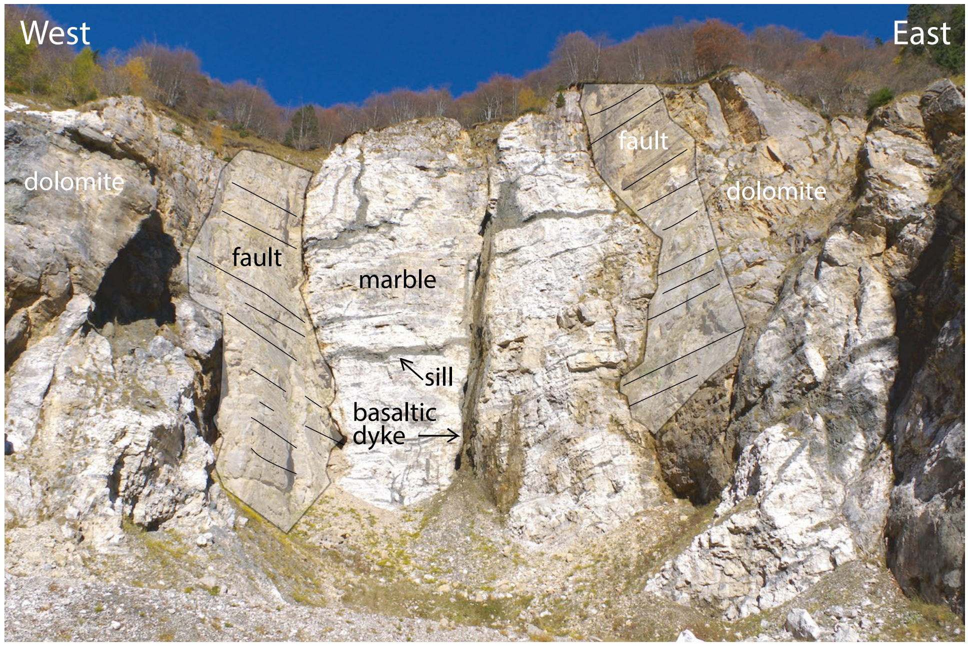

Fig. 4 View of the inactive Borcola Quarry of brucite marble, which originated in contact with the basaltic dykes and sills. The cliff face is about 40 m high

spread and consolidated. Later, the volcanic activity of the western Veneto was reported, among others, by scholars like Maraschini (1824, 1828), Fabiani (1930), Piccoli (1966), Schiavinato (1950), and De Vecchi et al. (1976). The petrography of the lamprophyre dykes widespread in the pre-Alpine mountains of the Vicenza province was analyzed by De Vecchi (1966). On the geodynamic significance of this magmatism, different models have been proposed by von Blanckenburg and Davies (1995), Zampieri (1995), and Macera et al. (2003). The most recent interpretation is that of Brombin et al. (2019), who attributed the Paleogene anorogenic volcanism of Veneto to the upwelling of mantle material in the context of the rollback of a subduction slab. The associated extensional tectonics may have resulted from the same mantle upwelling during the Paleogene. Basaltic dykes of the Veneto Volcanic Province are very well exposed on the walls of Borcola Quarry (Figs 4, 5), where they cut through upper Triassic dolomites of the Dolomia Principale, and generated brucite marbles by contact metamorphism.

Mineralogy

In the Borcola, quarry mineral collectors have found beautiful crystals of several minerals (Boscardin et al. 2011; Zorzi and Boscardin 2014), making it a renowned mineralogical locality.

The website https://www.mindat.org/ lists for this locality 24 valid minerals: analcime, antigorite, aragonite, augite, brucite, calcite, chabazite-Ca, diopside, dolomite, giorgiosite, goethite, graphite, hydromagnesite, hydrotalcite, lizardite, magnetite, phlogopite, pyrite, pyroaurite, quartz, saponite, scolecite, thomsonite-Ca, vesuvianite.

Among these minerals, aragonite occurs with typical acicular crystals (Fig. 6c, but sometimes also appears in coralloid forms (Fig. 6d); brucite, which normally forms massive white or bluish veins and colorless or bluish hexagonal crystals (Fig. 6b), has occasionally been found in a pinkish Mn-rich variety; the rare magnesium hydrate carbonate giorgiosite occurs as white globular incrustations.

Structural Geology

The effects of local tectonic activity are well represented in the Borcola Quarry and can be easily related to the more general picture of southern Alpine tectonics. The 40-m high quarry front is mostly made of dolomitic rock (Dolomia Principale) and shows spectacular sub-vertical fault planes adorned by sub-horizontal grooves (strike-slip regime). These faults belong to the fault damage zone of the Schio-Vicenza fault (Zampieri et al. 2021). The main plane of the fault runs along the NW trending valley bottom and through the Borcola Pass, from which the quarry is 200 m away. The fault planes on the quarry front are steep conjugate faults with sinistral (NNE trending) and dextral (NNW trending) kinematics respectively (Fig. 4). Mirror-like surfaces are common (Fig. 7), while in the eastern wall, the main fault shows polyphase activity, with near extensional dip-slip striae overprinted by strike-slip striae.

Industrial Archeology

The quarrying of marble had a significant role on the local economy between 1950 and 1970 ca. Due to the easy

Fig. 5 **A** Madonna del Carmine altar in the Valli del Pasubio church. **B** Close view of a column. The mixture of marble and dark lamprophyre rock is prominent. The breccia was quarried in the eighteenth century in the Ronchetta Quarry (Mount Novegno), the same sampled by Giovanni Arduino

accessibility, the Borcola quarry operated till 1988. Brucite marbles were appreciated because of their pearly luster and for the colors and fabric of marble breccia injected with basalt (Fig. 5). The extraction and processing of brucite marbles also left some sign on the landscape of the valley.

In the first years of the twentieth-century activity of the quarry, the marble breccia was transported downstream by a cableway. At present, nothing exists of a helical wire saw built in the 1950s to cut marble blocks of a certain size. An iron arrival station structure still exists above a concrete hopper a few kilometers to the south, where the road starts to climb the pass (Fig. 8). In 1958, the road was paved, and the cableway was abandoned in favor of trucks. Other constructions—an abandoned refuge in use by the quarrymens and

Fig. 6 Minerals from the Borcola Quarry. **A** Brucite vein within marble. Collection M. Boscardin, photo S. Castelli. **B** Brucite on calcite. Collection and photo A. Zordan. **C** Acicular crystals of aragonite on calcite. Collection and photo A. Zordan. **D** Coralloid crystal of aragonite. Collection and photo A. Zordan

Fig. 7 **A** Major fault plane in the western wall of the Borcola Quarry with strike-slip lineations (the vertical dimension of the photo is about 20 m). **B** A close view shows mirror-like surfaces, which are typical of faults in the dolomite rock

some associated minor buildings—are still visible near the quarry. These abandoned buildings are neglected and deteriorating, but there is potential for their recovery, if the Borcola Quarry site would be properly promoted and protected.

Eco-Geotourism

Borcola Pass is conveniently positioned at the boundary between Veneto Region and Trento Autonomous Province and at the divide between the Venetian plains (part of the Po plain) and the Adige Valley. In addition, the E5 European long-distance path passes through Borcola Pass. European long-distance paths are designated by the European Ramblers' Association, and the E5 path extends from the French Atlantic coast in Brittany through Switzerland, Austria, and Germany over the Alps to Venice in Italy. It is waymarked over its whole 3200 km (1988 mi) distance. The heaviest used section is the last part (600 km, around 30 days walking), which crosses Europe's highest mountains from Lake Constance (Germany/Switzerland) to Verona (Italy). the path goes along the west flank of the Dolomites, reaches the thermal resort of Levico Terme, and passes through the Borcola Pass—very close to the Borcola Quarry site—right before climbing over the Pasubio massif, which has been the scene of heavy fighting during WWI (Fig. 9).

Fig. 8 **A** Arrival structure of the cableway, which before the asphalting of the road served to lower the marble downstream. **B** The marble chunks were stored in the hopper, from which they were loaded onto trucks

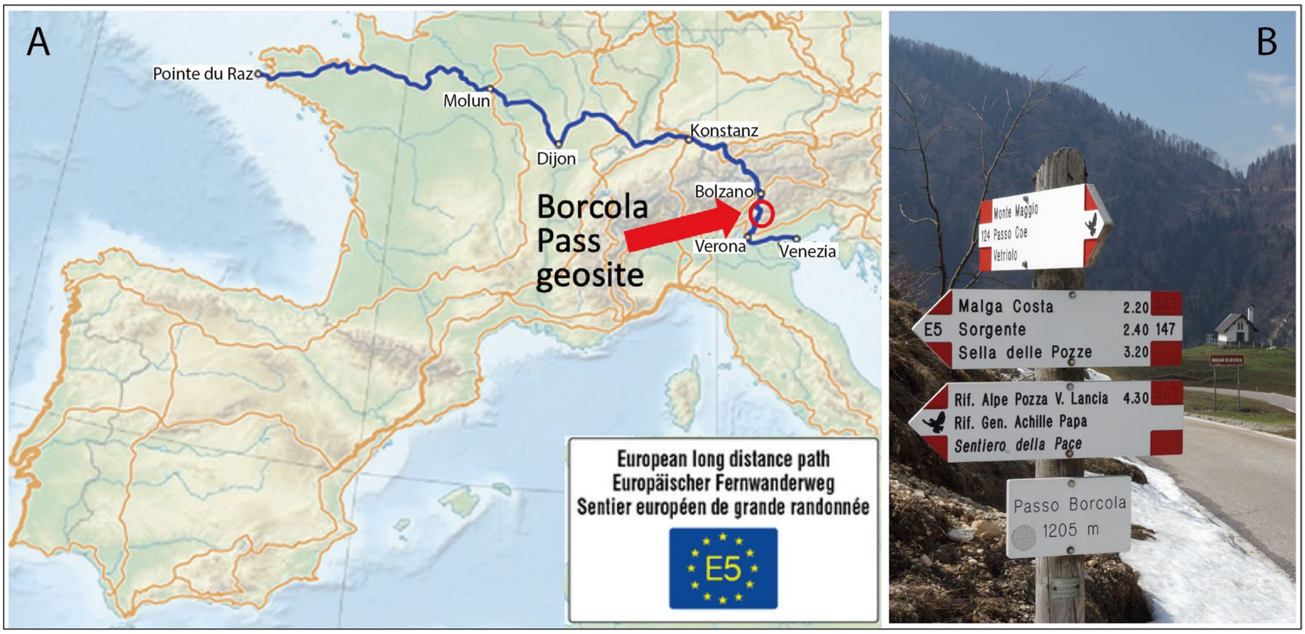

Fig. 9 **A** Map of the European path E5 from the Atlantic Ocean to the North Adriatic Sea. **B** Signs at the Borcola Pass

Geosite Inventories in Italy and Veneto

In Italy, the national inventory of geosites is maintained by ISPRA (https://www.isprambiente.gov.it). Initially, ISPRA collected proposals for geosites either from institutions (e.g., regional geological services) or private citizens through a recommendation form. However, this procedure is now under revision. At present, the task of collecting recommendations for new geosites is delegated to geological services at a regional level. It is envisaged that ISPRA will review the geosites in the regional inventories and will select those which are best representative of the national geodiversity to be included in a revised Italian national inventory.

Hence, the organization of reference for Borcola Quarry is the Veneto Region, which is maintaining its own geosites inventory (https://idt2.regione.veneto.it/portfolio/geositi-del-veneto//), parallel to the ISPRA one. This inventory includes 50 geosites, none of which is related to metamorphism, and only a few are somehow related to the history of geology. The Borcola Quarry Geosite would thus nicely complete the representation of Veneto geodiversity, but—due to the critical importance of the discovery of dolomite in the history of geology—it may also qualify as a geosite at a national level.

The geological service of Veneto prepared a form that includes criteria for the acceptance of a proposed location as a geosite, i.e., the location should be unique—or the best—at least at the regional level as follows:

- Didactical example of a geological feature or process.
- Record of geomorphological evolution.
- Record of a geological process.
- Record of a fossil environment or ecosystem.
- Being a geological rarity.
- Having value for geological research (e.g., a heavily studied outcrop for which several publications exist).
- Being a case of ecological support (e.g., a unique lithology on which specific plants grow).
- Having cultural value.
- Being a type locality (as it is for GSSPs).
- Having value for the history of geology.
- Being an iconic or symbolic place.

The Borcola Quarry fulfills most of the above criteria, being a didactical example of magmatic, metamorphic, and tectonic processes and perhaps the best record of contact metamorphism in Veneto Region; having a cultural value for the use of brucite marbles in regional architecture; and having finally a significant value in the history of geology, for the role of brucite marbles in the early (missed) discovery of dolomite.

Conclusions

In conclusion, the Borcola pass inactive quarry could represent a perfect geosite covering the history of geosciences, the petrography, the mineralogy, the structural geology, and the industrial archeology. It is located in an ideal position for the popularization of complex geological processes and geotouristic fruition. The beautiful exposition offered by this easily accessible inactive quarry offers an aesthetic appeal of the landscape produced by the "interaction of natural and/or human factors," as the European Landscape Convention (art. 1) defines the "Landscape." This site is suitable also for didactic experiences at all degrees of knowledge, from primary school to university level. The European path number 5 passes very close to the proposed geosite, offering an interesting cultural diversion from the path and also an easy boost to the valorization of the path.

The most prominent value of this proposed geosite is, however, its role in the history of geology. In a similar quarry, a few km from the Borcola Pass, in 1779, Giovanni Arduino studied the contact metamorphism process, and through chemical experiments, he obtained a mineral that was suggested to be dolomite, years before it was described and baptized by Nicolas-Théodore de Saussure in 1792.

Although the claim that Arduino discovered dolomite earlier than Dolomieu and de Saussure is probably false; nevertheless, a part of an important process in the formation of the geological mindset took place here, and the site should thus be considered for geoconservation.

Acknowledgements We thank the mineral collectors M. Boscardin and A. Zordan for making some mineral photos available. We also thank Matteo Belvedere and an anonymous reviewer for their thorough review.

Funding Open access funding provided by Università degli Studi di Padova within the CRUI-CARE Agreement.

Research activities have been carried out in the frame of the Italian PRIN Project (Research Projects of National Interest) "Fault segmentation and seismotectonics of active thrust systems: the Northern Apennines and Southern Alps laboratories for new Seismic Hazard Assessments in northern Italy (NASA4SHA)" (PI R. Caputo, UR Responsible S. Seno).

Declarations

Competing Interests The authors declare no competing interests.

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