Calcite–Dolomite Geothermometry of the Portoro Formation (Northern Apennines, Italy): Constraints on Metamorphic Grade

Marco Lezzerini[1*)], Tiziana Ciomei[2)], Marco Tamponi[3)]

[1*)] Department of Earth Sciences, University of Pisa, Via S. Maria 53, 56126 Pisa, Italy, marco.lezzerini@unipi.it; https://orcid.org/0000-0001-9204-4462
[2)] Department of Earth Sciences, University of Pisa, Via S. Maria 53, 56126 Pisa, Italy, tiziana.ciomei@unipi.it, https://orcid.org/0009-0008-5825-9345
[3)] Department of Earth Sciences, University of Pisa, Via S. Maria 53, 56126 Pisa, Italy, marco.tamponi@unipi.it, https://orcid.org/0000-0003-3218-0512

https://doi.org/10.29227/IM-2026-02-02-011

Submission date: *2026-31-07* | Review date: *2026-14-08*

Abstract

Portoro is a highly prized ornamental limestone characterized by a black carbonate matrix crossed by distinctive golden-yellow or silver dolomite veins. It is quarried mainly in the western sector of the Gulf of La Spezia, Northern Apennines. This study provides a quantitative estimate of the metamorphic temperatures recorded by the Portoro Formation through calcite–dolomite geothermometry. Calcite and dolomite grains in direct or close microstructural contact were analysed by scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy in samples representative of the four principal commercial varieties: Scalino, Banco, Sottobanco, and Silver. The $MgCO_3$ contents of calcite coexisting with dolomite were used to calculate apparent equilibrium temperatures according to the calibration of Anovitz and Essene. The 60 analysed calcite–dolomite pairs yielded temperatures predominantly between 250 and 300 °C, with a mean value of 260 ± 48 °C. The dispersion of the results is interpreted as reflecting variable degrees of local equilibration, recrystallization, compositional resetting, and fluid-mediated re-equilibration in the naturally deformed carbonate rocks. For comparison, calibrated Kübler-index data from the metapelitic Grotta Arpaia Layers immediately underlying the Portoro Formation indicate upper anchizonal conditions close to the anchizone–epizone transition. These phyllosilicate data are compatible with, but independent from, the temperature estimates obtained directly from the Portoro carbonate assemblages. The geothermometric results indicate an advanced very-low-grade to incipient low-grade regional metamorphic overprint. These thermal conditions promoted recrystallization of the carbonate matrix and partial reorganization of the dolomite veins while preserving carbonaceous matter and elements of the original sedimentary fabric. The results provide new quantitative constraints on the thermal evolution of the Portoro Formation and contribute to explaining its distinctive petrographic characteristics.

Keywords: *Portoro; calcite–dolomite geothermometry; carbonate recrystallization; very-low-grade metamorphism; Northern Apennines*

1. Introduction

Metamorphic carbonate rocks have been widely used in Mediterranean art and architecture since antiquity. Among them, Portoro is distinguished by an intense black matrix, produced by finely dispersed carbonaceous matter, and by striking golden-yellow or silver dolomite veins. This combination of colour contrast, fine grain size, and high polishability has made Portoro one of the most valuable Italian ornamental stones, used in prestigious interiors, architectural and decorative applications [1] .

Portoro crops out exclusively in the western sector of the Gulf of La Spezia, particularly on the Portovenere Promontory and the islands of Palmaria and Tino. Previous studies have mainly addressed its quarrying history, petrography, and technological properties. By contrast, the thermal conditions responsible for the recrystallized carbonate fabric and distinctive appearance of the stone have not yet been quantitatively constrained in detail using mineral compositions obtained directly from the Portoro Formation.

Calcite–dolomite geothermometry provides a suitable approach for estimating the temperatures recorded by dolomite-bearing carbonate rocks. The method is based on the temperature-dependent solubility of Mg in calcite coexisting with dolomite and has been widely applied to metamorphic carbonate assemblages [2][3][4]. Its reliability depends on the extent to which the analysed carbonate pairs approached and preserved local compositional equilibrium and were not substantially modified by later recrystallization, deformation, or fluid-mediated replacement. Temperatures calculated from carbonate compositions do not necessarily represent a single peak metamorphic event. In naturally deformed carbonate rocks, individual mineral pairs may preserve different stages of recrystallization and re-equilibration.

Recent studies have emphasized that carbonate geothermometric estimates may record variable combinations of peak temperature, cooling, fluid interaction, kinetic effects, and partial resetting [5][6]. In particular, carbonate minerals may preserve highly localized equilibration domains, with different apparent temperatures recorded over millimetre-scale distances as a function of recrystallization and fluid–rock interaction [7]. Consequently, the distribution of calculated temperatures, their microstructural context, and their statistical dispersion must be considered together.

The main aim of this study is to estimate the metamorphic temperatures recorded directly by the Portoro Formation using calcite–dolomite geothermometry. Samples representative of the four main commercial varieties (Scalino, Banco, Sottobanco, and Silver) were investigated to determine whether their carbonate assemblages preserve comparable thermal information.

Illite-crystallinity data from the metapelitic Grotta Arpaia Layers of the underlying La Spezia Formation are considered only as an independent term of comparison. These stratigraphically adjacent rocks experienced the same regional tectono-metamorphic evolution, but the Kübler index reflects the progressive ordering of phyllosilicates rather than calcite–dolomite equilibration. The illite data are therefore not used to calculate or refine the temperatures obtained from the Portoro carbonates, but to assess whether the geothermometric results are compatible with the regional very-low-grade metamorphic framework previously established for the La Spezia succession [8][9].

The study focuses on the thermal information recorded by carbonate mineral pairs within the Portoro Formation and places these results within the broader tectono-metamorphic context of the La Spezia mega-fold.

2. Geological Setting

The Portoro Formation is part of the Triassic–Oligocene sedimentary succession exposed in the La Spezia area and subsequently involved in the tectono-metamorphic evolution of the Northern Apennines. Its stratigraphic position reflects the evolution of the western Tuscan palaeogeographic domain during the Late Triassic–Early Jurassic transition from carbonate-platform to basinal conditions.

The formation outcrops along the western side of the Gulf of La Spezia, from the islands of Tinetto, Tino, and Palmaria to Mt. Santa Croce, following a prevailing NW–SE trend [10] (Fig. 1). The regional structure is characterized by an overturned anticline with a NW–SE-trending axis and southwestward vergence. Farther east, this contractional structure is overprinted by the extensional and strike-slip fault systems associated with the Gulf of La Spezia graben and the Lerici–Montemarcello horst [9].

Lithologically, the Portoro Formation consists of dark grey to black, partly dolomitized calcilutites containing nodular and stylolitic structures and white, yellowish, or golden dolomite patches and veins. The dark colour reflects deposition in a poorly oxygenated marine environment rich in organic matter, whereas the present fabric records subsequent carbonate recrystallization during regional deformation and metamorphism. The formation is generally only a few metres thick and becomes progressively thinner northward [10].

The commercial succession includes, from top to bottom, Scalino, Banco or Portoro macchia larga, Sottobanco, and Silver varieties [11]. The Portoro Formation overlies the Norian–Rhaetian La Spezia Formation and is, in turn, overlain by the Monte Castellana Dolomite. The La Spezia Formation consists mainly of dark grey calcilutites with subordinate marl and dolomite interbeds. Its uppermost portion, known as the Grotta Arpaia Layers, is 10–15 m thick and comprises thin-bedded limestone alternating with finely laminated marl and black clay [12]. During the regional tectono-metamorphic evolution, the clayey and marly sediments were transformed into metapelites dominated by illite, chlorite, quartz, and locally pyrite and iron oxides.

The Portoro Formation directly overlies the Grotta Arpaia Layers, and both units were involved in the same regional tectono-metamorphic evolution. Owing primarily to their contrasting bulk compositions, however, they recorded this evolution through different mineralogical responses: carbonate recrystallization and calcite–dolomite re-equilibration in the Portoro Formation, and progressive phyllosilicate ordering and recrystallization in the Grotta Arpaia metapelites.

More generally, carbonate successions affected by metamorphism and fluid circulation may undergo spatially heterogeneous recrystallization, dolomitization, dedolomitization, and geochemical re-equilibration, depending on bulk composition, fluid pathways, and pressure–temperature evolution [13][14]. These processes must be considered when interpreting calcite–dolomite geothermometric data from the Portoro Formation.

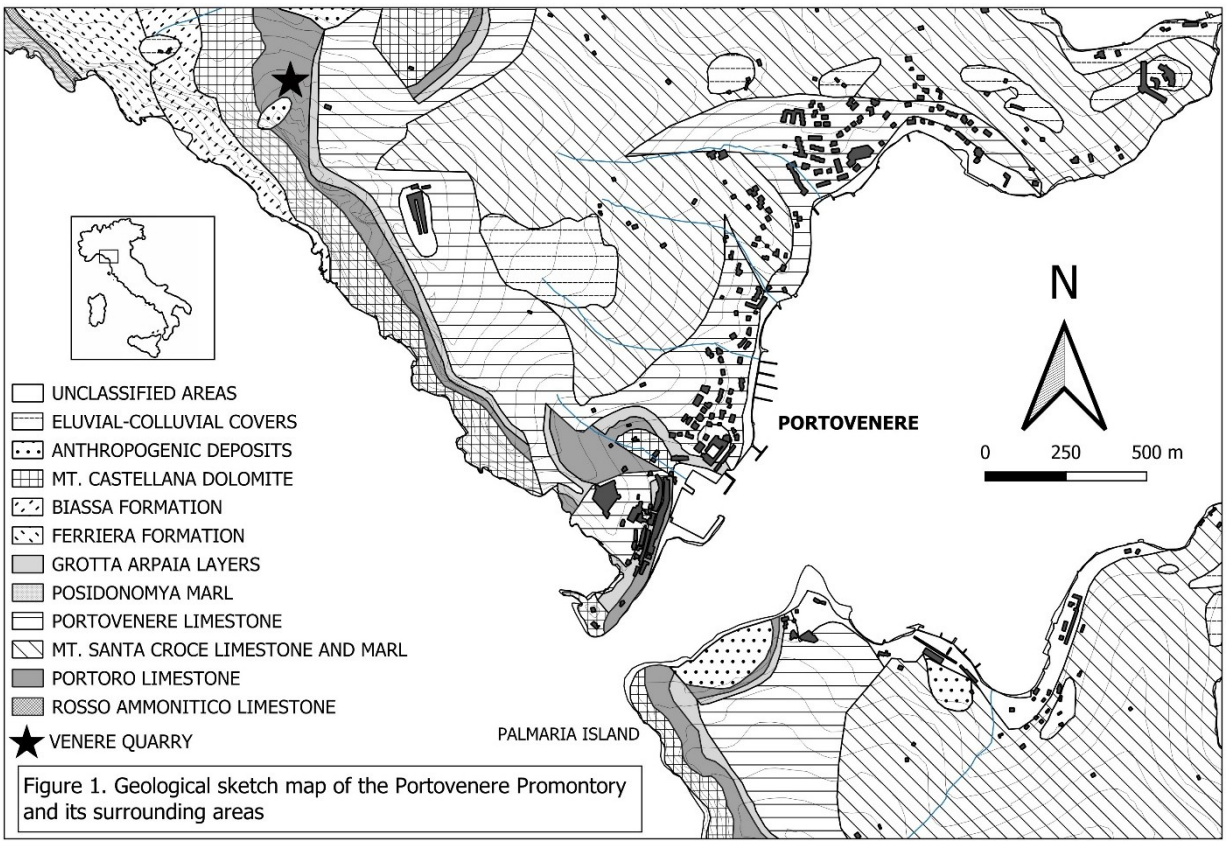

Fig. 1. Geological sketch map of the Portovenere Promontory and its surrounding areas.

3. Materials and Methods

The Portoro samples investigated in this study were obtained from fresh quarry blocks previously collected at the Venere quarry in the Municipality of Portovenere (44°03′39.7″ N, 9°49′24.9″ E) and characterized by Lezzerini et al. [11]. One sample from each of the four commercial varieties was analysed: Scalino (PSC 1), Banco (PBA 1), Sottobanco (PSB 1), and Silver (PSI 7) (Fig. 2). The bulk chemical composition, mineralogical assemblage, petrographic characteristics, and main physical properties were previously reported by Fratini et al. [1] and Lezzerini et al. [11].

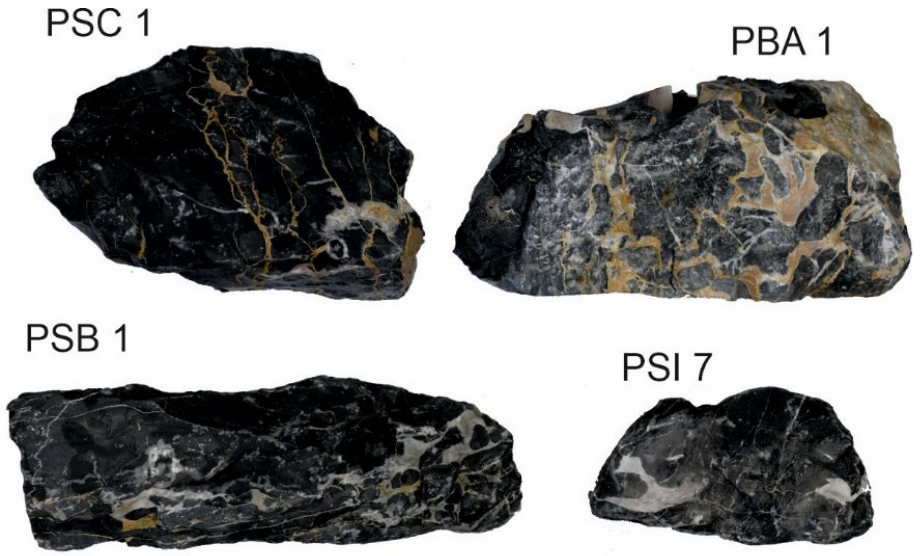

Fig. 2. Macroscopic appearance of the four Portoro samples investigated in this study: Scalino (PSC 1), Banco (PBA 1), Sottobanco (PSB 1), and Silver (PSI 7), showing the characteristic black carbonate matrix and the variable distribution of dolomite veins and patches. Scale bar: 10 cm.

Polished thin sections were prepared for scanning electron microscopy and energy-dispersive X-ray spectroscopy. The analyses were specifically directed towards determining the composition of calcite grains coexisting with dolomite. Whenever possible, calcite and dolomite grains in direct microstructural contact were selected, as such pairs are more likely to preserve evidence of local equilibrium or partial local re-equilibration than spatially separated grains.

SEM analyses were performed using a FEI Quanta 450 ESEM-FEG equipped with a Bruker QUANTAX XFlash 6|10 energy-dispersive X-ray detector. The analyses were conducted in high-vacuum mode at 15 kV, with a beam spot size of approximately 3 μm and a counting time of 100 s. Particular attention was paid to avoiding fractures, inclusions, alteration products, and visibly mixed analytical volumes.

The compositions of 60 calcite–dolomite pairs were determined. The composition of the associated dolomite grains was checked to verify that they were close to stoichiometric dolomite, whereas the principal parameter used for geothermometric calculation was the mole fraction of $MgCO_3$ in coexisting calcite. Because the $FeCO_3$ component in calcite was negligible, with mole fractions lower than 0.001, the Fe-free form of the geothermometric calibration was applied.

Apparent equilibrium temperatures were calculated using the calibration of Anovitz and Essene [3]. This calibration relates the $MgCO_3$ content of calcite to its equilibrium temperature in the presence of dolomite.

The resulting temperatures are referred to as apparent equilibrium temperatures because complete equilibrium at the thin-section or sample scale cannot be demonstrated. In addition, deformation, recrystallization, fluid circulation, and compositional resetting may have affected individual mineral pairs to different degrees.

An analytical and calibration uncertainty of approximately ±20 °C was considered for individual temperature estimates. This uncertainty does not include the potentially larger geological variability related to incomplete equilibration or later resetting, which is assessed from the overall distribution of the calculated values.

For comparison with the regional metamorphic framework, twenty metapelitic samples were collected from the Grotta Arpaia Layers of the upper La Spezia Formation. The <2 μm clay fraction was analysed by X-ray diffraction on oriented aggregates. The Kübler index was measured from the full width at half maximum of the 10 Å illite–muscovite reflection on Mg-saturated, ethylene-glycol-solvated mounts following established procedures [15][16]. Measured values were calibrated on the Crystallinity Index Standard scale. On this scale, values of 0.52 and 0.32 °Δ2θ define the lower and upper boundaries of the anchizone, respectively [17]. Because the Kübler index cannot be converted directly into a unique temperature, these data were used solely for comparison with the carbonate geothermometric results.

4. Results and Discussion

SEM–EDS analyses show that the analysed dolomite grains are close to stoichiometric composition. The coexisting calcite contains a small but consistently measurable $MgCO_3$ component, allowing the application of calcite–dolomite geothermometry.

Representative SEM images of the four investigated Portoro samples, acquired at different magnifications, are shown in Fig. 3. In all samples, the lighter areas correspond to calcite, whereas the darker domains correspond to dolomite. The images document the occurrence and spatial relationships of the two carbonate phases and illustrate the microstructural context in which the calcite–dolomite pairs were selected for compositional analysis.

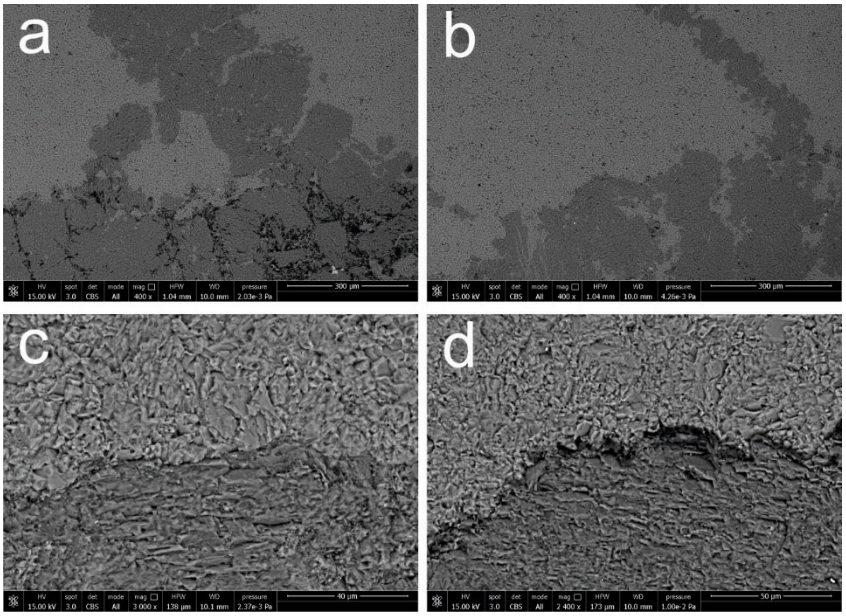

Fig. 3. Representative SEM images of the four investigated Portoro samples acquired at different magnifications: (a) Scalino, PSC 1; (b) Banco, PBA 1; (c) Sottobanco, PSB 1; and (d) Silver, PSI 7. The lighter areas correspond to calcite, whereas the darker domains correspond to dolomite. Mineral identification was confirmed by EDS analyses.

Calcite and dolomite grains in direct contact were preferentially selected. Where direct contacts were not available, grains belonging to the same closely associated microstructural domain were analysed. The carbonate microstructures indicate that the rocks underwent recrystallization during deformation, and individual calcite–dolomite contacts may consequently record different degrees or stages of re-equilibration. No significant $FeCO_3$ component was detected in calcite.

Application of the Anovitz and Essene [3] calibration to the 60 analysed calcite–dolomite pairs yielded a mean apparent equilibrium temperature of 260 ± 48 °C. Most calculated temperatures fall within the interval of 250–300 °C, although the complete distribution extends from approximately 100 to 400 °C (Fig. 4). The mean value provides a useful summary of the dataset, whereas the broad overall range indicates that the analysed mineral pairs did not all attain or preserve the same degree of equilibrium. The mean calcite compositions and apparent equilibrium temperatures calculated for each sample are reported in Table 1.

Tab. 1. Mean chemical composition of calcite and mean apparent equilibrium temperature calculated for each investigated Portoro sample using the calibration of Anovitz and Essene [3]. Values in italics represent one standard deviation.

Sample	MgO	CaO	Sum	$MgCO_3$ in Cc	X_{MgCO3} in Cc	T
	wt%	wt%	wt%	wt%	mol	°C
PSC1	0.99	97.62	98.61	1.18	0.014	262
	0.14	*0.10*	*0.11*	*0.17*	*0.002*	*38*
PBA1	0.94	97.84	98.79	1.12	0.013	244
	0.19	*0.28*	*0.21*	*0.22*	*0.003*	*65*
PSB1	1.01	97.77	98.78	1.20	0.014	272
	0.09	*0.11*	*0.17*	*0.10*	*0.001*	*21*
PSI7	1.02	97.82	98.84	1.21	0.014	262
	0.26	*0.15*	*0.29*	*0.30*	*0.004*	*57*

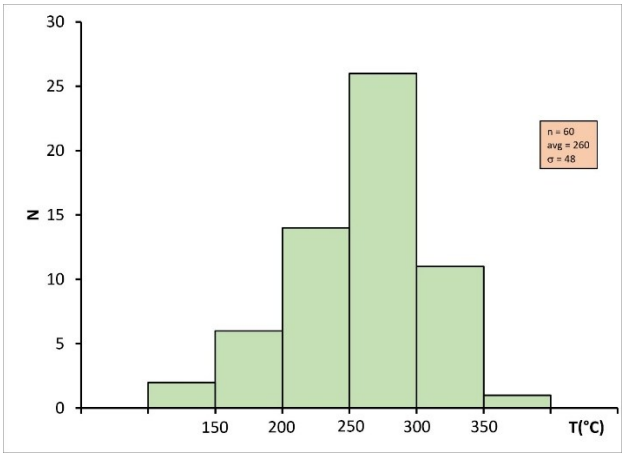

Fig. 4. Distribution of apparent calcite–dolomite equilibrium temperatures calculated using the calibration of Anovitz and Essene [3]. n = number of analysed calcite–dolomite pairs; avg = arithmetic mean; σ = standard deviation.

The temperature dispersion is greater than the estimated analytical uncertainty of approximately ±20 °C and must therefore have a significant geological component. Similar variability is not unexpected in naturally deformed carbonate rocks. Individual calcite–dolomite pairs may record different degrees of recrystallization, local compositional equilibration, fluid interaction, and subsequent resetting [5][6]. Dissolution–reprecipitation and diffusion may also affect different components of dolomite at different rates, producing persistent grain-scale compositional heterogeneity even within the same metamorphic event [18].

Comparable grain- to millimetre-scale heterogeneity in carbonate equilibration has been documented in low-grade metamorphic carbonate rocks, where recrystallized and unrecrystallized domains may preserve substantially different thermal records [7].

The lowest calculated values may reflect incomplete equilibration, late-stage recrystallization, or partial compositional resetting. Conversely, the highest values may represent locally preserved higher-temperature compositions or analytical and microstructural effects. Without additional microstructural or compositional evidence, however, the significance of the extreme values cannot be uniquely determined.

For these reasons, individual extreme temperatures should not be interpreted directly as minimum or maximum metamorphic temperatures. The concentration of most results between 250 and 300 °C and the mean value of 260 °C are more robust indicators of the thermal regime recorded by the Portoro carbonate rocks. The calculated temperatures indicate advanced very-low-grade to incipient low-grade metamorphic conditions. The data provides mineral-composition-based temperature estimates obtained directly from carbonate assemblages of the Portoro Formation.

The four investigated commercial varieties (Fig. 2) collectively record a comparable broad temperature range, consistent with a common regional thermal overprint. However, the limited number of samples and determinations for each lithotype does not permit statistically robust comparisons. The observed differences could reflect local variations in dolomitization, grain size, deformation intensity, fluid access, and recrystallization rather than distinct metamorphic conditions.

The Grotta Arpaia samples are metapelites dominated by illite, chlorite, and quartz, with subordinate calcite and albite. Minor mixed-layer illite–smectite and/or chlorite–smectite phases are locally present, whereas discrete smectite and kaolinite were not detected. Pyrite, apatite, rutile, and iron oxides occur as accessory phases. This assemblage is compatible with the mineralogical evolution generally observed under very-low-grade metamorphic conditions [19].

The CIS values have a mean of 0.36 ± 0.04 °Δ2θ (n = 20; Fig. 5). The values are mainly located in the upper anchizone, with part of the distribution approaching or crossing the anchizone–epizone boundary at 0.32 °Δ2θ.

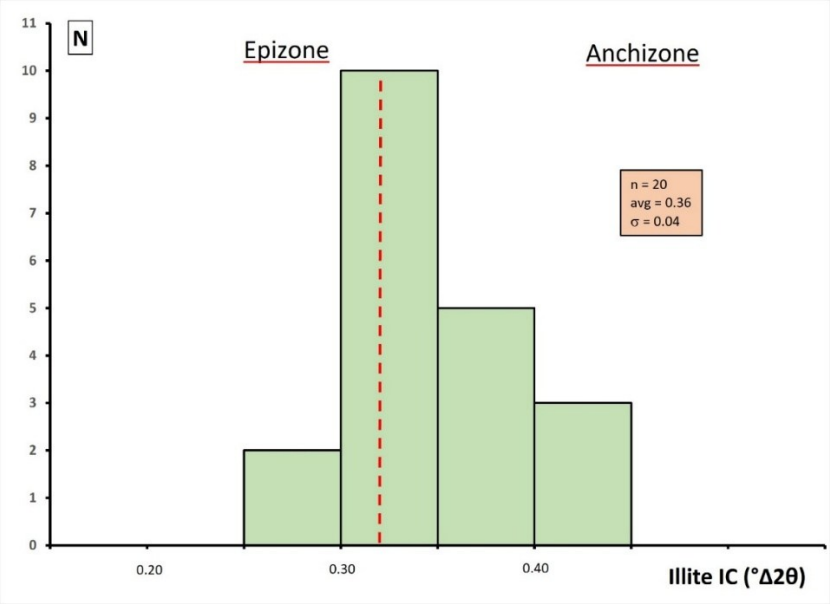

Fig. 5. Distribution of the calibrated Kübler-index values obtained from the Grotta Arpaia metapelites. The red dashed line indicates the anchizone–epizone boundary at 0.32 °Δ2θ on the CIS scale, according to Warr and Ferreiro Mählmann [17]. n = number of determinations; avg = arithmetic mean; σ = standard deviation.

These results indicate advanced very-low-grade metamorphic conditions close to the anchizone–epizone transition. However, the Kübler-index data should not be regarded as an additional geothermometric dataset equivalent to the calcite–dolomite results.

Illite crystallinity is influenced by several factors in addition to temperature, including reaction progress, lithology, fluid availability, deformation, grain size, detrital inheritance, and the duration of metamorphism. Moreover, the anchizonal and epizonal boundaries cannot be converted into unique temperature values that are universally applicable to all geological settings.

The Grotta Arpaia data are therefore used only to test the general consistency of the Portoro geothermometric estimates with the metamorphic grade recorded by adjacent metapelitic rocks. The upper anchizonal conditions indicated by the Kübler index are therefore qualitatively compatible with the advanced very-low-grade metamorphic conditions inferred from calcite–dolomite geothermometry. This agreement supports the geological plausibility of the carbonate geothermometric results, but it does not demonstrate that illite and carbonate minerals equilibrated simultaneously or at exactly the same temperature. The two mineral systems have different reaction kinetics, closure behaviour, and sensitivity to deformation and fluid circulation.

The geothermometric results are consistent with the regional very-low-grade metamorphic framework previously reported by Carosi et al. [9] for the La Spezia mega-fold.

The present study does not attempt to revise that regional framework. Instead, it provides a direct and detailed temperature estimate for the Portoro Formation itself, based on the compositions of coexisting carbonate minerals in its four principal

commercial lithotypes.

A strict numerical comparison with previous estimates should consider differences in sampling strategy, analytical procedures, geothermometric calibration, mineral-pair selection, and illite-crystallinity standardization. In addition, pressure was not independently constrained in the present study. Carosi et al. [9] proposed regional pressure conditions of approximately 2.5 kbar; however, pressure was not independently constrained in the present study, and this value is reported only as contextual information.

The mean apparent equilibrium temperature of 260 ± 48 °C is compatible with the thermal regime expected for an advanced very-low-grade regional metamorphic overprint. The data suggest that the Portoro Formation experienced temperatures sufficient to promote substantial recrystallization of the carbonate matrix and local calcite–dolomite re-equilibration, while preserving part of the original sedimentary fabric and without causing complete textural or compositional homogenization.

The dolomite veins and patches were modified during deformation and metamorphism but were not completely homogenized with the calcitic matrix. Their preservation indicates that recrystallization and fluid-assisted re-equilibration were spatially heterogeneous. Such a decoupling between petrographic transformation and complete geochemical re-equilibration has also been documented in metamorphosed limestone–dolomite successions [13]. This partial reorganization may have contributed to the modification and preservation of the characteristic golden-yellow, white, or silver veining.

The persistence of finely dispersed carbonaceous matter is consistent with the preservation of the black colour of the stone. Nevertheless, the structural organization of carbonaceous material may have been modified by both temperature and deformation-related processes [20].

The present results therefore indicate that Portoro owes its distinctive appearance to the interaction of inherited sedimentary heterogeneity, early diagenetic dolomitization, tectonic deformation, and metamorphic recrystallization under advanced very-low-grade to incipient low-grade conditions.

The metamorphic overprint may have contributed to the development of the fine and relatively cohesive carbonate fabric associated with the favourable cutting and polishing behaviour of Portoro. However, this relationship remains hypothetical because no direct correlations between metamorphic temperature and technological properties were investigated.

5. Conclusions

Calcite–dolomite geothermometry applied directly to samples of the Portoro Formation provides quantitative constraints on its thermal and metamorphic evolution. The main conclusions are as follows:

1. Calcite coexisting with nearly dolomite contains small but measurable amounts of $MgCO_3$ suitable for geothermometric calculation.
2. The 60 analysed calcite–dolomite pairs yield apparent equilibrium temperatures predominantly between 250 and 300 °C, with an arithmetic mean of 260 °C and a standard deviation of 48 °C.
3. The dispersion of the calculated temperatures exceeds the estimated analytical uncertainty and reflects natural variability in local equilibration, recrystallization, deformation, fluid interaction, and compositional resetting.
4. The concentration of most analyses between 250 and 300 °C indicates an advanced very-low-grade metamorphic overprint approaching incipient low-grade conditions.
5. The analysed pairs from the four principal commercial varieties fall within a broadly comparable temperature range, although the available dataset does not permit statistically robust comparisons among individual lithotypes.
6. Kübler-index data from the underlying Grotta Arpaia metapelites indicate upper anchizone conditions close to the anchizone–epizone transition. These data are compatible with the carbonate geothermometric results but are used only as an independent comparison and not as a primary temperature constraint.

The inferred thermal conditions promoted recrystallization of the carbonate matrix and partial reorganization of the dolomite veins while allowing the preservation of carbonaceous matter and relics of the original sedimentary fabric.

The calcite–dolomite geothermometric results provide the quantitative estimate of the metamorphic conditions attained by the Portoro Formation. The illite-crystallinity data confirm that these estimates are consistent with the broader regional metamorphic framework of the La Spezia succession.

Acknowledgments

The authors gratefully acknowledge Venere Marmo Portoro S.r.l. for granting access to the quarry and permitting the collection of the samples investigated in this study.

References

1. F. Fratini, E. Pecchioni, E. Cantisani, F. Antonelli, M. Giamello, M. Lezzerini, R. Canova, Portoro, the black and gold Italian “marble,” Rendiconti Lincei 26 (2015) 415–423. https://doi.org/10.1007/s12210-015-0420-7.
2. M.J. Bickle, R. Powell, Calcite-dolomite geothermometry for iron-bearing carbonates, Contributions to Mineralogy and Petrology 59 (1977) 281–292.
3. L.M. Anovitz, E.J. Essene, Phase Equilibria in the System $CaCO_3$-$MgCO_3$-$FeCO_3$, Journal of Petrology 28 (1987).
4. M. Fahad, Y. Iqbal, M. Riaz, R. Ubic, S.A.T. Redfern, Metamorphic temperature investigation of coexisting calcite and dolomite marble—examples from Nikani Ghar marble and Nowshera Formation, Peshawar Basin, Pakistan, Journal of Earth Science 27 (2016). https://doi.org/10.1007/s12583-015-0643-7.
5. D.C. Brenner, B.H. Passey, R.M. Holder, D.R. Viete, Clumped-Isotope Geothermometry and Carbonate U–Pb Geochronology of the Alta Stock Metamorphic Aureole, Utah, USA: Insights on the Kinetics of Metamorphism in Carbonates, Geochemistry, Geophysics, Geosystems 22 (2021). https://doi.org/10.1029/2020GC009238.
6. D.P. Sarkar, J. Ando, A. Kano, H. Kato, G. Ghosh, K. Das, Carbonate clumped isotope thermometry of fault rocks and its possibilities: tectonic implications from calcites within Himalayan Frontal Fold-Thrust Belt, Prog. Earth Planet. Sci. 8 (2021). https://doi.org/10.1186/s40645-021-00435-6.

References

7. E.M. Stewart, J.M. Eiler, C.E. Bucholz, Carbonate clumped isotopes record the heterogeneous onset of metamorphism in the Alta stock contact aureole, Utah, Contributions to Mineralogy and Petrology 178 (2023). https://doi.org/10.1007/s00410-023-02061-5.
8. M. Frey, Low Temperature Metamorphism, 1987.
9. R. Carosi, L. Leoni, C. Montomoli, F. Sartori, Very low-grade metamorphism in the Tuscan Nappe, Northern Apennines, Italy: Relationships between deformation and metamorphic indicators in the La Spezia mega-fold, Schweizerische Mineralogische Und Petrographische Mitteilungen 83 (2003).
10. A. Giuliani, A. Chelli, G. Mandrone, Portoro marble and quarry activities in the Gulf of La Spezia (N Italy): giacimentological framework and historical exploitation techniques, GEAM - Geoingegneria Ambientale e Mineraria 3 (2010) 29–38.
11. M. Lezzerini, T. Ciomei, M. Tamponi, S. Beraldo, L. Cinzi, M. Marschalko, P. Stecz, S. Pagnotta, Limitations of Standard Salt Crystallization Tests for Compact Carbonate Heritage Stones: Evidence from Extended Testing on Portoro Limestone, Heritage 9 (2026) 109. https://doi.org/10.3390/heritage9030109.
12. G. Ciarapica, L. Passeri, Late Triassic and Early Jurassic sedimentary evolution of the Northern Apennines: An overview, in: Bollettino Della Societa Geologica Italiana, 2005.
13. M. Mueller, C. Jacquemyn, B.F. Walter, C.L. Pederson, S.L. Schurr, O.A. Igbokwe, N. Jöns, S. Riechelmann, M. Dietzel, H. Strauss, A. Immenhauser, Constraints on the preservation of proxy data in carbonate archives – lessons from a marine limestone to marble transect, Latemar, Italy, Sedimentology 69 (2022). https://doi.org/10.1111/sed.12939.
14. S. Tamang, C. Groppo, F. Girault, F. Perrier, F. Rolfo, Metamorphism of Dolomitic and Magnesitic Rocks in Collisional Orogens and Implications for Orogenic CO2 Degassing, Journal of Petrology 65 (2024). https://doi.org/10.1093/petrology/egae021.
15. M. Jaboyedoff, F. Bussy, B. Kübler, P. Thelin, Illite “crystallinity” revisited, Clays Clay Miner. 49 (2001). https://doi.org/10.1346/CCMN.2001.0490205.
16. M. Lezzerini, F. Sartori, M. Tamponi, Effect of amount of material used on sedimentation slides in the control of illite “crystallinity” measurements, European Journal of Mineralogy 7 (1995) 819–824. https://doi.org/10.1127/ejm/7/4/0819.
17. L.N. Warr, R. Ferreiro Mählmann, Recommendations for Kübler Index standardization, Clay Miner. 50 (2015) 283–286. https://doi.org/10.1180/claymin.2015.050.3.02.
18. F. Bégué, L.P. Baumgartner, A.S. Bouvier, S. Escrig, R. Lafay, A. Meibom, T. Müller, Diffusion timescale conundrum in contact metamorphism: Oxygen isotope and trace element profiles in dolomite, Geochim. Cosmochim. Acta 358 (2023). https://doi.org/10.1016/j.gca.2023.08.010.
19. M. Do Campo, F. Nieto, G.L. Albanesi, G. Ortega, R. Monaldi, Outlining the thermal post-depositional evolution of the Ordovician successions of northwestern Argentina by clay mineral analysis, chlorite geothermometry and Kübler index, Andean Geology 44 (2017). https://doi.org/10.5027/andgeov44n2-a04.
20. M.R. Stokes, A.M. Jubb, R.J. McAleer, D.L. Bish, R.P. Wintsch, Deformation-induced graphitization and muscovite recrystallization in a ductile fault zone, Journal of Metamorphic Geology 42 (2024). https://doi.org/10.1111/jmg.12763.