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Is The α - β Quartz Transition a Significant Contributor to Porosity Generation in Unconventional Crystalline Hydrocarbon Reservoirs? A review

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ABSTRACT - This study evaluates the potential contribution of differential thermal contraction between quartz and feldspars to secondary porosity generation during cooling of quartz-bearing crystalline rocks. We reassess and extend the thermomechanical framework proposed by Rossello and Gallardo (2026) by integrating its quantitative model with published thermal-expansion data and experimental evidence for thermally induced microfracturing in granite. The model predicts theoretical thermally induced porosity of approximately 0.4–1.2%, depending mainly on quartz abundance and the contrasting thermal behaviour of quartz and feldspars. The $\beta \rightarrow \alpha$ quartz transition at approximately 573–575 °C at atmospheric pressure produces a marked change in the thermal and elastic behaviour of quartz and may contribute to differential strain and damage within the crystalline framework. However, experimental studies demonstrate that thermal microcracking begins over a broader temperature range, commonly before the quartz transition, and may subsequently propagate and coalesce during thermal evolution. The calculated porosity therefore represents potential secondary pore space rather than directly measured effective reservoir porosity. Its reservoir significance depends on subsequent tectonic deformation, fluid circulation, fracture reactivation, and preservation of fracture connectivity. The results support differential thermal contraction, including the $\beta \rightarrow \alpha$ quartz transition, as a potentially significant contributor to the initial development of secondary porosity in quartz-bearing crystalline rocks and provide a testable framework for evaluating fractured basement hydrocarbon reservoirs.

Keywords: crystalline basement reservoirs; fractured basement; quartz; $\beta \rightarrow \alpha$ quartz transition; thermal contraction; thermal microcracking; secondary porosity; hydrocarbon reservoirs.

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1. Introduction

Crystalline basement rocks constitute productive hydrocarbon reservoirs in numerous petroleum basins worldwide, despite their generally negligible primary matrix porosity and permeability. Hydrocarbon production from basement has been documented in numerous sedimentary basins and petroleum provinces, with important examples including the Bach Ho field in Vietnam, the Zeit Bay field in Egypt, fractured basement reservoirs in Yemen, and crystalline basement targets in the Neuquén Basin of Argentina (P'an 1982; Schutter 2003a,b; Cuong & Warren 2009; Neff 2014; Bawazer et al., 2018; Chiarella et al., 2022; Usman 2014). These occurrences demonstrate that crystalline rocks, particularly granites and other quartz-bearing lithologies, can locally acquire sufficient storage capacity and permeability to constitute economically productive unconventional reservoirs.

Unlike conventional sedimentary reservoirs, in which pore space is primarily associated with the depositional and diagenetic history of the sediment, basement reservoirs depend largely on secondary porosity and fracture permeability. Their effective storage and fluid transmissibility are controlled by the abundance, geometry, aperture, connectivity, and evolution of fractures. These networks may result from tectonic deformation, faulting, weathering, hydrothermal alteration, rifting, and dissolution or replacement processes (Koning 2003; Neff 2014; Trice et al., 2022).

Nevertheless, an important question remains unresolved: how can significant fracture-related porosity initially develop within competent crystalline rocks before or independently of major tectonic deformation?

Several mechanisms have been proposed to explain secondary porosity and permeability in crystalline rocks. Near-surface weathering can produce dissolution and mechanical disaggregation, whereas tectonic deformation can generate faults, joints, and fracture networks. Hydrothermal alteration may further enhance permeability through dissolution, mineral replacement, and repeated fracture opening and sealing. These processes are well documented, but they do not necessarily explain the initial development of distributed microfractures throughout large volumes of otherwise competent crystalline rock, particularly at depth where weathering effects are negligible.

Thermal processes provide an additional mechanism that may contribute to this problem. Minerals within crystalline rocks have different coefficients of thermal expansion and contraction, so cooling from magmatic or metamorphic temperatures can generate differential strain between adjacent grains. In quartz-bearing granitoids, this effect becomes particularly important near the structural transition between β -quartz and α -quartz at approximately 573–575 °C at atmospheric pressure. During cooling, β -quartz transforms to α -quartz, accompanied by a significant change in crystal structure and thermal properties. The differential response of quartz relative to feldspars may generate stress concentrations at grain boundaries and contribute to microcrack initiation (Raman & Nedungadi 1940; Skinner 1966; Johnson et al., 2021).

Experimental investigations demonstrate that heating and cooling of granitic rocks can produce thermally induced microcracks over a broad temperature range. Microcracking may begin well below the quartz transition temperature and subsequently propagate and coalesce with increasing temperature or during thermal cycling, particularly along grain boundaries and quartz–feldspar contacts (Fredrich & Wong 1986; Avanthi Isaka et al., 2019; Junique et al., 2021; Xu et al., 2023; Pan et al., 2024). These observations indicate that thermal damage cannot be attributed exclusively to the β – α transition. Rather, the transition represents one particularly important stage within a broader process of differential thermal deformation in quartz-bearing crystalline rocks.

Rosello & Gallardo (2026) proposed that differential thermal behaviour of quartz and feldspars, particularly the β – α quartz transition, may contribute substantially to the development of secondary porosity in crystalline rocks. The present study builds upon that hypothesis by combining a critical synthesis of published mineral-physics and experimental evidence with an independent first-order thermomechanical calculation of thermally induced porosity in representative granitoid compositions. The analysis evaluates how quartz abundance and the contrasting thermal response of quartz and feldspars affect the potential generation of secondary pore space during cooling.

The principal objective is therefore not to demonstrate that the β - α quartz transition alone creates an effective hydrocarbon reservoir, but to determine whether it represents a physically significant mechanism capable of generating a measurable initial porosity and microfracture framework that can subsequently be modified and enhanced by tectonic and hydrothermal processes. The resulting quantitative estimates are compared with experimental evidence for thermal microfracturing and are discussed in terms of their implications for fractured crystalline basement reservoirs. This approach provides a critical and quantitative extension of the hypothesis of [Rosello and Gallardo \(2026\)](#), while explicitly considering the effects of confining pressure, cooling history, fracture connectivity, and subsequent mineral sealing.

1.1 Fractured crystalline basement hydrocarbon reservoirs

Fractured crystalline basement reservoirs represent an unconventional type of petroleum system in which hydrocarbon storage and production depend predominantly on secondary porosity and fracture permeability rather than on primary depositional pore space. The reservoir may consist of intrusive igneous rocks, particularly granites, as well as volcanic and metamorphic lithologies exposed beneath a regional unconformity. Although these rocks commonly have negligible primary porosity, they may become productive when a sufficiently extensive and interconnected fracture network develops ([Landes et al., 1960](#); [P'an 1982](#); [Koning 2003](#); [Schutter 2003](#); [Chiarella et al., 2022](#); [Usman 2014](#)).

Hydrocarbon-bearing crystalline basements have been documented in numerous petroleum provinces worldwide. Notable examples include the Bach Ho field in the Cuu Long Basin of Vietnam, the Zeit Bay field in Egypt, fractured basement reservoirs in Yemen and Venezuela, and crystalline basement targets in the Neuquén Basin of Argentina ([Cuong & Warren 2009](#); [Neff 2014](#); [Bawazer et al., 2018](#); [Rosello & Barrionuevo 2007](#)). These occurrences demonstrate that basement rocks can locally develop sufficient storage and transmissibility to sustain significant hydrocarbon production, even where matrix porosity is intrinsically very low ([Figure 1](#)).

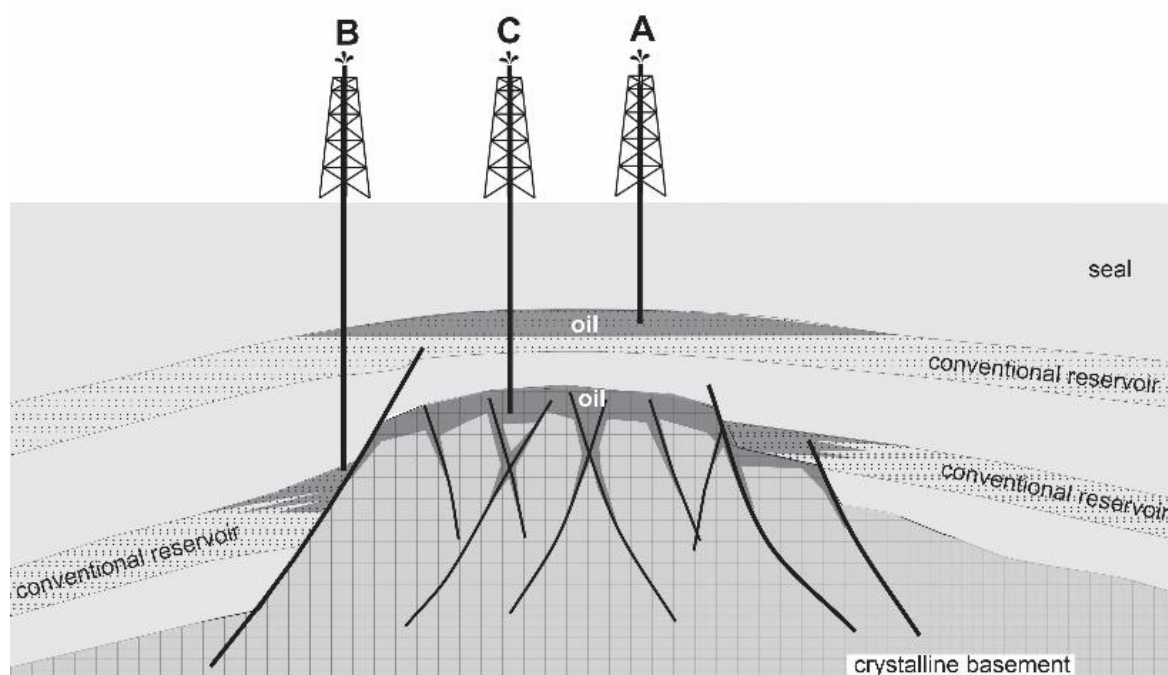


Figure 1.

A representative geological section illustrating the hydrocarbon accumulation system in both conventional reservoirs and fractured basement settings, including the associated fracture network, is shown. A and B: production well from conventional reservoir. C: production well from conventional and unconventional reservoir.

The origin and evolution of basement fracture systems are complex and commonly involve several superimposed processes. Tectonic deformation can generate faults, joints, and damage zones, whereas weathering, hydrothermal alteration, dissolution, mineral replacement, and rifting may modify fracture apertures and connectivity (P'an 1982; Koning 2003; Neff 2014). Consequently, reservoir quality is highly heterogeneous and may vary over short distances according to lithology, structural position, fracture density, orientation, aperture, and subsequent sealing. An important distinction must therefore be made between matrix porosity, microfracture porosity, and effective fracture permeability. The crystalline matrix generally provides little storage capacity, whereas fractures provide the principal pathways for fluid migration and production. However, a fracture network does not necessarily arise exclusively from large-scale tectonic deformation. Distributed microfracturing at the grain scale may provide an initial population of interconnected discontinuities that can subsequently be enlarged, reactivated, or hydraulically connected by tectonic and hydrothermal processes.

The thermal history of crystalline rocks provides a potential mechanism for generating such initial microfractures. During cooling from magmatic temperatures, quartz and feldspars undergo different thermal contraction, producing differential strain within the crystalline framework. In quartz-bearing granitoids, this effect is particularly relevant near the β - α quartz transition. The resulting local stress concentrations may promote grain-boundary cracking and contribute to the development of secondary pore space. The quantitative significance of this mechanism is examined in the following sections using the thermomechanical framework previously developed by Rossello & Gallardo (2026).

The exploration and development of fractured basement reservoirs remain challenging because the relevant fracture dimensions are generally below the direct resolution of conventional seismic methods. Seismic interpretation can nevertheless identify structural highs, fault zones, and areas potentially associated with enhanced fracturing, while well logs, borehole imaging, cores, pressure data, and production tests provide progressively higher-resolution information on reservoir heterogeneity. Purpose-designed three-dimensional seismic surveys and seismic attributes such as curvature, variance, amplitude, and impedance may further assist in identifying structurally favourable zones. The inability to directly image most microfractures reinforces the importance of understanding the physical processes capable of generating them.

2. Methodology

This study combines a critical synthesis of published mineral-physics and experimental data with a quantitative thermomechanical assessment of secondary porosity generated by differential thermal contraction in quartz-bearing crystalline rocks. The approach is based on the analytical model developed by Rossello & Gallardo (2026), which relates the temperature-dependent volume changes of quartz and feldspars to the potential generation of residual pore space during cooling. The present study reassesses this framework in the context of fractured crystalline hydrocarbon reservoirs and incorporates additional experimental evidence for thermally induced microfracturing.

2.1 Mineral thermal properties and literature synthesis

Published experimental data on the thermal expansion and contraction of quartz, alkali feldspars, and plagioclase were compiled to establish representative temperature-dependent mineral behaviour. Particular emphasis was placed on the α - β structural transition of quartz and on the contrasting thermal expansivity of feldspar minerals. Representative coefficients of thermal expansion were selected from experimentally determined values reported in the mineral-physics literature and applied to typical quartz-bearing granitoid compositions.

The literature synthesis also included experimental and microstructural studies documenting thermal microcracking in granitic and other crystalline rocks. These studies were used independently of the analytical calculations to evaluate whether the magnitude and distribution of calculated thermal volume changes are physically compatible with the formation of microfractures. Evidence from grain-boundary cracking, quartz-feldspar interfaces, fracture propagation, and permeability changes was considered particularly relevant.

2.2 Thermomechanical model

The quantitative assessment follows the analytical framework developed by Rosello & Gallardo (2026), which relates the temperature-dependent volume changes of quartz and feldspars to potential residual pore space during cooling. Published thermal-expansion data for quartz and feldspars are used to define representative mineral responses, while the modal quartz content of the modeled granitoids is varied to evaluate its influence on the calculated porosity (Rosello & Reynard 1997; Hovis et al., 2010; Henderson 2021; Rosello & Gallardo 2026).

The model does not assume that all calculated differential volume becomes effective porosity. Instead, it provides a theoretical estimate of the pore space that may result if differential thermal strain is accommodated by permanent microfracturing. This distinction allows the calculated results to be evaluated independently against experimental observations of thermal cracking and changes in pore connectivity (Fredrich & Wong 1986; Avanthi Isaka et al., 2019; Junique et al., 2021; Xu et al., 2023).

For a unit volume of crystalline rock, the volume occupied by each mineral phase at a given temperature (T) is calculated from its initial modal abundance and temperature-dependent volumetric expansion. Quartz is treated separately because its thermal behaviour changes abruptly across the β - α transition, whereas feldspar is represented by an effective thermal-expansion coefficient appropriate for the assumed mineral assemblage.

The resulting differential volume is converted into a theoretical thermally induced porosity:

$$V_{\text{granit}}^{(575)} = 1 \left[1 - X_{\text{quartz}}(0) \left(1 + \int_0^{575} \frac{ZV_{\text{feldspar}}}{ZT} dT \right) + X_{\text{quartz}}(0) \left(\frac{V_{\beta\text{-quartz}}(575)}{V_{\alpha\text{-quartz}}(0)} \right) \right] \quad (1)$$

where V_{granit} , $V_{\alpha\text{-quartz}}$, $V_{\beta\text{-quartz}}$, V_{feldspar} , and X_{quartz} are unit volume of the granite, volume of α -quartz, volume of β -quartz, volume of feldspar; and quartz percentage in the rock, respectively.

The first term can then be written as:

$$X_{\text{initial}}^{(T)} = X_{\text{initial}}^{(0)} \left[1 + \int_0^T \frac{ZV_{\text{feldspar}}}{2T} dT \right] \quad (2)$$

where $X_{\text{initial}}^{(575)}$ right before the transition α - β corresponds to:

$$X_{\text{initial}}^{(575)} = X_{\text{initial}}^{(0)} \left[\frac{V_{\beta\text{-quartz}}(575)}{V_{\alpha\text{-quartz}}(0)} \right] \quad (3)$$

Combining (2) y (3) then:

$$X_{\text{initial}}^{(0)} = \frac{X_{\text{quartz}}(0) \left[\frac{V_{\beta\text{-quartz}}(575)}{V_{\alpha\text{-quartz}}(0)} \right]}{\left[1 + \int_0^{575} \frac{ZV_{\text{feldspar}}}{ZT} dT \right]} \quad (4)$$

and replacing (4) by (2):

$$X_{\text{initial}}^{(T)} = \left[X_{\text{quartz}}(0) \left[\frac{V_{\beta\text{-quartz}}(575)}{V_{\alpha\text{-quartz}}(0)} \right] \left[\frac{1 + \int_0^T \frac{ZV_{\text{feldspar}}}{ZT} dT}{1 + \int_0^{575} \frac{ZV_{\text{feldspar}}}{ZT} dT} \right] \right] \quad (5)$$

The intrinsic volume of the quartz fraction at any given temperature is defined by:

$$X_{\text{quartz}}(T) = X_{\text{quartz}}(0) \left[1 + \int_0^T \frac{ZV_{\text{quartz}}}{zT} dT \right] \quad (6)$$

The calculation specifically evaluates the cooling path across the β – α quartz transition at approximately 573–575 °C at atmospheric pressure. Representative granitoid compositions with different quartz contents are used to determine the sensitivity of calculated porosity to mineral proportions. The resulting values are compared with the previously published model results of [Rossello & Gallardo \(2026\)](#), which predicted thermally induced porosity of approximately 0.4–1.2% depending on quartz abundance and the thermal response of the feldspar framework.

2.3 Assumptions and limitations

The model is deliberately first-order and is intended to quantify the potential contribution of differential mineral contraction to secondary porosity rather than to reproduce the complete thermo-mechanical evolution of a natural plutonic body. The calculations assume that the mineral assemblage remains compositionally stable during cooling and that the differential volume change is not completely accommodated by ductile deformation, grain-boundary sliding, or mineral reactions.

Several processes may reduce, modify, or redistribute the calculated void space in natural rocks. These include confining pressure, the anisotropic thermal expansion of individual crystals, cooling rate, crystal size and texture, pre-existing fractures, tectonic stress, fluid pressure, and subsequent mineral precipitation or fracture sealing. Consequently, the calculated values represent theoretical thermally induced secondary porosity, rather than directly measured effective porosity.

The distinction is essential for interpreting the results. The model quantifies the physical capacity of differential mineral contraction to generate pore space, whereas the development of an effective reservoir requires that at least part of this pore space remain open and become sufficiently interconnected. The subsequent development of microfractures and their hydraulic connectivity is therefore evaluated separately using published experimental and microstructural observations.

2.4 Thermal behaviour of quartz and feldspars

- **Quartz**

Quartz exhibits two principal polymorphic forms under the pressure–temperature conditions relevant to crystalline basement rocks. At atmospheric pressure, α -quartz has trigonal symmetry and is stable below approximately 573 °C, whereas β -quartz has hexagonal symmetry and is stable above this temperature ([Figure 2](#)). The transformation is a displacive structural transition accompanied by marked changes in the thermal expansion, elastic properties, and crystal structure of quartz ([Raman & Nedungadi 1940](#); [Skinner 1966](#); [Johnson et al., 2021](#)).

The direction of the transformation depends on the thermal path. During heating, α -quartz transforms to β -quartz, whereas during cooling the reverse β → α transition occurs. At atmospheric pressure, the transition takes place at approximately 573–575 °C, although its precise behaviour depends on pressure and the thermal history of the material. This distinction is fundamental to the present study because the proposed reservoir-forming mechanism concerns the cooling of quartz-bearing crystalline rocks from high-temperature conditions.

[Johnson et al. \(2021\)](#) demonstrated that the quartz α ↔ β transition can generate substantial changes in elastic properties and differential stresses within polycrystalline rocks. Their analysis indicates that the transition may contribute to damage development and facilitate fluid access to previously less permeable regions of the crust. These observations provide an important physical basis for evaluating the potential role of the β → α transition in secondary porosity generation.

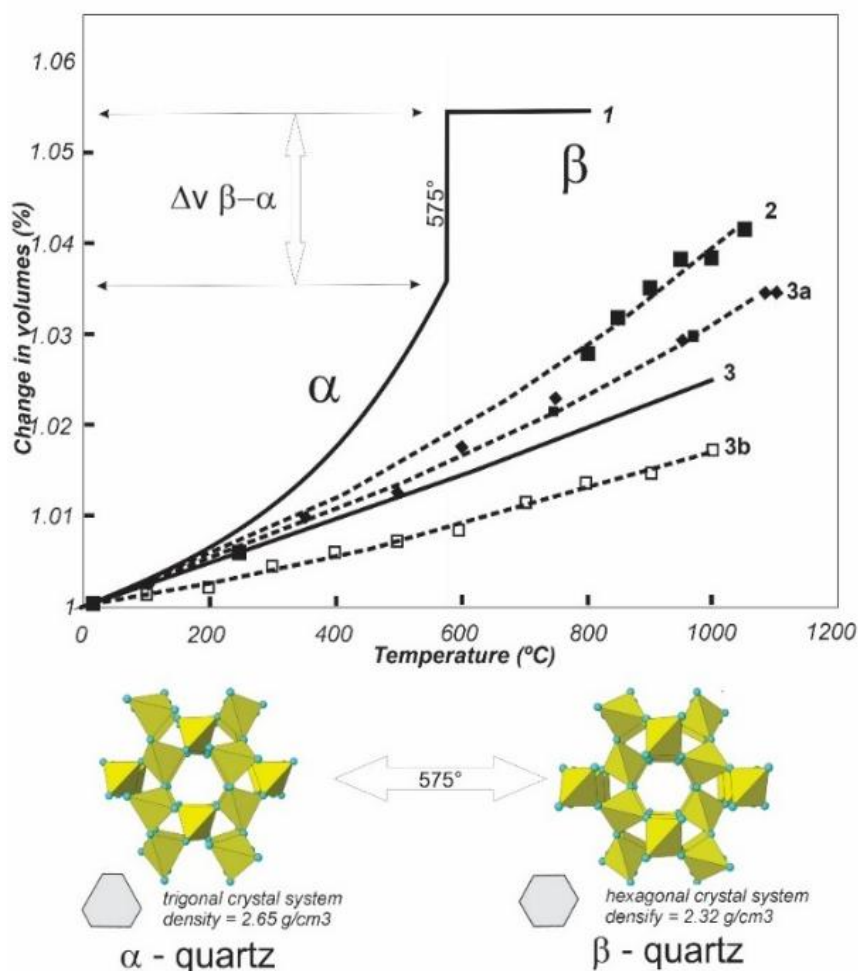


Figure 2.

Variation in mineral volume as a function of temperature for (1) quartz (α - and β -phase), (2) alkali feldspar (representing an average of orthoclase, microcline, and sanidine), and (3) average plagioclase (3a: albite; 3b: anorthite).

Modified after [Rossello & Reynard \(1997\)](#) and [Rossello & Gallardo \(2026\)](#).

However, the experimental evidence also demonstrates that thermal microcracking is not restricted to the quartz transition interval. Thermally induced cracks may develop from approximately 300 °C and increase in abundance and connectivity during subsequent heating and cooling cycles ([Avanthi Isaka et al., 2019](#); [Xu et al., 2023](#)). The quartz transition should therefore be interpreted as an important perturbation superimposed on a broader process of differential thermal contraction rather than as the sole cause of thermal microfracturing.

• Feldspars

Feldspars constitute the dominant mineral framework of many granitoids and provide the principal mechanical matrix surrounding quartz grains. They include alkali feldspars, represented principally by K-rich compositions, and plagioclase feldspars ranging from albite to anorthite. Their thermal behaviour is affected by composition, structural ordering, crystallographic orientation, and the degree of equilibrium achieved during cooling ([Tribaudino et al., 2010](#); [Hovis et al., 2010](#); [Henderson 2021](#)).

For the first-order calculations developed here, the complex behaviour of individual feldspar species is represented by an effective coefficient of thermal expansion. Values of approximately $(2.1 - 2.5 \times 10^{-5} \text{ K}^{-1})$ provide a representative range for the feldspar framework considered in the model, consistent with published experimental measurements ([Hovis et al., 2010](#); [Henderson 2021](#); [Rossello & Gallardo 2026](#)). This simplification is justified because the objective is not to reproduce the detailed thermal behaviour of each feldspar composition, but to quantify the differential response between the feldspar framework and quartz.

The contrast between quartz and feldspar thermal behaviour becomes particularly significant during cooling through the quartz transition. Because feldspars do not undergo an equivalent abrupt structural transformation within this temperature interval, their response remains comparatively continuous. Quartz grains embedded within the feldspar framework therefore experience a different volumetric contraction, generating differential strain at mineral interfaces. The resulting stress concentrations may promote intergranular and transgranular microfracturing, particularly where the aggregate cannot accommodate the strain through elastic or ductile deformation.

Other feldspar reactions, including albitization and dissolution–reprecipitation processes, can independently generate porosity and microfractures (Engvik et al., 2008; Norberg et al., 2011). These processes are important in natural hydrothermal systems but are not included in the thermal model presented here. They are considered secondary mechanisms that may subsequently modify or enhance the pore and fracture network initially generated by differential thermal contraction.

• 4Differential thermal contraction in granitoids

The contrasting thermal behaviour of quartz and feldspars provides the physical basis for the quantitative assessment developed in the following section. A cooling granitoid can be regarded, to a first approximation, as a mechanically coherent polycrystalline aggregate in which mineral grains attempt to contract according to their individual thermal properties. Because the grains are mutually constrained, differential contraction produces internal strain rather than simple independent mineral-volume reduction.

The magnitude and distribution of this strain depend strongly on quartz abundance. A granitoid containing little quartz will experience a smaller contribution from the quartz-specific transition, whereas quartz-rich compositions provide a larger population of mineral interfaces at which differential strain can develop. The theoretical porosity predicted by the model therefore increases with increasing quartz proportion, although the relationship between calculated void space and effective permeability is not necessarily linear.

The thermal mechanism proposed here should consequently be viewed as an initial stage in the development of secondary porosity. Subsequent tectonic deformation, fluid pressure, hydrothermal alteration, and fracture reactivation may enlarge, connect, or seal the thermally generated microfractures. The quantitative significance of this process is evaluated below by applying the thermomechanical model of Rosello & Gallardo (2026) to representative granitoid compositions.

• Thermally induced porosity generation

The contrasting thermal behaviour of quartz and feldspars provides a physical basis for estimating the amount of secondary pore space that may develop during cooling of quartz-bearing crystalline rocks. The quantitative assessment presented here follows the analytical framework developed by Rosello & Gallardo (2026), which relates the temperature-dependent volumetric changes of quartz and feldspars to potential residual pore space generated during cooling. Published thermal-expansion data for quartz and feldspars are used to define representative mineral responses, while the modal quartz content of the modeled granitoids is varied to evaluate its influence on the calculated porosity (Rosello & Reynard 1997; Hovis et al., 2010; Henderson 2021; Rosello & Gallardo 2026).

The model considers an idealized quartz–feldspar aggregate representative of felsic crystalline rocks. Feldspars are treated as a mechanically coherent framework with an effective coefficient of thermal expansion, whereas quartz is described using its temperature-dependent thermal response. This simplification allows the differential volumetric behaviour of the two principal mineral groups to be evaluated without introducing the additional complexity associated with minor minerals, crystallographic orientation, grain-size distributions, and heterogeneous deformation.

Under idealised conditions, secondary porosity in a rock composed principally of quartz and feldspars can result from the differential thermal behaviour of the constituent minerals during cooling, including the volumetric change associated with the $\beta \rightarrow \alpha$ quartz transition. The quantitative formulation used here follows

the model originally proposed by [Rossello & Reynard \(1997\)](#) and subsequently reproduced and applied by [Rossello & Gallardo \(2026\)](#).

The model assumes that the feldspar assemblage constitutes a mechanically coherent framework, whereas quartz undergoes a distinct temperature-dependent volumetric evolution. For a unit volume of granite immediately before the $\beta \rightarrow \alpha$ transition, the total rock volume can be expressed as:

$$V_{\text{granite}}(575) = (1 - X_{\text{quartz}}(0)) \left[1 + \int_0^{575} \frac{1}{V_{\text{feldspar}}} \frac{\partial V_{\text{feldspar}}}{\partial T} dT \right] + X_{\text{quartz}}(0) \frac{V_{\beta\text{-quartz}}(575)}{V_{\alpha\text{-quartz}}(0)} \quad (7)$$

where V_{granite} , X_{quartz} , $V_{\beta\text{-quartz}}$, and $V_{\alpha\text{-quartz}}$ granite volume, quartz volume, quartz β volumen, and quartz α volumen.

The interpretation is important: the first term represents the volume of the feldspar framework, while the second represents the volume corresponding to the quartz initially incorporated into the system. The first quantity can be expressed

$$\text{as: } X_{\text{initial}}(T) = X_{\text{initial}}(0) \left[1 + \int_0^T \frac{1}{V_{\text{feldspar}}} \frac{\partial V_{\text{feldspar}}}{\partial T} dT \right] \quad (8)$$

The second thermal with $X_{\text{initial}}(575)$ just before the $\beta - \alpha$ transition is expressed by:

$$X_{\text{initial}}(575) = X_{\text{quartz}}(0) \frac{V_{\beta\text{-quartz}}(575)}{V_{\alpha\text{-quartz}}(0)} \quad (9)$$

From the combination of (2) and (3):

$$X_{\text{initial}}(0) = \frac{X_{\text{quartz}}(0) \frac{V_{\beta\text{-quartz}}(575)}{V_{\alpha\text{-quartz}}(0)}}{1 + \int_0^{575} \frac{1}{V_{\text{feldspar}}} \frac{\partial V_{\text{feldspar}}}{\partial T} dT} \quad (10)$$

Replacing (4) with (2) results in:

$$X_{\text{initial}}(T) = X_{\text{quartz}}(0) \frac{V_{\beta\text{-quartz}}(575)}{V_{\alpha\text{-quartz}}(0)} \frac{1 + \int_0^T \frac{1}{V_{\text{feldspar}}} \frac{\partial V_{\text{feldspar}}}{\partial T} dT}{1 + \int_0^{575} \frac{1}{V_{\text{feldspar}}} \frac{\partial V_{\text{feldspar}}}{\partial T} dT} \quad (11)$$

The intrinsic volume of quartz at any temperature is defined by:

$$X_{\text{quartz}}(T) = X_{\text{quartz}}(0) \left[1 + \int_0^T \frac{1}{V_{\text{quartz}}} \frac{\partial V_{\text{quartz}}}{\partial T} dT \right] \quad (12)$$

And finally: The porosity ρ induced by differential thermal expansivity is simply given by:

$$\rho(T) = X_{\text{initial}}(T) - X_{\text{quartz}}(T) = X_{\text{quartz}}(0) \left[\left(\frac{V_{\beta\text{-quartz}}(575)}{V_{\alpha\text{-quartz}}(0)} \right) \frac{\left(1 + \int_0^T \frac{\dot{Z}V_{\text{feldspar}}}{ZT} dT \right)}{\left(1 + \int_0^{575} \frac{\dot{Z}V_{\text{feldspar}}}{ZT} dT \right)} - \left(1 + \int_0^T \frac{\dot{Z}V_{\text{quartz}}}{ZT} dT \right) \right] \quad (13)$$

This formulation allows the theoretical pore volume to be calculated as a function of temperature and quartz abundance. The resulting calculations, subsequently reproduced by [Rossello & Gallardo \(2026\)](#), yield maximum theoretical porosity values of approximately 0.4% for quartz-poor granitoids and up to approximately 1.2% for felsic granitoids containing about 30% quartz and abundant feldspars.

Importantly, the model predicts that porosity does not cease to evolve immediately below the $\beta \rightarrow \alpha$ transition. Instead, the calculated porosity shows a pronounced increase associated with the transition, followed by a more gradual increase during cooling from approximately 573 to 200 °C and comparatively stable values below approximately 200 °C ([Figure 3](#)). The $\beta \rightarrow \alpha$ transition therefore represents the most abrupt volumetric contribution to the modeled porosity, whereas subsequent differential thermal contraction continues to influence the calculated pore volume during cooling. The resulting porosity–temperature relationships show three principal trends ([Figure 3](#)).

First, a pronounced change in the calculated porosity occurs within the temperature interval associated with the $\beta \rightarrow \alpha$ quartz transition. This reflects the marked modification of the structural and thermal properties of quartz during the transition ([Raman & Nedungadi 1940](#); [Skinner 1966](#); [Johnson et al., 2021](#)). Second, a more gradual increase in calculated porosity develops during cooling outside the transition interval, reflecting the cumulative differential thermal contraction of quartz and feldspars. Third, the calculated porosity approaches a comparatively stable trend at lower temperatures, where the differential thermal response of the mineral assemblage becomes progressively smaller. The overall response therefore results from both continuous differential contraction and the additional volumetric and elastic effects associated with the quartz transition.

The magnitude of the calculated response increases with quartz abundance because a larger quartz fraction contributes more strongly to the differential volumetric behaviour of the crystalline framework. For representative granitoid compositions, the model predicts theoretical thermally induced porosity values of approximately 0.4% for quartz-poor compositions and up to approximately 1.2% for felsic granitoids containing about 30% quartz and abundant feldspars ([Rossello & Gallardo 2026](#)). The relationship between quartz content, temperature, and calculated porosity is illustrated in [Figure 3](#).

These values should be interpreted carefully. The calculated 0.4–1.2% represents potential secondary pore space generated by differential mineral contraction under the assumptions of the model, rather than directly measured effective porosity. In a natural crystalline rock, part of the differential strain may instead be accommodated elastically, by grain-boundary adjustment, crystal-plastic deformation at elevated temperature, or by the reactivation of pre-existing fractures. Conversely, if the differential strain exceeds the local strength of the aggregate, permanent microfractures may develop and preserve part of the calculated volume change as secondary porosity.

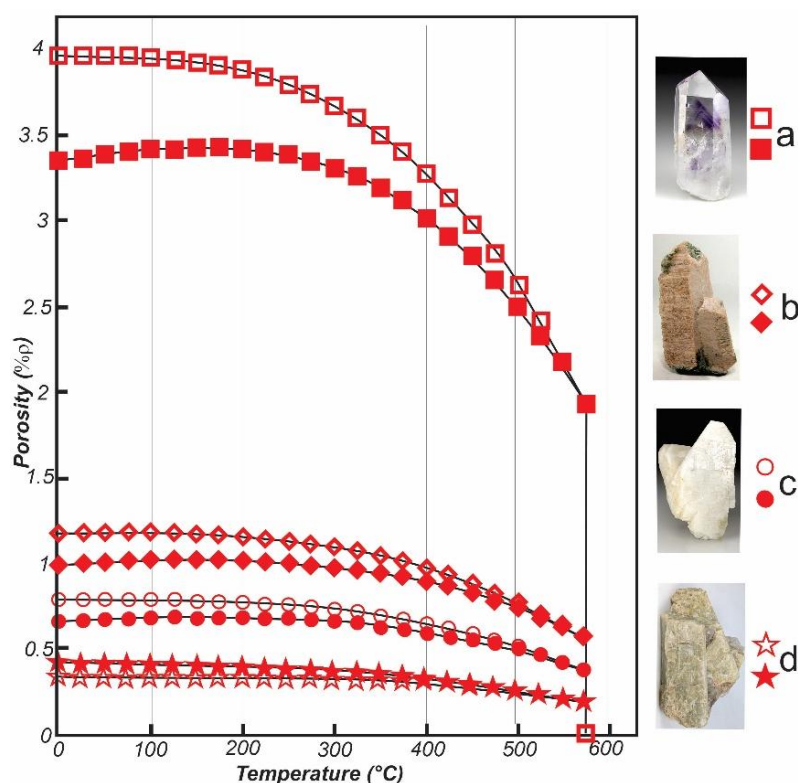


Figure 3.

Porosity in granitoids varies as a function of temperature due to differences in the thermal contraction behaviour of constituent minerals, including quartz (a), alkali feldspar (b), albite (c), and anorthite (d). Within this framework, maximum porosity is estimated to range from approximately 0.4% in quartz-poor granitoids to around 1.2% in typical felsic compositions, such as granites containing ~30% quartz and abundant feldspars (Rossello & Reynard 1997).

Experimental observations provide independent support for this latter mechanism. Thermally induced microfracturing in granite has been documented over a broad temperature range and is not restricted to the quartz $\beta \rightarrow \alpha$ transition. Experimental and X-ray CT studies demonstrate that microcracks may begin to develop at temperatures of approximately 300 °C and subsequently increase in abundance, length, and connectivity during further heating and cooling (Avanthi Isaka et al., 2019; Junique et al., 2021; Xu et al., 2023; Pan et al., 2024). Microfractures commonly occur along grain boundaries and at contacts between quartz and feldspars, providing a plausible microstructural mechanism for accommodating the differential thermal strain predicted by the model.

The modeled porosity increase should not be regarded as an instantaneous generation of an equivalent volume of open pores (Figure 3). Instead, it represents the magnitude of differential deformation that may potentially be converted into permanent void space through microfracturing. The actual proportion converted into open porosity will depend on the mechanical properties of the rock, the thermal path, confining pressure, cooling rate, fluid pressure, and the presence of pre-existing discontinuities.

The $\beta \rightarrow \alpha$ quartz transition nevertheless remains particularly relevant because it represents a major change in the structural and physical properties of quartz. Johnson et al. (2021) demonstrated that the transition can generate significant changes in elastic properties and differential stresses within polycrystalline rocks, potentially contributing to damage and facilitating fluid access. Consequently, the transition should be regarded as an important perturbation superimposed on a broader process of differential thermal deformation rather than as the sole origin of thermal microfracturing.

The development of effective reservoir properties requires an additional stage beyond the generation of thermal microfractures. Individual microcracks may remain isolated, become partially closed during subsequent burial, or be sealed by hydrothermal mineral precipitation. Alternatively, tectonic deformation, fluid overpressure, and natural hydraulic fracturing may enlarge and connect these discontinuities, transforming an initially distributed population of thermal microfractures into a hydraulically significant fracture network. The conceptual

progression from differential thermal contraction to microfracture development and subsequent fluid connectivity is summarized in Figure 4.

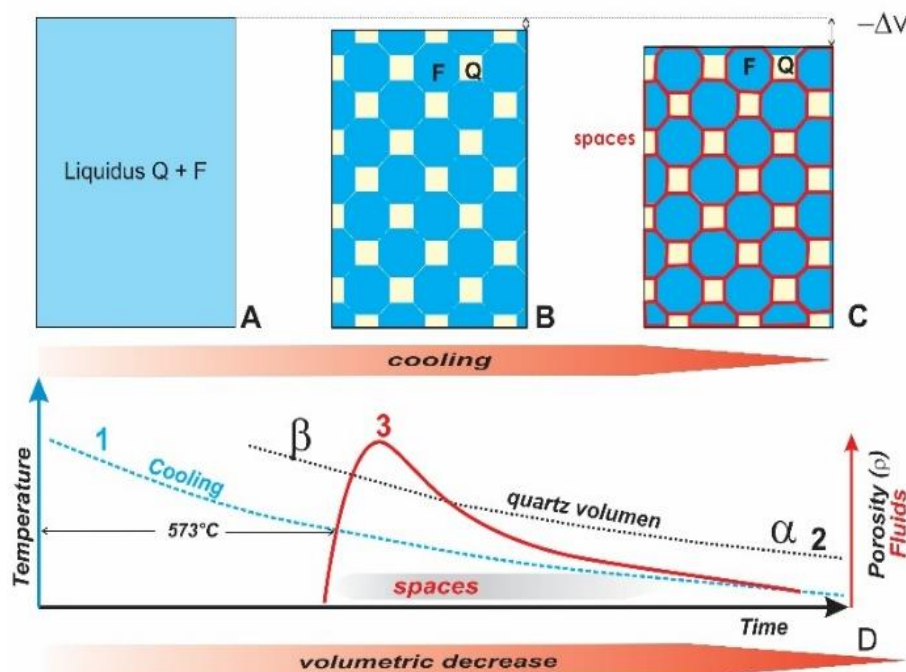


Figure 4.

Schematic of differential thermal contraction in an ideal granite as temperature decreases: A) Cooling of a rock composed mainly of quartz (Q) and feldspar (F). B) Quartz contracts differently than feldspar below 575 °C. C) Total rock volume decreases (ΔV), creating new porosity (red lines) available for fluids. D) Idealized sequence showing cooling over time (1), quartz α - β transition (2), and emplacement of mineralization (3).

The distinction between theoretical porosity and effective reservoir properties is therefore fundamental to the proposed model. Thermally generated microfractures may provide an initial population of discontinuities, while subsequent geological processes determine whether these discontinuities become interconnected and hydraulically active. X-ray CT observations indicate that thermal treatment can modify both microcrack abundance and pore connectivity in granite, supporting the possibility that thermal damage may contribute to the development of connected secondary porosity under favourable conditions (Avanthi Isaka et al., 2019).

Accordingly, the modeled porosity range of 0.4–1.2 % should be considered a first-order quantitative estimate of the potential thermal contribution to secondary porosity in quartz-bearing crystalline rocks. It does not imply that all crystalline basement rocks will develop equivalent reservoir properties. Rather, it establishes a physically and quantitatively testable contribution that can subsequently be enhanced or reduced by tectonic deformation, hydrothermal alteration, fluid circulation, burial, and fracture sealing. In this sense, the thermal mechanism provides a possible initial step in the progressive transformation of otherwise low-porosity crystalline rocks into fracture-controlled unconventional reservoirs.

3. Result and discussion

The results presented above support a potential relationship between the thermal evolution of quartz-bearing crystalline rocks and the development of secondary porosity in fractured basement reservoirs. The calculated values of approximately 0.4–1.2% represent a relatively small pore volume compared with conventional sedimentary reservoirs, but they may be significant in crystalline rocks, where primary matrix porosity is generally negligible. The principal significance of this mechanism is therefore not the absolute magnitude of the calculated porosity alone, but the possibility that differential thermal deformation initiates a population of microfractures

that can subsequently be modified and connected by geological processes.

A critical aspect of the proposed mechanism is the distinction between continuous differential thermal contraction and the $\beta \rightarrow \alpha$ quartz transition. The transition at approximately 573–575 °C at atmospheric pressure involves a structural reorganization of quartz accompanied by marked changes in its thermal and elastic properties (Raman & Nedungadi 1940; Skinner 1966; Johnson et al., 2021). In a mechanically constrained quartz–feldspar aggregate, this change may generate additional differential strain and local stress concentrations. However, the available experimental evidence indicates that thermal microcracking is not restricted to the transition temperature. Microcracks may develop at temperatures substantially below the $\beta \rightarrow \alpha$ transition and progressively increase in abundance during subsequent thermal evolution (Fredrich & Wong 1986; Avanthi Isaka et al., 2019; Xu et al., 2023). Consequently, the $\beta \rightarrow \alpha$ transition should not be considered the sole cause of thermal fracturing, but rather an important perturbation within a broader process of differential thermal deformation.

This distinction is fundamental to the interpretation of the model. The calculated 0.4–1.2% does not represent an instantaneous volume of interconnected pores produced exclusively at the quartz transition. Instead, it represents the theoretical differential volume that can develop as quartz and the feldspar framework follow different thermal contraction paths. The actual conversion of this differential volume into permanent pore space requires mechanical accommodation by deformation, particularly microfracturing. The model therefore establishes a potential source of secondary pore space, whereas the experimental studies provide evidence for a physical mechanism capable of accommodating the associated thermal strain.

Experimental investigations of granite provide particularly relevant evidence. Fredrich & Wong (1986) demonstrated the importance of thermally induced cracking from a micromechanical perspective, while subsequent studies have documented the development and evolution of thermal microfractures using laboratory experiments and X-ray computed tomography. Avanthi Isaka et al. (2019) showed that thermal treatment can generate microcracks in granite and modify both porosity and pore connectivity. Junique et al. (2021) demonstrated that repeated heating and quenching cycles can progressively modify the physical properties of granitic rocks. Xu et al. (2023) further showed that thermally induced microcracks may develop from approximately 300 °C and increase through propagation and coalescence at higher temperatures. Pan et al. (2024) similarly documented the development of intergranular and intragranular cracking and its influence on the mechanical behaviour of granite. Together, these studies provide independent support for the physical plausibility of converting differential thermal strain into secondary microfracture porosity.

The spatial distribution of these microfractures is also relevant. Thermal stresses are expected to concentrate preferentially at interfaces between minerals with different thermal expansion coefficients. In granitoids, quartz–feldspar contacts therefore represent favourable sites for stress concentration and microcrack nucleation. The resulting fractures may initially be discontinuous and isolated, but repeated thermal cycles and subsequent deformation can promote their propagation and coalescence. The conceptual relationship between differential contraction, microfracturing, and the generation of secondary pore space is illustrated in Figure 5.

The potential reservoir significance of this mechanism depends principally on what happens after the initial generation of microfractures. Effective hydrocarbon reservoirs require not only storage space but also sufficient permeability to allow fluid migration and production. A population of isolated thermal microcracks may therefore have little reservoir significance unless it becomes interconnected. Subsequent tectonic deformation, faulting, fluid overpressure, and natural hydraulic fracturing can enlarge and connect pre-existing discontinuities, whereas compaction, ductile deformation, and hydrothermal mineral precipitation may reduce fracture apertures or completely seal them. The transformation from thermally generated microfractures into an effective fracture-controlled reservoir should consequently be regarded as a multistage geological process, as summarized in Figure 5.

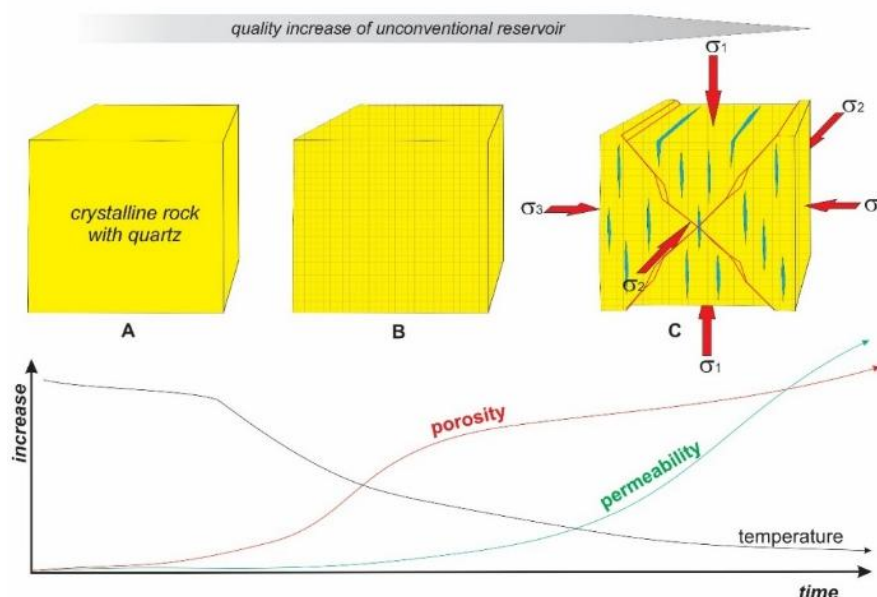


Figure 5.

Schematic evolution of the porosity and permeability increase in the unconventional reservoirs of a granitic crystalline basement (A) due to the α to β quartz change (B) and the action of natural hydraulic fracturing (C).

This multistage interpretation also provides a possible explanation for the heterogeneous nature of fractured basement reservoirs. Productive intervals may occur where several processes overlap: a quartz-bearing crystalline protolith provides the initial mineralogical susceptibility; cooling generates differential thermal strain and microfracturing; later tectonic deformation reactivates or enlarges the fractures; and fluid circulation modifies their geometry, aperture, and connectivity. Conversely, crystalline rocks lacking sufficient quartz, structural deformation, or preserved fracture connectivity may remain effectively impermeable despite having undergone the same general cooling process.

The role of confining pressure represents an important limitation. The temperature of the quartz $\beta \rightarrow \alpha$ transition and the magnitude of thermal expansion are pressure dependent, while increasing confining pressure can suppress fracture opening and promote mechanical closure. Natural plutonic rocks also undergo continuously changing pressure, temperature, stress, and fluid-pressure conditions during exhumation and burial. The theoretical porosity values derived from the model should therefore not be extrapolated directly to reservoir depths without considering the pressure–temperature history of the specific basement system.

Another limitation concerns the mechanical behaviour of the mineral aggregate. The model assumes a simplified quartz–feldspar system and does not explicitly incorporate grain size, crystallographic orientation, anisotropic thermal expansion, pre-existing fractures, or the mechanical behaviour of accessory minerals. In natural granitoids, some of the differential strain may be accommodated by elastic deformation, grain-boundary adjustment, crystal-plastic deformation, or reactivation of inherited discontinuities. The calculated values should therefore be interpreted as a first-order estimate of the potential thermal contribution to secondary porosity rather than as a direct prediction of effective porosity.

The temporal relationship between thermal cracking and hydrocarbon charge is also important. Thermally generated microfractures develop during the cooling and geological evolution of the crystalline basement, potentially long before hydrocarbon generation and migration. Their later preservation and reactivation therefore determine whether they can contribute to a petroleum system. If the fractures remain open or are subsequently reopened, they may provide pathways for hydrocarbon migration and storage. If they become extensively sealed by hydrothermal minerals or closed during burial, their contribution to reservoir quality may be negligible. Thus, the thermal mechanism proposed here is best regarded as an early-stage process capable of preconditioning the crystalline basement for later development of reservoir properties.

The geological evidence from productive basement reservoirs is consistent with this multistage interpretation. Hydrocarbon-bearing crystalline reservoirs are commonly associated with intensely fractured granites and other crystalline lithologies, and their productivity is strongly controlled by fracture density, orientation, connectivity, and structural position (P'an 1982; Schutter 2003a,b; Cuong & Warren 2009; Le Garzic et al., 2011; Neff 2014). The thermal mechanism proposed here does not replace these established controls. Rather, it provides a possible physical explanation for how an initially low-porosity crystalline rock may acquire an early population of secondary discontinuities that can subsequently be exploited or modified by tectonic and hydrothermal processes.

The exploration implications are therefore indirect but potentially important. Conventional seismic methods generally cannot resolve individual microfractures, and the prediction of fractured basement productivity remains inherently uncertain. However, the proposed mechanism suggests that quartz abundance, thermal history, evidence of thermal or hydrothermal alteration, and the presence of later tectonic deformation may be integrated as indicators of basement reservoir potential. High-resolution seismic attributes, borehole image logs, core fracture analysis, pressure data, well-test behaviour, and mineralogical characterization may then be used to identify zones where thermally generated microfractures have potentially evolved into connected fracture systems.

The present study extends the framework proposed by Rossello & Gallardo (2026) in three principal respects. First, their thermally induced volumetric model is evaluated specifically in the context of crystalline hydrocarbon reservoirs rather than primarily in relation to hydrothermal mineralization. Second, the theoretical porosity range is explicitly linked to quartz abundance and the differential thermal response of quartz and feldspars. Third, the model is evaluated against experimental evidence for thermally induced microfracturing and pore-connectivity changes in granite (Fredrich & Wong 1986; Avanthi Isaka et al., 2019; Junique et al., 2021; Xu et al., 2023; Pan et al., 2024). This integration provides a more complete interpretation in which thermal contraction generates a potential source of secondary pore space, while subsequent geological processes determine whether that pore space becomes hydraulically effective.

Overall, the evidence supports the interpretation that differential thermal contraction is a physically plausible contributor to secondary porosity in quartz-bearing crystalline rocks. The $\beta \rightarrow \alpha$ quartz transition is potentially important because of the abrupt change in the structural, volumetric, and elastic behaviour of quartz, but it should be considered within the broader thermal evolution of the rock rather than as an isolated fracturing event. The modeled 0.4–1.2% porosity range demonstrates that the magnitude of the potential thermal contribution is not negligible for rocks with essentially zero primary matrix porosity. Whether this contribution ultimately becomes economically relevant, however, depends on the subsequent development and preservation of an interconnected fracture network.

4. Conclusion

This study evaluates the potential contribution of differential thermal contraction to secondary porosity generation in quartz-bearing crystalline rocks and its implications for fractured basement hydrocarbon reservoirs. The analysis extends the thermomechanical framework proposed by Rossello & Gallardo (2026) by integrating the model with experimental evidence for thermal microfracturing and pore-connectivity development in granitic rocks.

The model predicts theoretical thermally induced porosity values of approximately 0.4–1.2 %, depending principally on quartz abundance and the contrasting thermal behaviour of quartz and feldspars. Although these values are modest compared with conventional sedimentary reservoirs, they may be significant in crystalline rocks where primary matrix porosity is negligible. The calculated values should nevertheless be regarded as potential secondary pore space rather than as directly measured effective reservoir porosity.

The $\beta \rightarrow \alpha$ quartz transition at approximately 573–575 °C at atmospheric pressure represents an important perturbation in the thermal and elastic behaviour of quartz and may contribute to differential strain and damage within a mechanically constrained crystalline aggregate. However, experimental studies demonstrate that thermal microcracking begins over a broader temperature range, commonly before the quartz transition, and may

subsequently propagate and coalesce during continued thermal evolution and cooling. The transition should therefore be regarded as one important stage within a broader process of differential thermal deformation rather than as the sole cause of thermal fracturing.

The development of an effective reservoir requires subsequent mechanical and geological processes. Thermally generated microfractures may remain isolated or become sealed, but tectonic deformation, fluid overpressure, natural hydraulic fracturing, and hydrothermal circulation may enlarge and connect them, producing fracture networks capable of storing and transmitting hydrocarbons. Conversely, compaction and mineral precipitation may substantially reduce their reservoir significance.

The principal contribution of this study is therefore to establish a testable link between mineral-scale thermal behaviour, secondary microfracture generation, and the initial development of reservoir properties in crystalline basement rocks. The proposed mechanism does not imply that all quartz-bearing crystalline rocks are prospective; rather, it identifies thermal history and quartz–feldspar differential contraction as potentially important components of a multistage process controlling secondary porosity.

Accordingly, quartz-bearing crystalline basement should not be considered inherently impermeable or non-prospective. Where favorable thermal, structural, and hydrothermal histories have generated and preserved interconnected fracture networks, these rocks may constitute viable unconventional hydrocarbon reservoirs. Further validation should combine laboratory experiments, high-resolution microstructural characterization, borehole observations, and reservoir-scale petrophysical and geomechanical data to determine the proportion of thermally generated pore space that can ultimately contribute to effective storage and permeability.

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6. Declarations

6.1 Author contributions

All authors contributed equally as the main contributor of this paper. All authors read and approved the final paper.

6.2 Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

6.3 Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

6.4 The use of AI or AI-assisted technologies

The authors also acknowledge the use of OpenAI's ChatGPT as a language and editorial assistance tool during the preparation of this manuscript. The system contributed to improving the consistency of the text but all scientific concepts and responsibility for the content remain exclusively those of the authors.

7. Glossary of terms and symbols

Terms & symbols	Definition	Unit
mD	Porosity	miliDarcy
3D	Tri dimensional	m ³
ΔV	Volumen variation	%
MP	MegaPascal	N/mm ²
V _{granit}	Volume of the granite	m ³
V _{α-quartz}	Volume of α -quartz	m ³
V _{β-quartz}	Volume of β -quartz	m ³
V _{feldspar}	Volume of feldspar	m ³
ZV _{feldspar}	Feldspar expansion coefficient	m ³ /K
X _{quartz}	Quartz percentage in the rock	%
X _{initial}	Initial percentage in the rock	%

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