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Hydrothermal alteration and physical and mechanical properties of rocks in a volcanic environment: A review

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Title Page

[Title] Hydrothermal alteration and physical and mechanical properties of rocks in a volcanic environment: a review

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[Abstract]

Volcanic rocks are the prominent host rocks in geothermal and volcanic systems in general, displaying heterogeneity. Although various external factors such as temperature, pressure, time, fluid chemistry, and subsurface geology have been thoroughly researched regarding the source of hydrothermal minerals in geothermal fields, the effect of hydrothermal alteration on volcanic hosts is still controversial in the literature. This review compiles data on the physical and mechanical properties of the host rocks composing volcanic environments exhibiting hydrothermal alteration or remaining unaltered. The considered data is originated from hydrothermal areas from Kuril-Kamchatka (Russia), Los Humeros (Mexico), Ngatamaraki, Rotokawa, Kawerau and Ohakuri geothermal fields and Mt. Ruapehu, Mt. Taranaki, and Whakaari volcanoes (New Zealand), Solfatara (Italy), Reykjanes, Nesjavellir, and Theistarereykir geothermal fields (Iceland), La Soufrière de Guadeloupe (Caribbean) volcano, and Merapi volcano (Indonesia).

Analysis of average values displayed in several graphical representations and correlations finds that dense rocks (such as lavas and intrusive rocks) exhibit greater competence and lower porosity than fragmental rocks. However, altered dense rocks display greater variability in mechanical properties compared to pyroclastic rocks, primarily influenced by mineral dissolution leading to rock weakening. Exceptions occur for high-temperature hydrothermal alteration, such as advanced silicification and propylitic alteration, with the latter influenced by minor types of alteration. Fragmental rocks have diverse behaviour with the extent of hydrothermal alteration and welding/compaction. According to the compiled data, an overall strengthening of pyroclastic rocks develops as hydrothermal alteration increases, regardless of the type of hydrothermal alteration.

The complexity of hydrothermal systems, the variability shown by different hydrothermal settings and histories in terms of temperature, fluid chemistry and secondary mineral assemblage, and the variety of rock materials with different microstructures contribute to moderate correlations between properties compared to those established in an unaltered state. However, the same trends (linear, nonlinear, positive, negative) are preserved along hydrothermal alteration. This review emphasizes the significance of the type and degree of hydrothermal alteration, along with the rock type and pre-existence of fractures, in shaping the development of alteration in volcanic environments and modifying the properties of host rocks. The relevance of the review relies on the fact that these properties are considered to enhance the productivity of geothermal fields and improve the assessment of volcanic hazards. Future research is expected to expand on this groundwork.

[Keywords]

Hydrothermal alteration; physical properties; mechanical properties; degree of hydrothermal alteration; hydrothermal alteration facies; intrusion-related geothermal systems

[Declarations]

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List of variables, acronyms, and abbreviations

- ρ – bulk density (g/cm^3)
- n – porosity (%)
- k - permeability (m^2)
- Vp – P-wave velocity (km/s)
- Vs – S-wave velocity (km/s)
- UCS – unconfined/ uniaxial compressive strength (MPa)
- ITS – indirect tensile strength (MPa)
- E_d – dynamic Young's modulus (GPa)
- ν_d – dynamic Poisson's coefficient
- E_s – static Young's modulus (GPa)
- ν_s – static Poisson's coefficient
- c – cohesion (MPa)
- ϕ - angle of internal friction (˚)
- H – hardness according to Mohs scale
- min – minimum
- max – maximum
- avg – average
- arg – argillic facies
- trans – transitional facies
- prop – propylitic facies
- AA – advanced argillic facies
- K – potassic facies
- Phy – phyllic facies
- Adv. Sil – advanced silicic alteration
- Al – alunitic alteration
- Sil – silicic alteration
- Oxi – oxidation
- Alb – albitic alteration
- Pyroclastics – pyroclastic rocks

Glossary of the considered lithologies

- Breccia: in this review, this lithotype stands for a pyroclastic breccia that mainly contains angular blocks.
- Debris flow: also known as *lahar*, which is specific to volcanic environments. Debris flow corresponds to a gravity flow and is a mixture of sediment and water.
- Hyaloclastite: a consolidated pyroclastic rock with angular fragments of volcanic glass.
- Hydrothermal vein: a deposit of hydrothermally formed minerals occupying an open fracture.
- Ignimbrite: a rock formed by widespread deposition and consolidation of pyroclastic density currents (pyroclastic flows). Also known as welded tuff or ash flow tuff.
- Intrusive rock: igneous rock that results from the solidification of magma that has penetrated a pre-existing rock.
- Lava: general term used to refer to any rock that results from the solidification of a lava flow. Its further classification is based on the silica and alkalis content.
- Lava breccia: rock that is in the transition between a volcanic clastic rock and lava.
- Marble: a metamorphosed limestone produced by recrystallization.
- Pyroclastic rocks: volcanic rocks composed of fragmented particles and produced by an explosive volcanic eruption. This review uses this collective term when the texture and composition are not specified.
- Sandstone and siltstone: sedimentary rocks composed of lithified sand and silt, respectively.
- Silicified lavas: lavas with extensive silicification.
- Skarn: a contact metamorphic rock that results from limestone or dolomite in contact with an igneous intrusion.
- Tuff: a general term for any consolidated or welded pyroclastic rock. An ash tuff contains ash-size pyroclasts, while a lapilli tuff contains lapilli-size pyroclasts. A general term in this review that includes both ash-tuffs and lapilli tuffs.
- Tuffite: a tuff with both detrital and pyroclastic materials, with the latter being predominant.
- Unconsolidated ash/ lapilli: pyroclasts of any shape, with a size of less than 2 mm or between 2 mm and 64 mm, respectively, generated by a volcanic eruption.

1. Introduction

The generation of hydrothermal alteration in volcanic rocks and the timescale involved are of critical importance. This is due to the influence of such processes on the mechanical and physical properties of host rocks, regulating essential mechanisms like fluid circulation, ore deposit formation, fracture propagation, and the geotechnical performance of rock masses, such as slope stability.

Porosity controls the capacity of the reservoir while permeability limits fluid flow and transfer from the depth to the surface. Hydrothermal fluids percolating through rocks interact under specific conditions such as temperature, pressure, fluid composition, and redox conditions (Frolova et al., 2010). Although most of the hosted fractures sustain the reservoir permeability, percolating fluids might promote mineral precipitation, ultimately decreasing the porosity and permeability. Over time, the fluid pressure within the pores will increase, enhancing the formation of fractures, thus restarting the cycle (Siratovich et al., 2016; Kennedy et al., 2020). Furthermore, the dissolution of hydrothermal phases may lead to the rejuvenation of permeable networks due to their sensitivity to pressure, temperature, and fluid chemistry, as demonstrated by Heap et al. (2017) and Farquharson et al. (2019. Fluid flow is affected by fault-fracture networks, which consequently influence the distribution of minerals, fluid, and heat within the upper crust (Callahan et al., 2019; Kennedy et al., 2020). Briefly, alterations to the porosity and/or permeability have an impact on the structure of the hydrothermal system and its hydrodynamic and temperature regimes over varying timescales, enhancing the construction and destruction of fluid flow barriers. Subsequently, hydrothermal alteration has the capacity to lead to erratic and explosive volcanic behaviour (Heap et al., 2019a), as it constrains the build-up and distribution of pore fluid pressure, and the outgassing and character of volcanic eruptions (e.g., Cassidy et al., 2018; Mordensky et al., 2019; Kennedy et al., 2010; Kennedy et al., 2020). Strength, and elastic properties/stiffness of rocks from hydrothermal systems define the in-situ state of the stress field (Frolova et al., 2014). Deformation or alteration-induced changes in the stress field can promote fracturing or fracture sealing, restricting the distribution and extent of the pressurised source.

Hydrothermal alteration of the subsurface geology has primarily been studied in geothermal fields for their characterisation (e.g., Browne, 1970; Browne, 1978; Marini, 2000; Lagat, 2009). Recent studies highlight the variation of rock properties when hydrothermally altered (e.g., Robb, 2005; Yildiz et al., 2009), as few unaltered rocks are present in a geothermal reservoir (Wyering et al., 2015). The objective of these studies is to elucidate the underlying poro-chemo-mechanical processes involved in rock-fluid interaction. This knowledge is essential for numerical modelling of geothermal reservoirs, interpretation of geophysical logs, optimization of drilling, and evaluation of heat transport within the reservoir (Gasshemi, 2012; Ochieng, 2013; Wyering, 2014; Frolova, 2014; Koros et al., 2015; Cant et al., 2018; Villeneuve et al., 2019; Bär et al., 2020; Heap et al., 2022a) and, ultimately, to enhance the exploitability of these fields. Moreover, the geotechnical implications of hydrothermal alteration on rocks can be evaluated in regard to slope instability related to altered rock masses (Reid et al., 2001; Coggan et al., 2013; Koros et al., 2015; Villeneuve et al., 2019; Heap et al., 2021; Villeneuve & Heap, 2021; Darmawan et al., 2022; Kanakiya et al., 2022; Heap et al., 2022b; Mordensky et al., 2022) or altered terrains interested in construction works (Rigopoulos et al., 2010; Frolova et al., 2014). Intact rock data, encompassing mechanical, physical, and dynamic properties, may serve as a valuable tool for evaluating seismic and volcanic hazards (Heap et al., 2019a; Kennedy et al., 2020).

Whilst there is a basic understanding of the principal hydrothermal alteration factors (temperature, pressure, fluid chemistry, permeability, subsurface geology, and time), their influence on the host rock properties remains elusive, as evidenced by contradictory findings in the literature, as higher degree of hydrothermal alteration does not necessarily imply the weakening of the host rocks, nor the reduction of permeability and porosity (e.g. Wyering et al., 2014; Frolova et al., 2014; Marmoni et al. 2017; Heap et al., 2020; Heap & Violay, 2021; Scott et al., 2023). This issue has prompted increasing laboratory investigations in the past few years, which demonstrate that the relation between the type of alteration and rock properties is quite variable, as it depends on several factors, such as the host rocks, P-T conditions, chemical composition of the fluid, and duration of fluid-rock interaction (Frolova et al., 2010; 2011; Frolova et al., 2014). Hydrothermal alteration can impact the mechanical and petrophysical properties of rocks by changing mineralogy, texture, and fabric, which in turn affects the rock's strength, stiffness, deformation, and overall stability. It is important to note that these changes are contingent on the properties of the rock, and that hydrothermal alteration both influences and constrains those same properties.

This review aims at generating a comprehensive data set on the mineralogical, physical, and mechanical properties of volcanic rocks that make up the substrates of worldwide volcanic systems. The available reviews on the properties of volcanic rocks (Heap & Violay, 2021; Lavallée & Kendrick, 2021) primarily focus on an unaltered condition, briefly covering the hydrothermal alteration. Furthermore, global and regional databases providing detailed petrophysical data have recently been developed (Bär et al., 2016; Bär et al., 2020; Scott et al., 2022; Scott et al., 2023), considering both fresh and altered rocks, but mainly focused on physical properties and less on mechanical properties of the rocks. This review aims to fill the knowledge gap about the influence of hydrothermal alteration, which is ubiquitous in most volcanoes. The available literature data has been analysed to demonstrate the impact of hydrothermal alteration on degree and alteration facies. Firstly, an overview of the factors influencing hydrothermal alteration is provided. Secondly, this review examines the physical and mechanical properties of both unaltered and altered rocks, projecting them graphically to identify significant patterns. The present review demonstrates that while hydrothermal alteration is a complex process, it affects the mechanical and physical properties of rocks according to these common aspects:

1) Dense rocks, including intrusive rocks and effusive lavas, have lower porosity, greater density, stiffness, and strength than fragmental and porous rocks. Nonetheless, the occurrence of hydrothermal alteration generally leads to greater modifications in the physical and mechanical properties of dense rocks.

2) Porous and fragmental rocks are more susceptible to alteration. However, the impact of hydrothermal alteration greatly varies because of the heterogeneity of these rocks and the external conditions they face, such as temperature and pressure.

3) The texture and microstructure, encompassing pore space and fractures, and compaction of the rocks, determine the extent and progression of hydrothermal alteration. As a result, these features contribute to the observed variability in the literature.

2. Data compilation from the literature

2.1 Selection criteria and parameters definition

Several papers were located using the keywords "volcanic rocks", "mechanical properties", "physical properties", "rock mechanics", and "rock deformation" in the online databases Google Scholar, Elicit, Web of Science, and Research Gate. The keyword "hydrothermal alteration" was subsequently considered to narrow the search and exclude research that did not include altered volcanic rocks. Reading was used to identify relevant research publications, and 32 studies encompassing the last 15 years, all written in English, developed in the locations represented in Fig. 1 were considered. The compiled data is presented in Table S1 (Supplementary Data) and accompanied by descriptive statistical parameters (minimum, maximum, average). The average values were further analysed using pivot tables in Microsoft Excel® and were used to produce graphical representations (pivot graphs) to facilitate the identification of underlying patterns. The data in Table S1 is grouped based on the location, host rocks, secondary mineralisation, hydrothermal alteration facies, fluid pH, and degree of alteration, depending on the availability of these details in the literature. Volcanic rocks are lavas with different compositions and pyroclastic rocks including tuffs, tuffites, and ignimbrites. Although this review focuses on volcanic rocks, it also encompasses other lithologies, including intrusive rocks, debris flows, marbles, skarns, and sedimentary rocks. It should be noted that the data collected may be heterogeneous and at times incomplete, as descriptions of pyroclastic rocks and lavas may lack precise details, for example, their nature (e.g. basalts, andesites). At the same time, other authors may present lithotypes individually or as groups (e.g., tuffs and tuffites). Secondary minerals, when reported, are usually linked to hydrothermal alteration facies and are typically presented as assemblages (e.g., "alunitic + silicic"). An effort has been made to preserve data fidelity to the original literature sources. Furthermore, values for unaltered rocks have been considered. While many studies focus on the mechanical properties of fresh rocks, this review includes explicitly data from papers that assess hydrothermal alteration to facilitate comparisons between altered and unaltered states. The degree of hydrothermal alteration is classified following the considered literature in Table S1 and ISRM (1981), spanning from unaltered to fully altered.

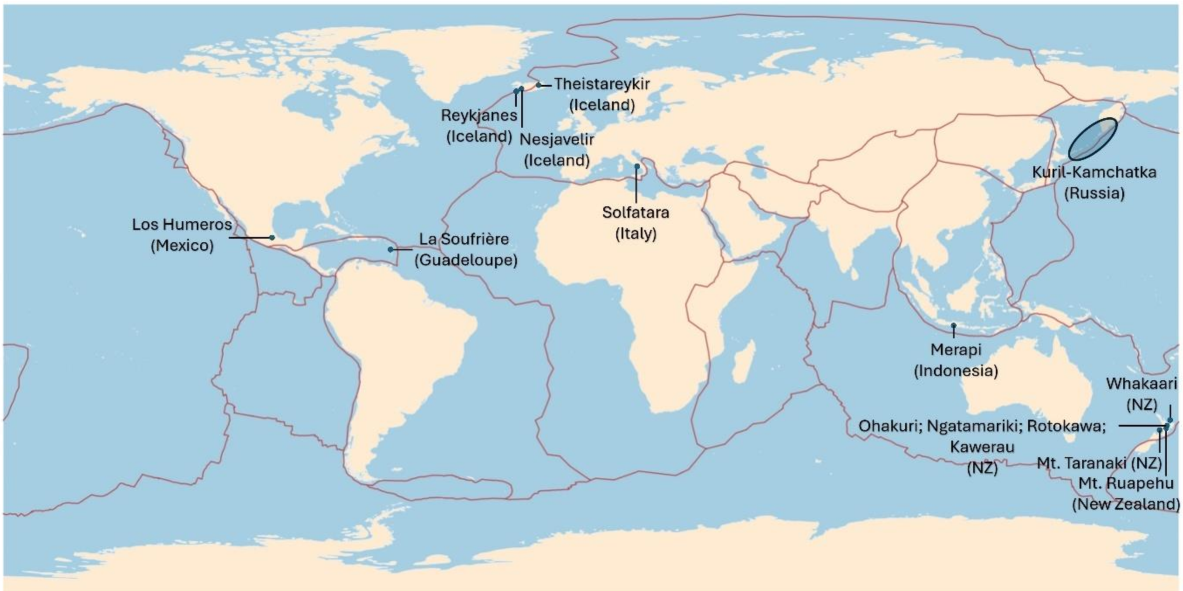

Fig. 1 Map with the geothermal regions (Kuril-Kamchatka; Los Humeros; Ngatamariki, Rotokawa, Kawerau, Ohakuri; Solfatara) and hydrothermal systems associated with volcanic environments (La Soufrière, Merapi, Mt. Ruapehu, Mt. Taranaki, and Whakaari volcanoes) considered on this study, in respect to the lithospheric plate boundaries (red; from Esri GIS Education, last updated in 2023).

The physical properties include bulk density (*ρ*; g/cm^3), open porosity (*n*; %), and permeability (*k*; m^2)[1]. The porosity in volcanic materials varies widely from a fraction of percent to 97 %, and their density spans from below 1 to 3.3 g/cm^3 (Mueller et al., 2011; Lamur et al., 2017; Lavallée & Kendrick, 2021). The pore space of volcanic rock (microfractures and vesicles) significantly influences the mechanical properties and failure mode of these rocks (Heap & Violay, 2021). It also affects pore pressure, which contributes to determining the explosive nature of an eruption (Mueller et al., 2011; Lamur et al., 2017; Cant et al., 2018). Bulk density and porosity (often connected porosity) can be determined according to established rock mechanics standards and recommendations (EN 1936:2006; ISRM, 2007; ASTM D2216–19, 2019). Moreover, X-ray computed tomographic imaging has more recently enabled the assessment of the porous network and the calculation of its properties (e.g., Baker et al., 2012; Pola et al., 2012; Pappalardo et al., 2018; Lield et al., 2019; Buono & Pappalardo, 2021; Jyoti & Haese, 2021; Liu et al., 2023). Permeability constrains the fluid flow of hydrothermal (and magmatic) systems (Heap et al., 2017; Farquharson et al., 2019; Kennedy et al., 2020) and the efficiency of degassing (Edmonds & Herd, 2007; Kennedy et al., 2010), dictating the explosivity of an eruption and volcanic hazard. The effect of structure and anisotropy on permeability varies with scale, spanning from intact rock to rock mass (Heap & Kennedy, 2016). The rock mass comprises the rock and its discontinuities, with permeability being primarily associated with faults and fractures, while the permeability of the rock itself (i.e., intact rock) reflects the connectivity and complexity of the porous network. Vesicles, which record magma degassing, along with microfractures and macrofractures, influence the connectivity of pore spaces and, consequently, permeability. Fracturing enhances permeability (e.g., Lamur et al., 2017) and promotes a localised fluid flow in hydrothermal environments.

Dynamic properties are expressed through ultrasonic velocities (or seismic velocities): P-wave (compressional; *Vp*; km/s) and S-wave (shear; *Vs*; km/s). In the laboratory, seismic waves are measured non-destructively using transducers, with velocity calculations based on the specimen's length and the arrival time of the seismic waves. These seismic waves are influenced by factors such as rock's crystallinity, mineralogy, porosity and degree of saturation, and have scale-dependent behaviour (e.g., González de Vallejo & Ferrer, 2011; Lesage et al., 2018). Denser and more compact rocks demonstrate increased values of seismic wave velocities, which are commonly used to predict the physical-mechanical behaviour of a rock. The dynamic Young's modulus ($E_{d;}$ GPa) and the dynamic Poisson's ratio (v_d) are derived from *Vp* and *Vs*, providing insight into the deformation characteristics of a rock.

Mechanical properties of rocks can be assessed by a variety of tests and using distinct apparatus. Further details can be found in Heap & Violay (2021) or in the applicable ISRM and ASTM standards (ISRM, 2007; ASTM D3967–08, 2008; ASTM D7012–14e1, 2014). Both uniaxial (unconfined) and triaxial (confined) laboratory tests are used to determine compressive strength.

[1] In this review, bulk density is expressed in g/cm^3, and ultrasonic velocities are given in km/s for better readability and to be in line with some authors (e.g., Lavallée & Kendrick, 2021).

The uniaxial test measures the compressive strength under unconfined conditions (UCS; MPa), which depends on the rock texture (degree of crystallinity and presence of phenocrysts/microlites), mineralogy, porosity (pore size and shape; presence of cracks), fabric of the rock (Heap et al., 2014; Siratovich et al., 2014; Bubeck, 2017; Coats et al., 2018; Zorn et al., 2018; Lavallée et al., 2019; Pereira et al, 2021; Heap & Violay, 2021). Due to the heterogeneity of volcanic rocks, compressive strength varies widely. External factors, such as the specimen volume and shape (L/D ratio), loading direction and rate with respect to anisotropies, temperature, water saturation, and strain rate (typically 10-5 s^{-1}; Paterson & Wong, 2005) should also be considered (González de Vallejo and Ferrer, 2011). Stress-strain curves typically start with the closure of pre-existing cracks and the elastic deformation of minerals, followed by an elastic phase in which the relationship between stress and strain is quasi-linear with recoverable strain (offloading) (e.g., Rocha 1981; González de Vallejo & Ferrer, 2011; Heap & Violay, 2021). Dense and compact rocks exhibit elastic behaviour over a wide range of stresses, whereas softer and porous rocks tend to display strain hardening (e.g., Rocha, 1981; González de Vallejo & Ferrer, 2011; Lavallée & Kendrick, 2021). The latter involves yielding at specific stress levels and the accumulation of damage, as materials deform more rapidly with increasing stress (e.g., Rocha, 1981; Lavallée & Kendrick, 2021). Tensile strength is important in volcanic environments hosting hydrothermal systems, as rocks are often subjected to tensile stresses due to pore pressure build-up or external forces (e.g., tectonics, intrusions). In this review, only the indirect tensile strength (ITS; MPa) determined by the Brazilian method (e.g., Lamur et al., 2017; Harnett et al., 2019; Hornby et al., 2019) is considered.

The Young's modulus (or elastic modulus), which defines the stiffness of a rock, i.e., the stress-strain relationship (e.g., González de Vallejo & Ferrer, 2011; Heap et al., 2019b), varies considerably in volcanic rocks. In particular, pyroclastic rocks have a lower stiffness due to their high porosity. Poisson's coefficient describes the elastic behaviour of a material by characterising the relationship between lateral and axial strain (e.g., González de Vallejo & Ferrer, 2011). Both the static Young's modulus and Poisson's coefficient are typically lower than their dynamic counterparts, with E_d typically being 1.5 to 3 times E_s.

Compressive strength under confined conditions is determined by the triaxial test, which also establishes the failure mode of a rock. A rock behaves in a brittle manner when it dilates and fails along localised fractures, whereas ductile rocks undergo compaction and pervasive deformation (Wong & Baud, 2012; Heap & Violay, 2021; Lavallée & Kendrick, 2021). The transition from brittle to ductile behaviour, known as the brittle-ductile transition (BDT), depends on the porosity of the rock. Highly porous rocks tend to display ductile behaviour under conditions of low strength, temperature, and strain rate (Lavallée & Kendrick, 2021; Heap & Violay, 2021). In this review, data from triaxial tests are presented qualitatively and concisely in Table S1, as the failure mode imposes constraints on the evolution of physical properties during deformation (Siratovich et al., 2016). For a more comprehensive understanding of both brittle and ductile deformation experiments, it is recommended to consult the review by Heap & Violay (2021). By utilising triaxial results as Mohr circles, the cohesion (c; MPa) and the angle of internal friction (φ; ˚) can be determined as part of the Mohr-Coulomb failure criterion. These variables delineate the failure criteria applicable to both rocks and soils, and in contrast to Young's modulus and UCS, their reporting for volcanic rocks is scarcer (Villeneuve & Heap, 2021 and references therein). Villeneuve & Heap (2021) present a thorough review for calculating both parameters concerning volcanic rocks and rock masses. The authors elucidate that both parameters decrease with increasing porosity and propose a method for scaling up these variables using the generalised Hoek-Brown failure criterion.

2.2 Review organisation

Section 2.3 includes some preliminary considerations based on the data compiled in Table S1. However, because no obvious conclusions can be reached immediately, further analysis was undertaken in Sections 3 and 4, which can be regarded as the review's results and discussion section. The results of this review are divided into two main parts: (a) physical and mechanical properties relating to unaltered rocks to elucidate the influence of lithology alone (Section 3), and (b) physical and mechanical properties of hydrothermally altered rocks (Section 4). A theoretical framework (Section 4.1) is presented to support the discussion of average values. This framework includes a description of the external factors that influence the formation of hydrothermal mineral assemblages and how hydrothermal facies fit into a conceptual model of a volcanic-related hydrothermal system. Section 4.2 discusses the effects of hydrothermal alteration. Given the intricate and multifaceted nature of the effect of hydrothermal alteration, the degree and type of alteration are delineated to ascertain their effect on the host rocks. Correlations between physical, dynamic and mechanical properties are established in Section 4.2.5 to evaluate their variations with hydrothermal alteration. Finally, Section 4.3 presents an overview and discussion to convey the key observations derived from this review. Within each section, the description of the graphs is divided into two distinct groups: dense rocks (characterised by high crystallinity lavas and intrusions) and fragmental rocks (defined by high porosity and low crystallinity deposits), following Stimac et al. (2015).

2.3 General considerations

The most critical parameters considered by most of the authors are:

- Bulk density varies from 0.62 to 3.05 g/cm^3. The maximum value occurs for a propylitic intrusive rock from the Reykjanes geothermal area (Gibert et al. 2020), while the lowest value occurs for unaltered pyroclastic rocks from La Soufrière volcano, Guadeloupe Island (Navelot et al., 2018).
- Porosity varies from 0.3 to 76% for a propylitic intrusive rock from the Reykjanes geothermal area (Gibert et al. 2020) and fresh to slightly altered vesicular lava from Whakaari volcano (Kanakiya et al., 2021), respectively. Porosity values are related to the structure of a rock.
- Permeability ranges from 1E-19 to 1E-11 m^2 from andesitic lava (unaltered to slightly/moderately argillic) to unaltered pyroclastic rock, both from La Soufrière volcano, Guadeloupe (Navelot et al., 2018).
- P-wave velocity varies between 0.50 and 6.23 km/s. The minimum value is obtained for a highly argillic andesitic lava, while the maximum value is obtained for fresh andesitic lava, both from the La Soufrière volcano (Guadeloupe; Navelot et al., 2018). Minimum S-wave velocity – 0.82 km/s – is obtained for an argillic rhyolitic ignimbrite collected in the Ngatamariki, Rotokawa, Kawerau geothermal systems (Wyering et al., 2014), while the maximum – 6.69 km/s – is obtained for a propylitic intrusive rock from the Reykjanes geothermal area (Gibert et al. 2020). Higher ultrasonic velocities occur for more compact

rocks, and the lowest was obtained for highly altered pyroclastic rocks. It appears to be independent of the geological setting.

- UCS ranges from 1 to 328 MPa, corresponding to an unaltered and an altered (propylitic facies) tuff/tuffite from Kuril-Kamchatka (Frolova et al., 2014), respectively.
- ITS ranges from 0.2 to 25 MPa for unaltered tuff/tuffite and unaltered lava from the Kuril-Kamchatka geothermal complex (Frolova et al., 2014).
- Young's modulus ranges from 2 to 74 GPa (E_d) and from 1 to 44 GPa (E_s). The dynamic modulus has the minimum for an argillic rhyolitic ignimbrite (Ngatamariki, Rotokawa, and Kawerau geothermal fields; Wyering et al., 2014) and the maximum for a tuff/tuffite with propylitic alteration (Kuril-Kamchatka; Frolova et al., 2014). The static Young's modulus values are lower than the dynamic homologue. The minimum is defined for rhyolitic pyroclastic rocks from Ohakuri (Heap et al., 2020) and the maximum for unaltered andesitic lava from Mt. Ruapehu (Schaefer et al., 2023).
- The dynamic Poisson's coefficient ranges from 0.12 to 0.38 for slightly altered by clay minerals intrusive rocks from the Ngatamariki geothermal field (Cant et al., 2018) and argillic rhyolitic ignimbrites (Ngatamariki, Rotokawa, Kawerau geothermal fields; Wyering et al., 2014), respectively. The static homologue, ranges from 0.09 to 0.34 in andesitic lavas/breccias from Rotokawa geothermal field (Siratovich et al., 2016).
- Unaltered tuffs and tuffites from the Kuril-Kamchatka geothermal complex are the least cohesive (0.5 MPa) (Frolova et al., 2020), while the unaltered andesite lava from Mt. Ruapehu (Schaefer et al., 2023) is the most cohesive (52 MPa) of the data set. The angle of internal friction is 35˚ to 57˚ for unaltered tuffs/tuffites from the Kuril-Kamchatka geothermal complex (Frolova et al., 2020) and unaltered andesite lava from Mt. Ruapehu (Schaefer et al., 2023), respectively.

The geological setting has a minor influence on the values of various parameters, with both maximum and minimum values observed in areas such as volcanoes (where geothermal resources are not being explored) and geothermal fields. The primary lithology plays an important role, together with the type and degree of alteration. Nevertheless, drawing conclusions about the impact of hydrothermal alteration remains challenging, as this requires more complex and detailed analyses.

3. Physical and mechanical properties of unaltered host rocks

The purpose of this section is to present the physical and mechanical properties of unaltered rocks, which are predominantly of volcanic[2] origin, using data listed in Table S1. It is widely acknowledged that these properties differ according to the original rock type (Wyering et al., 2014; Mielke et al., 2015; Mordensky et al., 2018; Dúran et al., 2019; Villeneuve et al., 2019). Before exploring the impact of hydrothermal alteration, it is essential to evaluate the singular influence of the rock type on the physical and mechanical properties.

3.1. Physical properties of unaltered host rocks

Porosity varies significantly across different types of rocks, as shown in Fig. 2a, and exerts primary influence on physical and mechanical behaviour, as previously stated (e.g., Mordensky et al., 2018; Villeneuve et al., 2019; Schaefer et al., 2023). Lower porosity results in higher bulk density (Fig. 2b) and lower permeability (Fig. 2c). Additionally, Fig. 2d illustrates that the P-wave velocity (*Vp*) is approximately twice the S-wave velocity (*Vs*). Dynamic properties typically show higher values in rocks with lower porosity and greater bulk density.

Among dense rocks, intrusive rocks are the least porous (4 %) and permeable (4E-17 m^2), with a significant density (2.65 g/cm^3) and high ultrasonic velocities (*Vp* = 4.77 km/s and *Vs* = 2.34 km/s). For lavas, the alkali content plays a role, with andesites being typically less porous (8 %) and denser (2.64 g/cm^3) than trachytes (11 % and 2.38 g/cm^3), likely due to mineralogical differences (pyroxene and plagioclase relative contents). Nonetheless, trachytes have greater ultrasonic velocities, potentially indicating the presence of heterogeneity in andesites and/or oriented microlites in trachytes that enhances ultrasonic velocities. Basalt lavas are denser (2.95 g/cm^3), more porous (10%), and have higher ultrasonic velocities (*Vp* = 4.31 km/s and *Vs* = 2.50 km/s) than andesites, richer in silica and with less ferromagnesian minerals. In this review, on average, basalts have higher porosity than andesites. Considering the minimum and maximum values, basalts have porosities from 3 % to 48 %, while andesites from 1% to 63 % (Table S1 – Supplementary Data). Nonetheless, it is noteworthy that more studies of andesites are considered in the compiled data. Conversely to the average data of the review, as provided by Heap & Violay (2021), basalts from Mt. Etna (Italy) exhibit an average porosity of 8 %, in contrast to andesites from Volcán de Colima, in Mexico, which display a porosity of 14 %. It is suggested that while ultrasonic pulse velocities and bulk density are directly influenced by the content of silica and ferromagnesian minerals, this is not the case for open porosity, which is mostly defined by the microstructure and tectonic and volcanic processes (vesiculation, fragmentation, and densification – Kennedy et al., 2010; Lamur et al., 2017; Colombier et al., 2017). Lava breccias, often found at the borders of lava flows, present significantly higher porosities (28%) than lavas (*s.l.*) (~ 4 %), as well as lower density (1.95 g/cm^3) and greater permeability (5E-13 m^2), resulting from their extensive fracturing. This fracturing also accounts for the observed reductions to 2.87 km/s in *Vp* and 1.22 km/s in *Vs* compared to lavas (*s.l.*). Lava breccias prove to be even more permeable than pyroclastic rocks, indicating a greater degree of interconnectivity among pores.

[2] For further volcanic rocks' description, the reviews of Lavallé and Kendrick (2021) and Heap and Violay (2021) are suggested for reading.

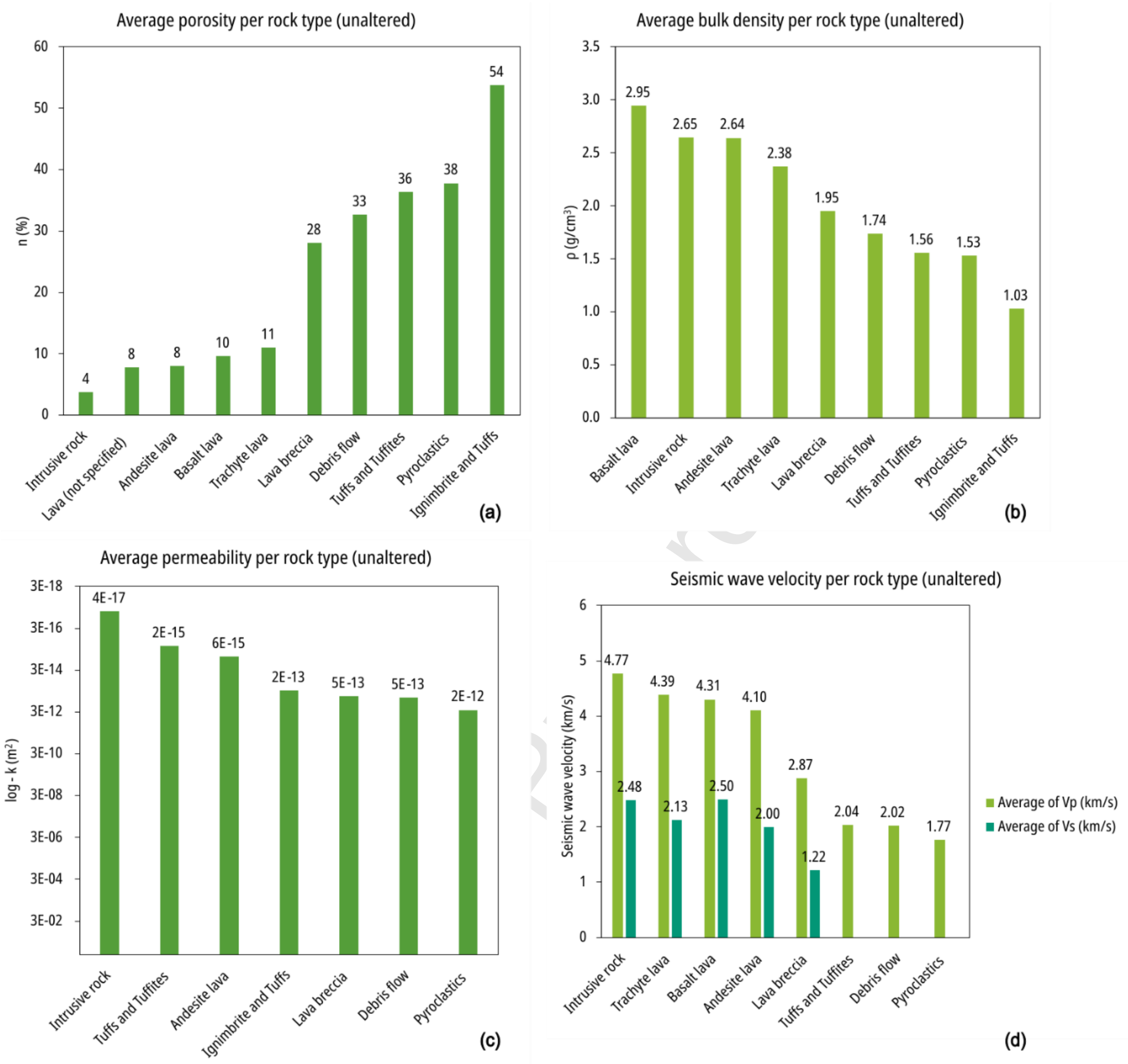

Fig. 2 Average values of physical and dynamic properties for several types of unaltered rocks (Pola et al., 2012; Pola et al., 2014; Frolova et al., 2014; Siratovich et al., 2014; Heap et al., 2015; Mayer et al., 2016; Navelot et al., 2018; Dúran et al., 2019; Farquharson et al., 2019; Heap et al., 2019a; Mordensky et al., 2018; Kennedy et al., 2020; Heap et al., 2020; Heap et al., 2021; Kanakiya et al., 2021; Frolova et al., 2020; Scott et al., 2022; Weydt et al., 2022; Darmawan et al., 2022; Kanakiya et al., 2022; Schaefer et al., 2023; Scott et al., 2023).

Fragmental rocks display greater porosity, reduced density, higher permeability, and lower P-wave velocities in comparison to lavas. Pyroclastic rocks, which cover a wide range of porosity (38% to 54%), are less dense (≤ 1.56 g/ cm^3) than lavas (≥ 2.38 g/ cm^3), resulting in lower P-wave velocities (< 2.04 km/s). Additionally, pyroclastic rocks are more permeable (≥ 2E-13 m^2) when compared to lavas (≤ 6E-15 m^{-2}). The compaction and welding of pyroclastic rocks, related to burial depth, influence their porosity, connectivity, and mechanical behaviour (e.g., Wyering et al., 2014; Stimac et al., 2015; Cant et al., 2018; Dúran et al., 2019). Despite having high porosity and low density, pyroclastic rocks may manifest less degree of pore space connectivity than lava breccias. As observed before, porosity does not reduce systematically with increasing burial depth (Cant et al., 2018). Debris flow is characterised by a porosity of 33 %, a bulk density of 1.74 g/cm^3, and a P-wave velocity of 2.02 km/s. Debris flow represents the transition from dense rocks (lavas and lava breccias) to fragmental rocks.

Fig. 3 illustrates multiple correlations between physical properties and the dynamic properties. Porosity demonstrates a linear negative correlation with both density and P-wave velocity (Fig. 3a and Fig. 3d), whereas Vp demonstrates a linear and positive correlation with bulk density (Fig. 3e). Furthermore, there exists a positive linear correlation between Vp and Vs (Fig. 3c). These established correlations agree with trends previously documented in the literature (e.g., Pereira et al., 2021). Permeability increases nonlinearly with increasing porosity, following a logarithmic trend (Fig. 3b), consistent with earlier studies (e.g., Kanakiya et al., 2022). However, the correlation, is weak (R^2 = 0.16) and indicates that permeability and porosity do not have a straightforward relationship. Permeability relies on the connectivity and geometry of pores (Heap et al., 2017; Cant et al., 2018), and porous rocks with isolated pores may yield low permeability values. Furthermore, the weak correlation implies that fluid flow in these rock masses may primarily be influenced by discontinuities (Weydt et al., 2021; 2022), a feature that is likewise suitable for lava breccias.

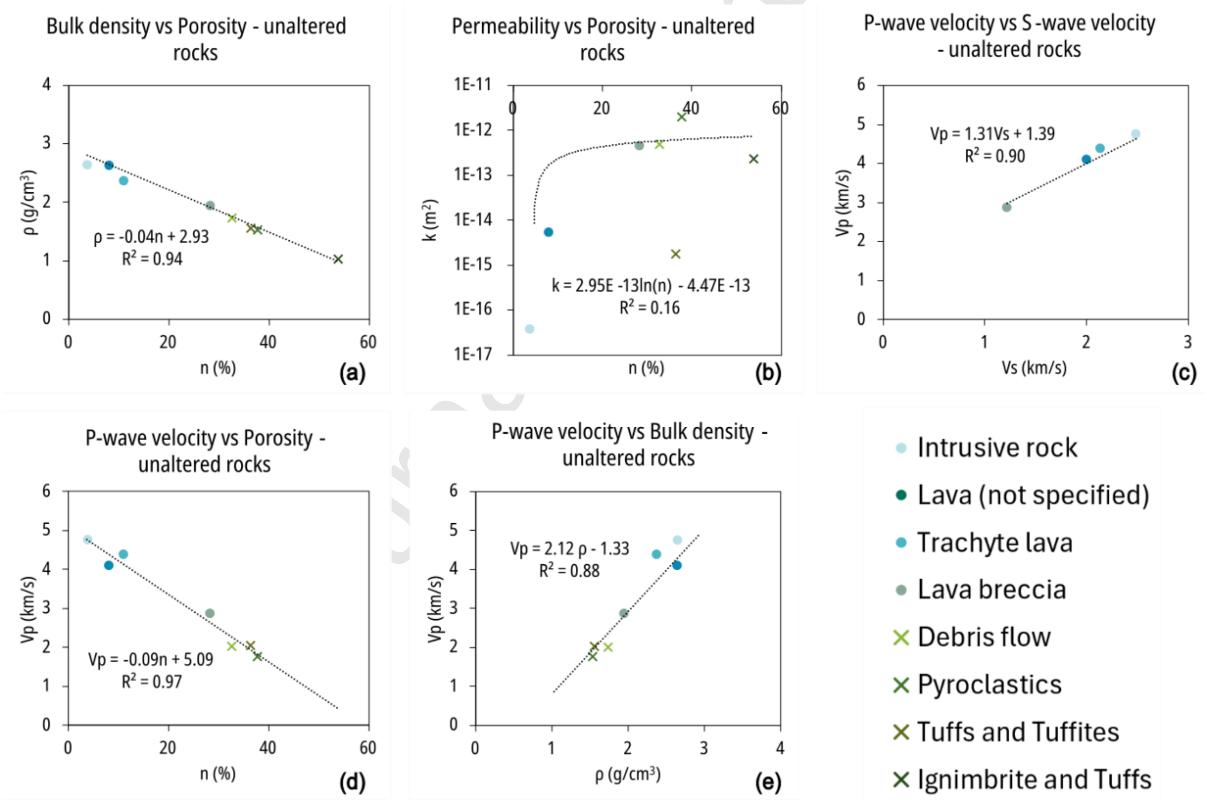

Fig. 3 Unaltered rocks: generalised correlation between physical and dynamic properties for several rock types.

3.2. Mechanical properties of unaltered host rocks

There are notable discrepancies in strength and stiffness between dense and fragmental rocks (Fig. 4). Within the category of dense rocks, intrusive rocks show the highest values for unconfined compressive strength (170 MPa) and Young's modulus (E_d = 44 GPa and E_s = 39 GPa), while also demonstrating relatively high Poisson's coefficient (ν_d = 0.31 and ν_s = 0.18), with a significant difference between static and dynamic Poisson's coefficients. It seems that the mechanical properties are affected by the alkali content of lavas. Andesites are more competent to unconfined compression (161 MPa), are more cohesive (42 MPa) and are stiffer (E_d = 39 GPa and E_s = 30 GPa) than trachytes (117 MPa; 34 MPa; E_d = 32 GPa and E_s = 18 GPa). Unexpectedly to what has been reported in the literature (e.g., González de Vallejo & Ferrer, 2011), trachytes have a slightly higher indirect strength (ITS = 10 MPa) than andesites. The dynamic Poisson's coefficient has very similar values for both andesites (0.31) and trachytes (0.32). It is important to note that the strength and stiffness of lavas may often be compromised by fractures and micro-fractures, leading to a wide range and unexpected mechanical values. Unaltered basalts, whose mechanical properties are not covered by the compiled data, can exhibit a wide range of UCS (200 to 25 MPa), ITS (12 to 40 MPa), and E_d (15 to 30 GPa), as reviewed by Pereira et al. (2021). In Heap & Violay (2021), basalts from Mt. Etna have an average UCS of 77 MPa compared to andesites from Volcán de Colima with 36 MPa of UCS. Lava breccias represent the transition from lavas to fragmental rocks in terms of mechanical behaviour (UCS = 25 MPa; E_d = 5 GPa and E_s = 7 GPa; v_d = 0.30 and v_s = 0.17; c = 9MPa). The group "lavas (not specified)" derived from Frolova et al. (2014) and Kennedy et al. (2020) comprises various effusive lavas of different composition (basalts, basaltic andesites, andesites, dacites) or lavas not specified in terms of nature, respectively. This group displays high competence, with UCS (121 MPa) and ITS (16 MPa) values aligned with those obtained for the remaining lavas (trachytic and andesitic).

Within the fragmental rocks, tuffs and tuffites tend to be less competent (UCS = 15 MPa and ITS = 2 MPa), less stiff (E_d = 8 GPa; v_d = 0.39), and have lower cohesion (3 MPa) than dense lavas. Furthermore, a reduction in the stiffness and competence of tuffs might be amplified by increasing temperature. The presence of thermally unstable zeolites in the rock matrix leads to a reduction in strength (Heap et al., 2012), and as thermal stressing temperatures increases, tuffs may experience increased permeability and reduced ultrasonic wave velocities and Young's modulus (Heap et al., 2014).

Overall, dense and less porous lavas are more competent, stiffer, and have higher cohesion than pyroclastic rocks, in agreement with the observations of Heap & Violay (2021). The UCS is eight to 18 times higher the ITS, and the difference is greater within the lavas (trachyte and andesite) (Fig. 4a). Dynamic values of Young's modulus and the Poisson's coefficient are generally superior to their static counterparts by 1.1 to 1.8 times and 1.7 to 1.8 times, respectively (Fig. 4b and Fig. 4c). Lava breccias constitute an exception, as Schaefer et al. (2023) obtain high values of E_s, amplifying E_s in respect to E_d. The Poisson's coefficient appears to be relatively consistent across lavas, suggesting that it is independent of the type of lava rock. Nevertheless, tuffs and tuffites show a 0.09 reduction in the Poisson's coefficient.

Fig. 5 depicts several correlations between distinct variables. Heap & Violay (2021) and González de Vallejo & Ferrer (2011) state that UCS decreases nonlinearly with porosity and increases nonlinearly with bulk density for the same lithotype, which is verified in the present review (Fig. 5a). All the remaining variables (ITS, Fig. 5b; E_s, Fig. 5c; Vp, Fig. 5f; c, Fig.5e) show a positive and linear correlation with UCS for different lithotypes. This suggests a dependence of strength on rock type. For E_s, a nonlinear correlation with higher R^2 is also obtained (Fig. 5b) but a linear correlation between these variables is more commonly reported for volcanic rocks (e.g. Pereira et al., 2021).

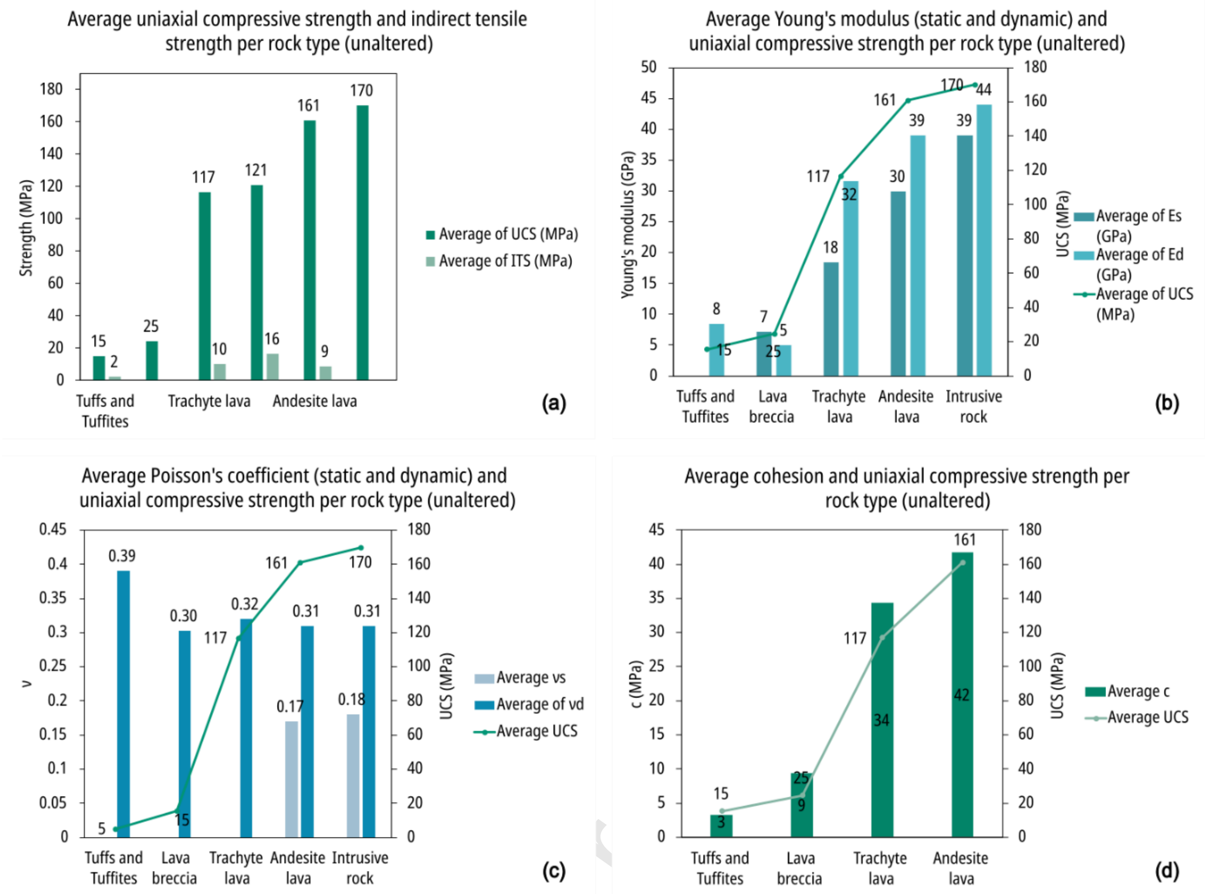

Fig. 4 Average values of physical and dynamic properties for several types of unaltered rocks (Pola et al., 2012; Pola et al., 2014; Frolova et al., 2014; Siratovich et al., 2014; Heap et al., 2015; Mayer et al., 2016; Navelot et al., 2018; Dúran et al., 2019; Farquharson et al., 2019; Heap et al., 2019a; Mordensky et al., 2018; Kennedy et al., 2020; Heap et al., 2020; Heap et al., 2021; Kanakiya et al., 2021; Frolova et al., 2020; Scott et al., 2022; Weydt et al., 2022; Darmawan et al., 2022; Kanakiya et al., 2022; Schaefer et al., 2023; Scott et al., 2023).

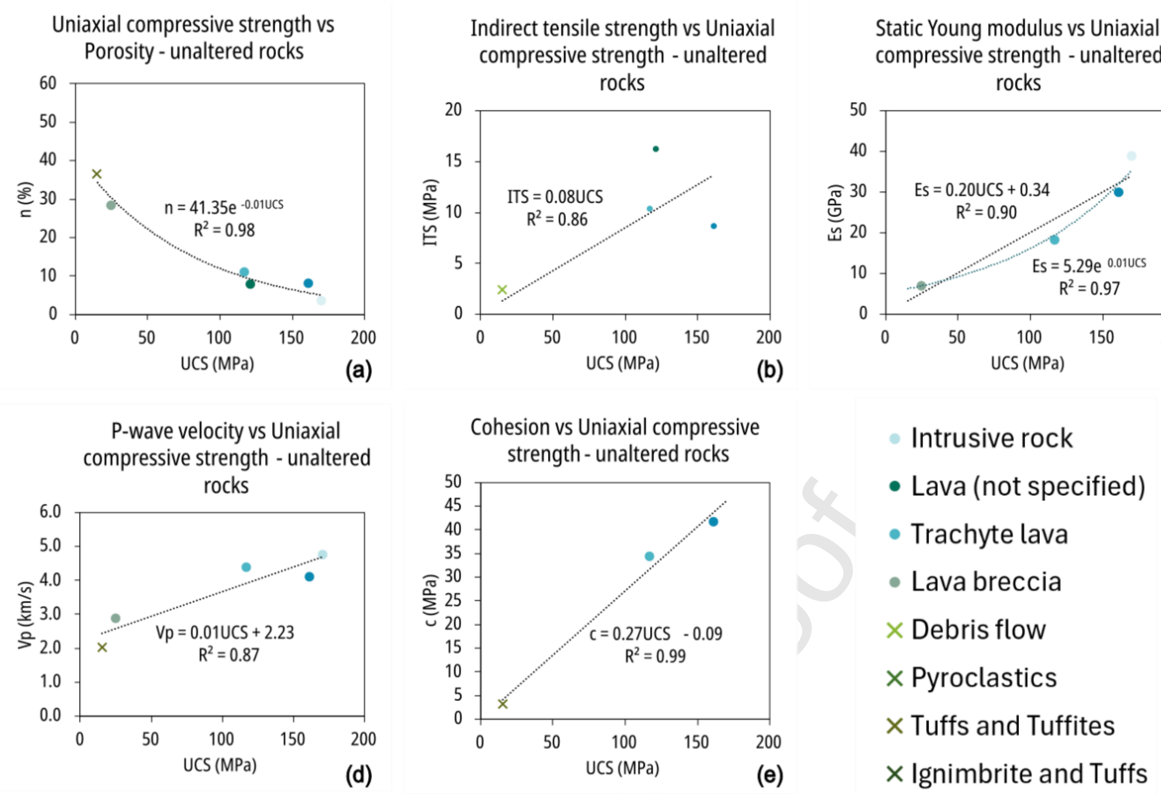

Fig. 5 Unaltered rocks: generalised correlation between mechanical, physical, and dynamic properties for several rock types.

4. Hydrothermal alteration effect on physical and mechanical properties

Hydrothermal systems in volcanic environments are predominantly composed of volcanic rocks with significant heterogeneity in texture, crystallinity, and mineralogy, all of which affect their petrophysical characteristics (Lavallée & Kendrick, 2021), controlling fluid flow dynamics, and the rate and intensity of hydrothermal alteration. It is generally accepted that hydrothermal alteration is favoured by high porosity and permeability, fractures, weak cementation, high volcanic glass content and mafic composition (Browne, 1984; Cathelineau et al., 1985; Lagat, 2009; Franzson et al., 2010; Frolova et al., 2010). In addition, denser rocks, such as lavas, are more prone to creating macrofractures (and microfractures), which enhance permeability and increase sensitivity to effective pore pressure. Deep and high-temperature fluids (> 200°C) typically reduce porosity and permeability, while increasing strength, density, and seismic wave velocities. Hydrothermal alteration at lower temperatures (<150°C) is complex and diverse, resulting in variable changes in physical and mechanical properties depending on the initial lithology, pressure, temperature, and fluid-rock interaction (Ladygin et al., 2000; Frolova et al., 2010; 2011; Frolova et al., 2014).

Hydrothermal alteration increases or decreases a specific physical and mechanical property of a rock, depending on (Kolawole et al., 2021; Heap et al., 2022b): (1) whether the alteration leads to an increase or decrease in rock porosity (e.g. through mineral dissolution or pore-filling mineral precipitation), which plays a key role (e.g. Heap & Violay, 2021); (2) whether secondary minerals are characterised by lower or higher values of specific properties (e.g., strength/hardness) compared to the primary mineral assemblage. Furthermore, the alteration process can modify the microstructure and failure mode of rocks, potentially promoting a transition from brittle to ductile behaviour as confining pressure and/or temperature increases.

To support the interpretation of the collected data, this review provides a theoretical assessment of hydrothermal alteration in geothermal systems. The degree of hydrothermal alteration is reported first, followed by the type of hydrothermal alteration. While the latter is the result of several external factors and the degree of alteration, reporting the intensity and type of alteration separately aims to provide a more detailed and comprehensive assessment of the data. Combining both elements would result in extensive graphs that could be challenging to interpret.

4.1 Theoretical framework on hydrothermal alteration within geothermal systems

4.1.1 Factors that influence the formation of hydrothermal minerals and the main facies of hydrothermal alteration

The factors that constrain the development of hydrothermal alteration are mainly defined in geothermal fields. Geothermal systems (Stimac et al., 2015; Arnórsson et al., 2015) exist in all geodynamic contexts, but most high-temperature systems (>230 °C) are associated with recent or active volcanism and structural settings that support fluid circulation. There are several classifications of geothermal resources, summarised by Rezaie & Aghajani (2013). Based on geological, hydrological, geophysical, and engineering characteristics, Stimac et al. (2015) propose five categories of geothermal resources: (1) intrusion-related systems; (2) tectonic systems; (3) deep sedimentary aquifers and geopressured systems; (4) hot dry rock systems or engineered geothermal systems; and

(5) supercritical and/or magma tap systems. Geothermal systems are also defined by their phase distribution (vapour or liquid dominated), as this has significant implications for the technology used to exploit the system for energy and affects heat transfer. Most geothermal systems are liquid-dominated (maximum temperatures of 370 ˚C), with hot water as the continuous phase in open pathways and possible minor bubbles of steam and gas (two-phase regions). In these systems, the hydrostatic pressure and temperature increase continuously with depth, and the boiling point curve of the water limits the maximum temperature. Vapour-dominated regimes (> 240 ˚C) have more than 85 % of steam and are less numerous than liquid-dominated systems, as a strong heat source and isolation from circulating groundwater are required conditions (Truesdell & White, 1973; Ingebritsen & Sorey, 1988; Stimac et al., 2015). Steam zones can be found in shallow parts of the crust, corresponding to impermeable caprocks, where pressure and temperature are kept constant with increasing depth (Stimac et al., 2015). Like liquid-dominated systems, two-phase regimes show a steady increase in temperature and pressure with increasing depth and are typical of well-sealed reservoirs and areas of hot fluid upwelling. In addition to phase distribution, several classifications refer to reservoir temperatures and thermodynamic properties due to their simplicity (Lee, 1996; Sanyal, 2005; Kaya et al., 2011). Sanyal (2005) defines hot water systems as (1) non-electric (<100 °C), (2) very low temperature (100 °C to <150 °C), (3) low temperature (150 °C to 190 °C), (4) medium temperature (190 °C to <230 °C), (5) high-temperature (230°C to <300°C), and (6) ultra-high temperature (>300°C), where (5) and (6) are two-phase systems that can be subdivided according to enthalpy (Kaya et al., 2011). Temperatures of hydrothermal fluids, major phase distributions, and subsurface geology are presented in Table S2 (Supplementary Data), which primarily considers high-temperature, often liquid-dominated systems.

Hydrothermal minerals and their assemblages are good indicators of the temperature, pH, and redox conditions of a hydrothermal system, and thus constrain the system conditions. Temperature plays an important role in the formation of hydrothermal minerals as they define the major alteration zones/facies with depth according to their thermal stability. Most exploitable geothermal systems are associated with the argillic (< 140 ˚C), transitional (140 – 220 ˚C) and propylitic alteration (> 220 ˚C) facies that develops with increasing temperature. The propylitic facies may also be associated with potassic alteration (biotite-adularia ± amphibole ± tourmaline) when high-temperature conditions are reached due to the proximity of a magmatic intrusion. Argillic and transitional zones are typically associated with caprocks of low permeability that seal the upper part of the geothermal system. In contrast, the high permeability reservoir coincides with the propylitic facies. The propylitic facies is described as low-temperature (clay minerals, zeolites, and calcite) or medium-high-temperature by Frolova et al. (2010; 2011; Frolova et al.,2014). The latter has similar properties to rocks with advanced silicic alteration where quartz is the dominant hydrothermal mineral. A strengthening, porosity, and permeability reduction of host rocks in the propylitic facies are expected when hard minerals fill in the pore space and fractures (Frolova et al., 2010; 2011; Nasimov et al., 2005; Frolova et al., 2014). An update of the Henley & Ellis (1983) diagram is presented in Fig. 6, which relates the thermal stabilities of minerals, defining specific hydrothermal facies to their hardness (Mohs scale – H) and specific gravity (Deer et al., 2013). Indeed, veins with soft minerals and their replacement by the same minerals (H < 4 – Brzovic & Villaescusa, 2007) have been described to reduce rock strength (Shang et al., 2016; Turichsev & Hadjigeorgiou, 2017). Nevertheless, vein strength and the overall rock strength are also influenced by the non-uniformity of the mineral structure (cleavage, joints, inclusions; Kovaleva, 1974). Clay minerals and zeolites (except for wairakite), typical of lower temperatures and argillic facies, are softer and are expected to reduce rock strength. Conversely, propylitic facies mineral assemblages are harder. Calcite (H = 3) and biotite (H = 2 – 3) are exceptions as their mineral structure (cleavage) reduces their strength. In addition to the hydrothermal facies described above, advanced argillic alteration forms from an acidic and oxidising fluid over a wide temperature range and includes kaolinite (< 140 ˚C), dickite ± kaolinite (~120 – 200 ˚C), dickite ± pyrophyllite (~200 – 260 ˚C), and pyrophyllite ± illite (~220 – 320 ˚C) (Stimac et al., 2015). Alunite and pyrite can be present along all these hydrothermal subzones, while diaspore and anhydrite are typical of higher temperatures (> 120 ˚C; Fig. 6). This acid-sulphate alteration can be associated with the argillic and transitional facies, where it is more pervasive, or cut the propylitic facies, limited to discontinuities' zones (faults and fractures) (Heald et al., 1987; Stimac et al., 2015). The minerals of advanced argillic alteration have low hardness on the Mohs scale (H < 4; Deer et al., 2013) and are expected to promote a weakening of the hydrothermal alteration host rocks. Unlike hardness, there is no relation between specific gravity and temperature, as denser minerals can exist at higher and lower temperatures and vice versa.

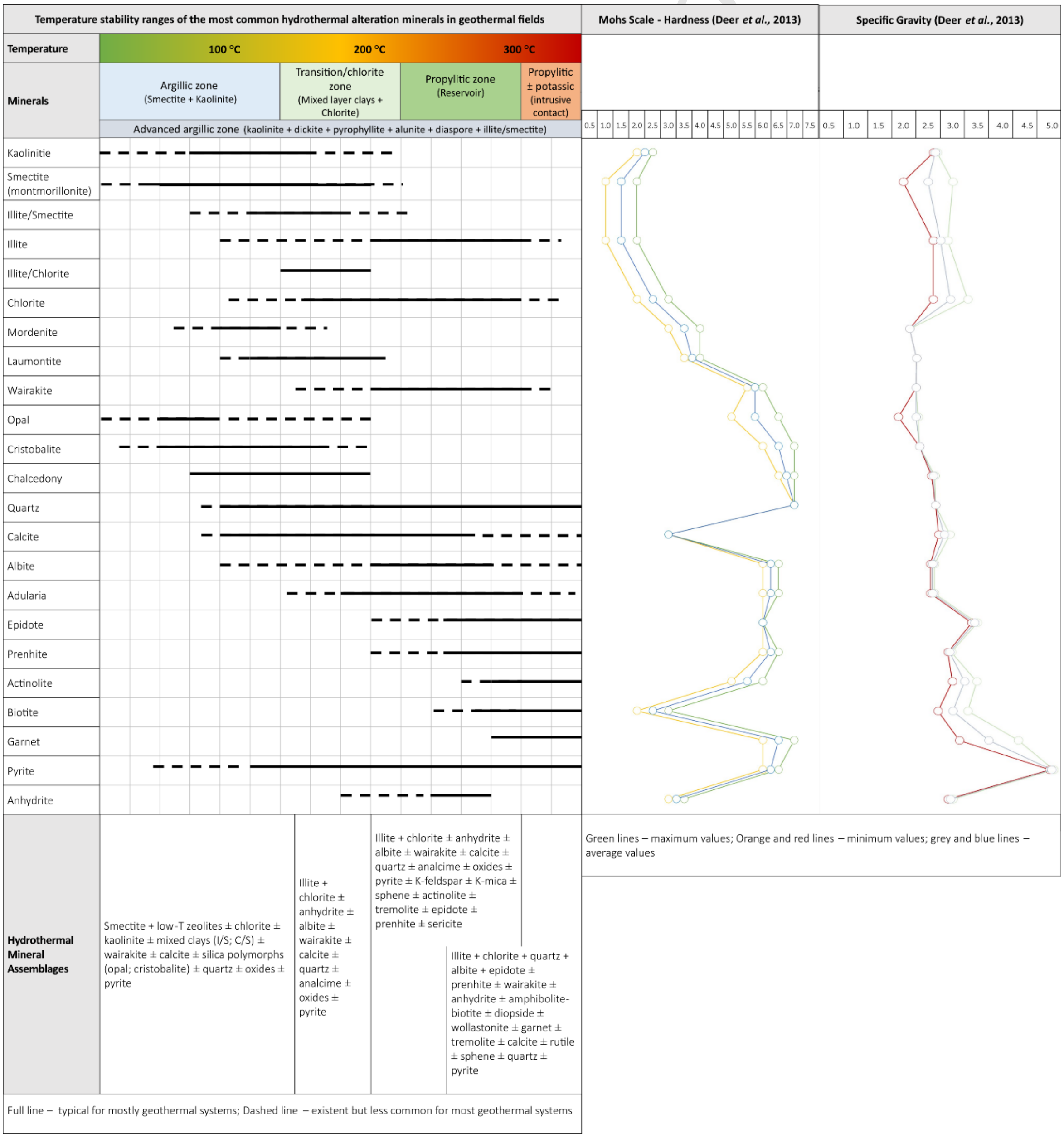

Fig. 6 Diagram with temperature, hardness (Mohs scale), and specific gravity ranges of the main hydrothermal minerals. Definition of the main hydrothermal facies and hydrothermal mineral assemblages with temperature (Steiner, 1953; Browne &Ellis, 1970; Kristmannsdóttir & Tómasson, 1976; Browne, 1978; Kristmannsdóttir, 1979; Elders et al., 1981; Browne & Ellis, 1981; McDowell & Elders, 1980; Schiffman et al., 1985; Cathelineau et al., 1985; Cavarretta et al., 1982; Muffler & White, 1969;; Reyes, 1990; Izquierdo Montalvo et al., 1995; Teklemariam et al., 1996; Şener & Gevrek, 2000; González, 2000; Karamaderesi & Helvaci, 2003; Pandarinath et al., 2006; Lagat, 2009; Franco, 2016).

The presence of clay minerals characterises the final stages of the hydrothermal process (Frolova et al., 2014) at shallow depths and lower temperatures. High acidity levels inhibit clay formation (Frolova et al., 2014), with the exception of kaolinite (H = 2–2.5), typically formed via steam heating in acidic superficial environments. Kaolinite can develop as part of the argillic alteration facies at low fluid temperatures (<150–200°C) and a pH of ∼4.5–6 (Fulignati, 2020) or as a mineral of the advanced argillic alteration facies (pH < 3; T < 300°C), produced by extreme acid attack and high sulphidation (e.g., Gifkins et al., 2005; Pirajno, 2009). Montmorillonite and other smectites (H = 1–2) are clays that form at low-temperatures and are typically found in argillic facies. They result from the alteration of silicates under slightly acidic to sub-neutral pH conditions (e.g., Frolova et al., 2010; 2011; Frolova et al., 2014; Fulignati, 2020). Smectites are affected by water saturation since they soak and swell (Frolova et al., 2010; 2011; Frolova et al., 2014). Vermiculite, a member of the smectite group, is commonly associated with argillic alteration and may occur at higher temperatures (Table S1). Smectites swell, depending on saturation and thermal effect (e.g., Ladygin et al., 2000; del Potro & Hürlimann, 2009; Frolova et al., 2014, Nicolas et al., 2020; Heap et al., 2021; Kanakiya et al., 2022). High temperatures cause smectites to convert into chlorite and/or illite, with interlayered clays serving as intermediate compounds. The mixed-layer clays formation depends on the permeability and the fluid flow type (Harvey & Browne, 1970; Utami & Browne, 1999; Pandarinath et al., 2006) - a diffuse flow typical of low permeable host rocks promotes a progressive transition between clays and mixed-layer, while for higher permeability of the rocks, the channelised fluid flow inhibits the origin of interlayered clays (Harvey & Browne, 1991). The mixed-layer chlorite/smectite (C/S) often occurs for the argillic and phyllic alteration facies and can evolve continuously or discontinuously (Fulignati, 2020). The mixed-layer illite/smectite (I/S) is the most common mixed-layer type reported for geothermal systems, marking the transition to phyllic/propylitic alteration facies, occurring from 120 to 240 °C (Fig. 6) and reported to relate with highly porous, weak, and strongly altered host rocks interbedded with horizons of higher strength and density (Ladygin et al., 2000). Mixed clays form at 80 °C in presence of montmorillonite. Chlorite and illite, typical of the propylitic alteration facies, are found in a wide temperature range but typically coexist for temperatures above 200/220 °C (Fig. 6). Chlorite (H = 2–3) is typical of the transition argillic-propylitic or propylitic facies and has varying properties with temperature (swelling to non-swelling with increasing temperature, Marini, 2000). Several chlorite and illite (H = 1–2) geothermometers, reviewed by Fulignati (2020), are defined since they show chemical variations with increasing temperature. Clays have a variable effect whether they replace the primary mineralogy or fill the open spaces (fractures and pores). Alongside zeolites, they may explain rock weakening, particularly under saturation conditions (Heap et al., 2012; Heap et al., 2018).

Zeolitic alteration frequently superimposes argillic alteration as a function of temperature. Si-rich zeolites (mordenite, clinoptilolite, and heulandite; H = 3–4) are found for T < 150 °C, produced by alkaline fluids, and laumontite for T < 200 °C, while wairakite (H = 5.5–6) is a high-temperature Ca-zeolite in most geothermal fields.

Opal (H = 5–6.5) and cristobalite (H = 6-7) typically form in lower temperature regimes and transform into chalcedony and quartz (H = 7) at pressures and temperatures typical of the lower crust (Keith et al., 1978; Keith & Muffler, 1978). Quartz is the main silica mineral in geothermal fields (e.g., Keith & Muffler, 1978; Kristmmansdóttir, 1979; Franco, 2016). Silicification is a common type of hydrothermal alteration. It is commonly associated with alunitic facies and oxidation, with its development near the surface or close to fractures and under acidic environments where acid leaching occurs (e.g., Heald et al., 1987; Frolova et al., 2014; Mayer et al., 2016).

Albite (H = 6–6.5) and K-feldspar (H = 6–6.5) tend to coexist above 140 °C and albite is a good temperature tracer if found in veins since albitization occurs for a broad array of temperatures (Reyes, 1990). Large amounts of feldspars have been found to contribute to water-weakening in sandstones (Baud et al., 2000).

Silicate minerals including epidote, prehnite, actinolite, garnet, and biotite are commonly found as relicts in some geothermal systems at temperatures above 250 °C. The key-mineral assemblage of the propylitic alteration zone comprises of chlorite + albite ± carbonates ± epidote. Furthermore, the crystallinity of epidote varies with temperature (Reyes, 1990).

Fluid chemistry (pH, components in solution and their concentration) partly defines the secondary mineralogy (Fig. 7), location, and intensity of hydrothermal alteration (Browne, 1978; Lagat, 2009). Fluid composition varies in depth and in space. In volcanic geothermal systems the acid-sulphate and the argillic-propylitic alteration are considered the main endmembers of hydrothermal alteration (Wohletz and Heiken 1992). Acid-sulphate alteration takes place in the uppermost regions of a volcano or along caldera ring fractures, where there is abundance of circulating groundwater that mixes with rising magmatic gases. This process produces more sulphate-acidic waters, which are typically more oxidised and have higher sulphur content (Heald et al., 1987). Alunite, together with kaolinite, defines the alunitic facies. The presence of alunite and kaolinite reveals an acidic steam-heated zone of the subsurface or in proximity of fractures. According to Mayer et al. (2016), near fracture zones, a pH < 2 produces a strongly acidic alteration forming amorphous silica. Towards the periphery, alunite and amorphous silica form at 2< pH < 4 and kaolinite forms at pH > 4. From the fracture to the periphery, permeability decreases and the leaching results in the weakening of rocks. On the other hand, Frolova et al. (2014) found that the effect of alunitic and silicic alteration depended on the presence of oxides and kaolinite. While alunite and kaolinite are typical of acidic environments (argillic to advanced argillic alteration facies) (Fig. 6 and Fig. 7), the argillic to propylitic alteration facies are formed by neutral pH and alkali-chloride waters (Heald et al., 1987), which induce a reduced environment with low-sulphur content. Furthermore, the influence of low-temperature subsurface fluids appears to be more complex (Frolova et al., 2010).

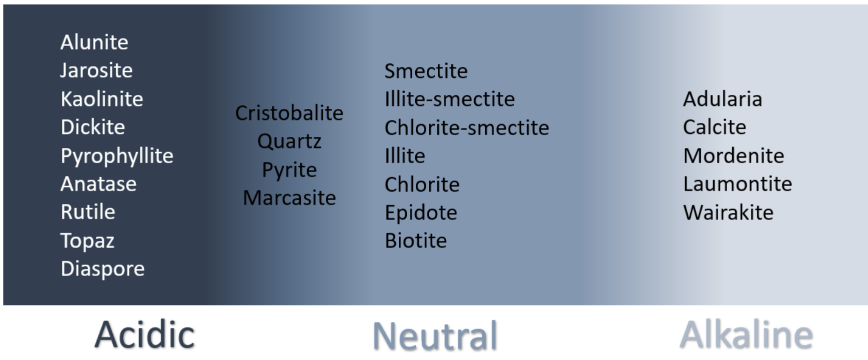

Fig. 7 pH range of some hydrothermal phases (adapted from Reyes, 1990; and Wohletz and Heiken, 1992).

Pressure_influences mineral solubility (Browne, 1984) and controls secondary mineral formation. Boiling zones are marked by the occurrence of adularia, calcite, quartz and sometimes wairakite (Browne, 1970; Browne & Ellis, 1970; Browne, 1970; Keith & Muffler, 1978). Besides the degree and type of alteration, welding and compaction due to *in situ* pressures, have an important control on the physical and dynamic properties, especially in the propylitic facies as they occur for higher depths (Frolova et al., 2014; Mielke et al., 2015). Tuffs from high-temperature systems of the Kuril-Kamchatka complex have higher density, strength, P-wave velocity, and lower porosity than tuffs from low-temperature systems (Frolova et al., 2014). Sometimes, the increase in seismic wave velocities and bulk density can be amplified by the higher welding/compaction of pyroclastic rocks (Dúran et al., 2019).

Permeability and subsurface geology_influence the distribution and type of hydrothermal alteration. Both permeability and porosity of the host rock, dependent on the lithotype, influence the rate and intensity of hydrothermal alteration, as high-porous, fractured, and weak cemented rocks are more prone to be hydrothermally altered (e.g., lavas versus tuffs; Frolova et al., 2014). Secondary permeability, namely faults and fractures which are preferential channelling paths, promotes the hydrothermal fluid-rock interaction, and associate with mineral precipitation and formation of veins with quartz, anhydrite, wairakite, illite, adularia, hyalophane, celadonite, abundant pyrite and calcite (Keith et al., 1978; Reyes, 1990). These minerals point out former high-permeability conditions. At the same time, for rocks with low permeability, the diffuse fluid flow promotes the origin of mixed-layer clays (Harvey & Browne, 1991), as well as prehnite, pumpellyite, pyrrhotite, abundant laumontite, abundant sphene (e.g., Reyes, 1990). Also, high-permeability rocks and high-steam production wells lead to the following feldspar sequence with increasing temperature: primary andesine → albite → albite + adularia → adularia (Browne, 1970).

The primary mineralogy has a higher influence on the formation of secondary assemblages at temperatures below 280 °C (Frolova et al., 2014). The ease of alteration is dictated by Bowen's series, with volcanic glass and ferromagnesian minerals being the most reactive and prone to replacement and dissolution (e.g., Browne, 1984; Cathelineau et al., 1985; Lagat, 2009; Frolova et al., 2010). On the contrary, rocks with low porosity, permeability, good crystallinity, and rhyolitic composition are more resistant to hydrothermal alteration. However, the influence of rock type diminishes at higher temperatures compared to hydrothermal alteration. Regardless of lithology, the high-temperature mineral assemblage, including chlorite ± albite ± adularia + calcite + quartz ± illite ± pyrite, is documented (Henley & Ellis, 1983; Browne, 1978; Cox & Browne, 1998; Table S2).

The intensity and location of hydrothermal alteration are conditioned by the time of geothermal activity, which depends on the hydrological model of the field, external factors, and evolution of the field itself (Browne, 1978; Keith et al., 1978; Moore & Gunderson, 1995; Moore et al., 2001). Increasing duration of the fluid-rock interaction promotes homogenisation of the composition and properties of the hydrothermal system (e.g., Frolova et al., 2010). According to Weydt et al. (2022), the impact of hydrothermal alteration on physical and mechanical properties becomes unclear due to multiple or repeated hydrothermal events.

In summary, external factors affect both the type and intensity of hydrothermal alteration. High temperatures, increased permeability, fragmental, mafic and/or low crystallinity host rocks, extended geothermal activity, and proximity to the discharge zone enhance the degree of hydrothermal alteration. Conversely, the type of alteration is mainly determined by fluid chemistry, permeability, and temperature. Argillic and propylitic facies are linked to neutral to alkaline fluids, evolving with changes in depth and temperature, leading to varying mineral compositions. Minerals typically become harder with increased depth and temperature, with clay minerals and zeolites being softer and higher temperature propylitic facies minerals being harder. Alunitic and advanced argillic facies, associated with acidic fluids, occur in shallow or deeper crustal regions with fluid flow channelled by fractures and faults. Acid-sulphate alteration generally weakens host rocks due to the prevalence of soft minerals. However, in boiling zones, quartz, adularia, and wairakite formation can strengthen the host rock, and calcite and quartz in fracture networks and vesicles may contribute to overall rock strength. While temperature-mineral hardness correlations are noted, the complex impact of external factors on host rock's mechanical and physical properties remains underexplored.

4.1.2 Conceptual model of a volcanic hydrothermal system

Intrusion-related systems attain specific attributes of the volcano-tectonic environment (Stimac et al., 2015) and are affected by an array of factors, comprising depth, temperature, hydrothermal alteration, and episodic events, which lead to either brittle or ductile behaviour of the composing rocks.

Fig. 8 provides a cross-sectional diagram of a hydrothermal system associated with an intrusion, illustrating the formation of hydrothermal mineral assemblages in respect to the heat source and thermal and fluid compositional gradients.

Intrusion-related systems exhibit a clear distinction between the magmatic domain and the hydrothermal domain. This separation is delineated by the brittle-ductile transition (BDT), as elucidated by Fournier (1999) and Stimac et al. (2015). The BDT, typically occurring around 400 °C, serves as a natural, impermeable barrier between these two domains, acting as the depth limit of seismicity and hydrothermal circulation in the crust (Sibson, 1982; Violay et al., 2012; Violay et al., 2015; Violay et al., 2017). Above the BDT, rocks are brittle and experience irreversible deformations mainly as localised shear fractures, whereas below the BDT, where pressure and temperature increase, rocks are ductile, i.e., deformations are distributed and controlled by plastic mechanisms (Patterson & Wong, 2005; Scholz, 2019). Close to the surface, above the hydrothermal zone, an impermeable argillic cap rock, usually volcaniclastic in nature (Franzson et al., 2010), partially isolates the groundwater regime from the hydrothermal realm, a common occurrence in many geothermal systems.

Hydrothermal fluid circulation in these systems depends on several factors: (1) the presence of a heat source; (2) the existence of permeable reservoir rocks, often facilitated by tectonic and hydrothermal fracturing, and (3) the availability of hot fluid carrying solutes (Pirajno, 2009; Stimac et al., 2015). Intrusion-related geothermal systems usually maintain temperatures ranging from 220°C to 350°C, with reservoirs extending from 1 to 3 kilometres below the Earth's surface. Beyond depths of about 4 km, maintaining permeability is challenging, and it is assumed that fractures will not remain opened or preferentially oriented for long periods in high-temperature and high-enthalpy geothermal reservoirs (e.g., Scott et al., 2015; Eggertson et al., 2020). The brittle failure of rocks is relatively independent of rock type (coefficient of friction), strain rate, and temperature, while rocks undergoing plastic deformation (Byerlee, 1978; Fournier, 1999) are sensitive to these factors. The BDT of a rock depends on the porosity (Wong & Baud, 2012; Heap & Violay, 2021 and references therein), as high-porosity rocks tend to be ductile at lower effective pressures (depth) than rocks with low porosity. Furthermore, this transition is also controlled by pore fluid pressure, which can either promote brittle conditions by reducing the effective stresses or enhance ductile deformation by chemically active mechanisms (Carter & Tsenn, 1987; Nöel et al. 2021).

Under typical circumstances, undisturbed by any external factors, the movement of magmatic fluids - primarily steam - from the magmatic region to the hydrothermal realm occurs at a leisurely pace, resulting in the accumulation of brine and steam in isolated pockets within the lithostatic plastic zone. Occasional breaches of the self-sealed BDT zone may occur due to different factors (Fournier, 1999), including the continuous degassing of the crystallised magma, causing the tensile failure of the top carapace of the crystallised body, influx of new magma with volatiles, increasing strain rates, and large seismic events that influence permeability and flow rates in the hydrothermal system, potentially inducing heat loss. Variations in temperature cause changes in depth of the brittle-ductile transition (BDT). As the temperature decreases, once ductile rocks become brittle and fail under shear stress, resulting in faulting, brecciation, hydrothermal alteration, and vein formation (Fournier, 1999; Fig. 7). The BDT is influenced by clay minerals such as smectite and illite found in rocks with argillic facies, which exhibit a reduction in the physical properties, such as an increase in porosity, compared to chlorite (Wyering et al., 2014). Clays are considered a key factor constraining the mechanical and physical characteristics of an altered rock by several authors (e.g. del Porto Hürlimann, 2009; Nicolas et al., 2020; Heap et al., 2021; Kanakiya et al., 2022) capable of creating a shallow ductile zone, as it affects both effusive lavas and more porous rocks (Violay et al., 2012; Heap et al., 2015; Mordensky et al., 2018), which impacts the explosivity of volcanoes and the functioning of the hydrothermal systems.

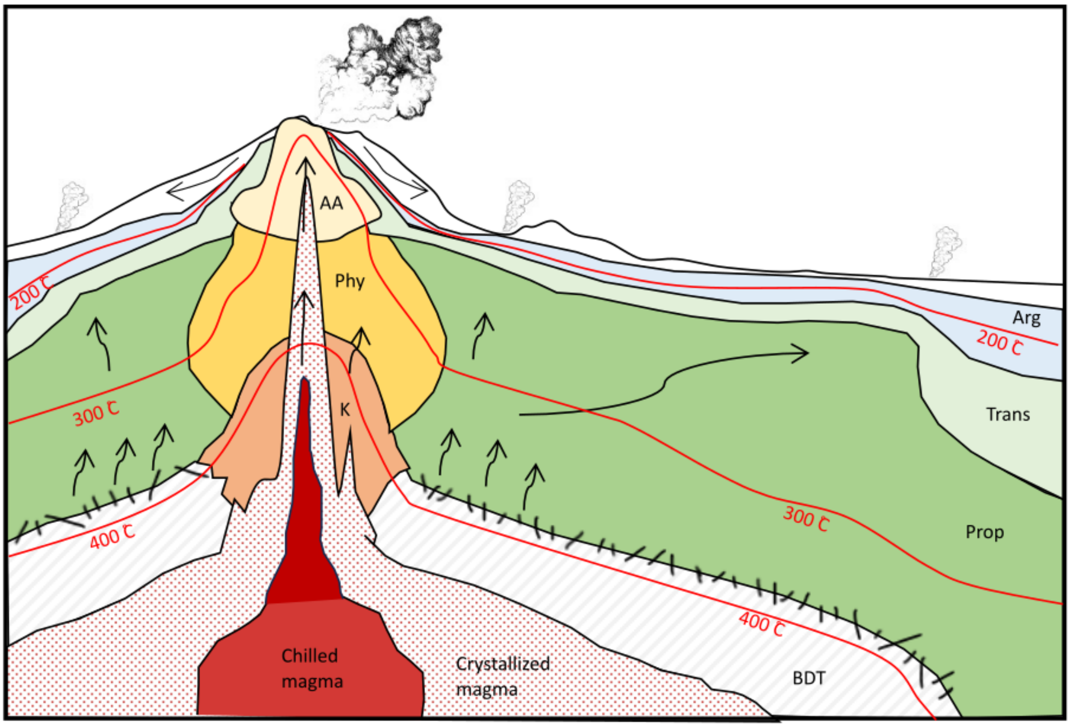

Fig. 8 Schematic cross-section of a subvolcanic hydrothermal system. Isotherms are represented as red lines. The main hydrothermal facies are formed by long-term circulation. They are represented with increasing depth and temperature as argillic (Arg), transitional (Trans), and propylitic (Prop) facies constituting the hydrothermal domain in which the pressure is hydrostatic. Close to the volcano conduit, where temperature, strain rate, and magmatic volatiles are higher and magmatic-hydrothermal fluids circulate, a potassic (K), phyllic (Phy), and advanced argillic (AA) alteration occurs with decreasing depth. Below the hydrothermal regime, a brittle-ductile transition (BDT) is illustrated and overlies the crystallised magma body (magmatic realm – lithostatic pressure and plastic behaviour). In this scheme, the BDT is being disrupted, increasing the influx of magmatic fluids to the hydrothermal system. The deep fluids (ascent arrows) and meteoric fluid (descending arrows) are depicted. Fumaroles, hot springs, cold CO_2-rich springs, and diffuse degassing areas occur at the surface and are visible manifestations of the geothermal system (adapted from Fournier, 1999 and Stimac et al., 2015).

4.2. Hydrothermal alteration effect on physical and mechanical properties

In contrast to the constraints on hydrothermal alteration development outlined in geothermal fields (Table S2), most of the physical and mechanical data on hydrothermally altered rocks comes from volcanic settings, which do not necessarily include exploitable geothermal systems (Table S1).

The properties of rocks forming volcanic edifices hosting hydrothermal systems, as well as the extent of hydrothermal processes (degree of alteration), are influenced by the type of hydrothermal alteration. The latter is a consequence of several external factors (Section 4.1.1), including the structure of the intrusion-related geothermal system (Section 4.1.2).

Fig. 9 illustrates the main facies (and sub-facies) of hydrothermal alteration of the compiled data (Table S1 – Supplementary Data), which are the main argillic, transition, and propylitic facies, often associated with silicification and alunitic alteration.

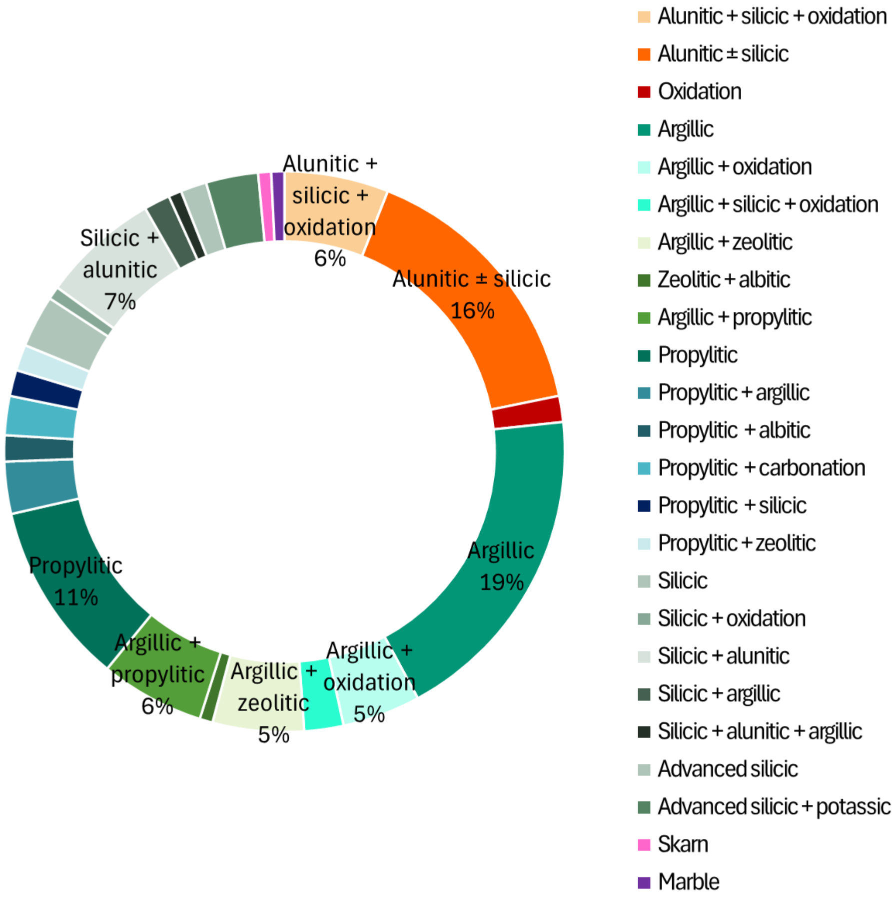

Fig. 9 Main types of hydrothermal alteration (based on Table S1 – Supplementary Data; Franzson & Tulinius, 1999; Ladygin et al., 2000; Nasimov et al., 2005; Pola et al., 2012, Pola et al., 2014; Frolova et al., 2014; Mayer et al., 2015; Heap et al., 2015; Siratovich et al., 2014; Wyering et al., 2014; Mayer et al., 2016; Siratovich et al., 2016; Cant et al., 2018; Mordensky et al., 2018; Navelot et al., 2018; Dúran et al., 2019; Farquharson et al., 2019; Heap et al., 2019a; Heap et al., 2020; Gibert et al., 2020; Heap et al., 2021; Kennedy et al., 2020; Nono et al., 2020; Kanakiya et al., 2021; Weydt et al., 2022; Scott et al., 2022; Kanakiya et al., 2022; Darmawan et al., 2022; Schaefer et al., 2023; Scott et al., 2023).

To clarify the sole role of the type of hydrothermal alteration, Fig. 10 depicts the average values of physical and mechanical properties of the compiled data for each hydrothermal alteration facies. Dashed polygons delineate the main facies (alunitic, argillic, propylitic, and silicic) in Fig. 10 to facilitate the reading of the graph. Despite Fig. 10 provides some insights, assessing the effect of the hydrothermal facies alone is challenging without considering the rock type. As Wyering et al. (2014) noted, rocks from the same lithology can have distinct properties due to the different hydrothermal alteration facies. For instance, andesites from different fields with the same alteration have more similar UCS than andesites with different hydrothermal alteration facies. On the other hand, conclusions about the effect of the degree of hydrothermal alteration should not be dissociated from the type of alteration, as the latter influences them. Thus, this review discusses the influence of the main types of alteration (alunitic, argillic, propylitic, and silicic) regarding the rock type and degree of alteration. Firstly, it is discussed the general effect of hydrothermal alteration, followed by an assessment of how the alteration pervasiveness varies across different lithologies and hydrothermal alteration types. To complement, the sole effect of hydrothermal alteration type per lithotype (Fig. S1) is presented in the Supplementary Data.

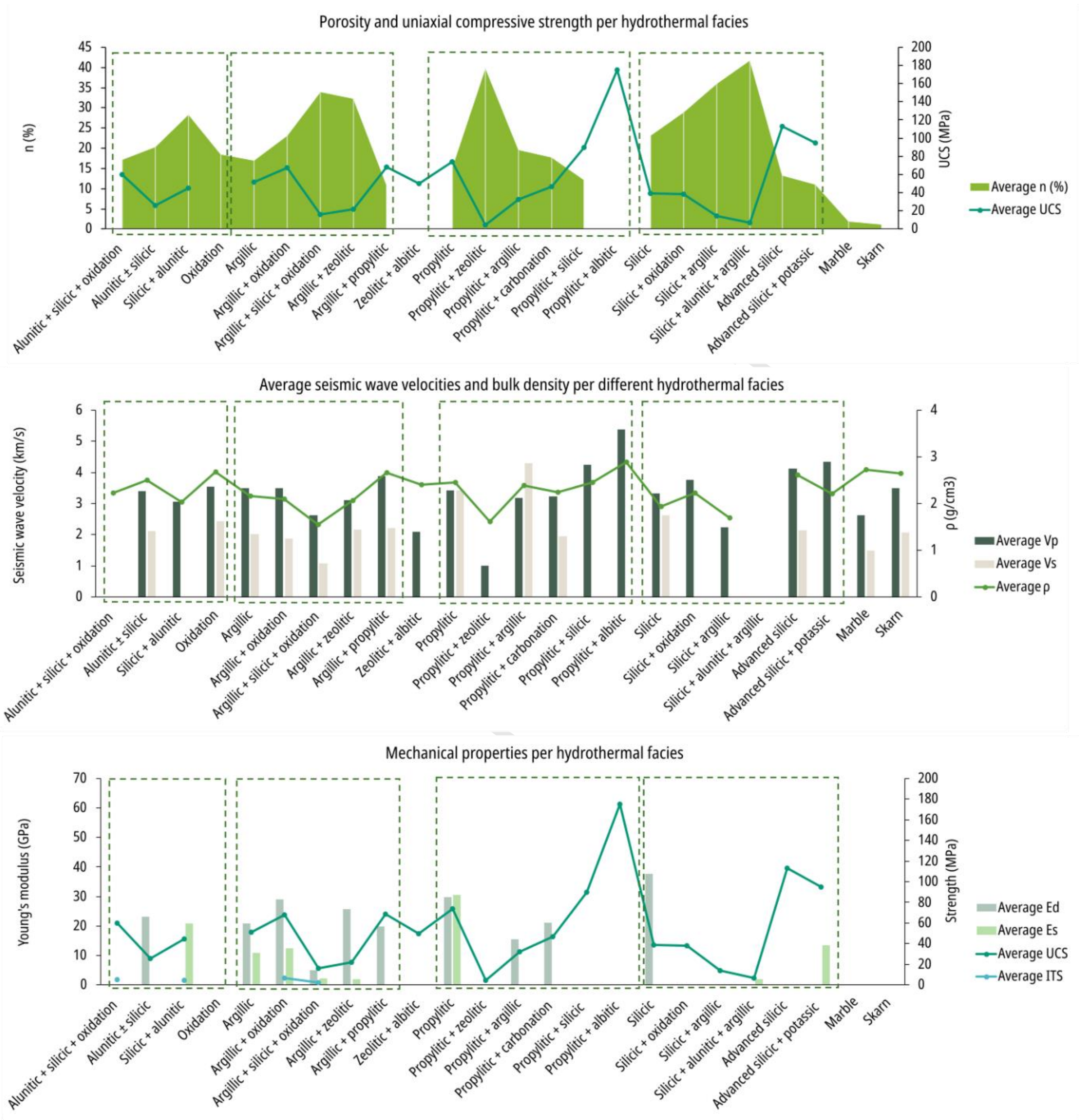

Fig. 10 Effect of hydrothermal alteration facies on physical and mechanical properties based on the compiled data (Table S1 – Supplementary Data; Franzson & Tulinius, 1999; Ladygin et al., 2000; Nasimov et al., 2005; Pola et al., 2012, Pola et al., 2014; Frolova et al., 2014; Mayer et al., 2015; Heap et al., 2015; Siratovich et al., 2014; Wyering et al., 2014; Mayer et al., 2016; Siratovich et al., 2016; Cant et al., 2018; Mordensky et al., 2018; Navelot et al., 2018; Dúran et al., 2019; Farquharson et al., 2019; Heap et al., 2019a; Heap et al., 2020; Gibert et al., 2020; Heap et al., 2021; Kennedy et al., 2020; Nono et al., 2020; Kanakiya et al., 2021; Weydt et al., 2022; Scott et al., 2022; Kanakiya et al., 2022; Darmawan et al., 2022; Schaefer et al., 2023; Scott et al., 2023).

4.2.1 Alunitic and oxidation hydrothermal alteration

While kaolinite weakens the rock and reduces the permeability, the opposite was found for the presence of the assemblage alunite + silica polymorphs and quartz ± oxides. According to Fig. 10, alunitic facies (alone or combined with silicification and oxidation) results in rocks with the following average values: porosities between 17 % and 28 %, bulk densities between 2.03 and 2.50 g/cm^3, P-wave velocity between 3.05 and 3.40 km/s, UCS between 26 and 60 MPa and ITS between 4 and 5 MPa. When alunite is associated with silicification, porosity is enhanced while strength is decreased. Bulk density can either increase, if alunite prevails, or decrease, if silica polymorphs occur in higher proportion. The "silicic+alunitic" facies comprises several rock types with several degrees of alteration (Table S1 – Supplementary Data)

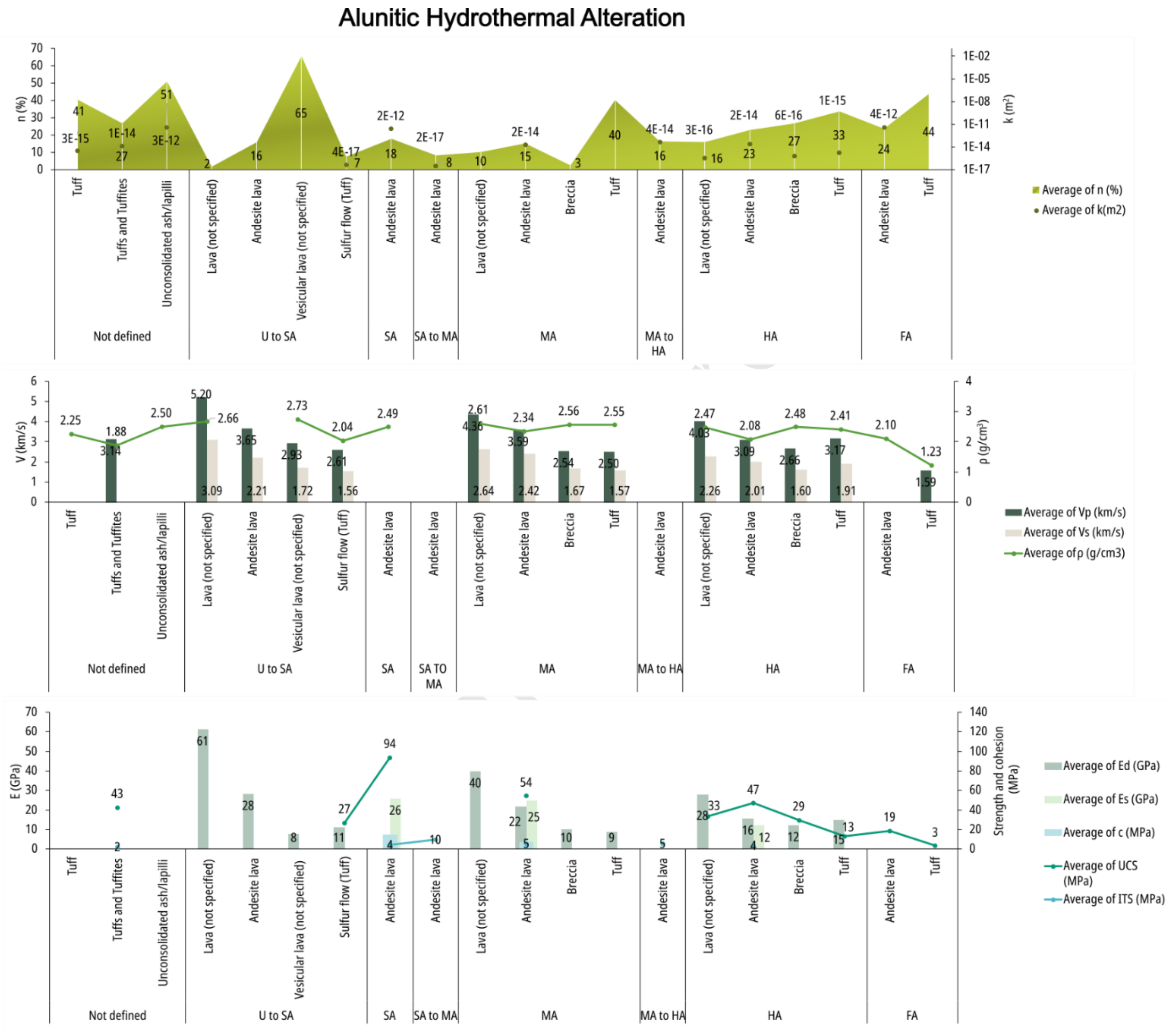

Fig. 11 Effect of alunitic hydrothermal alteration facies on physical and mechanical properties along different hydrothermal degrees and per rock type (U – unaltered; SA – slightly altered; MA – moderately altered; HA – highly altered; FA – fully altered). Based on the compiled data (Table S1 – Supplementary Data; Franzson & Tulinius, 1999; Ladygin et al., 2000; Nasimov et al., 2005; Pola et al., 2012, 2014; Frolova et al., 2014; Mayer et al., 2015; Heap et al., 2015; Siratovich et al., 2014; Wyering et al., 2014; Mayer et al., 2016; Siratovich et al., 2016; Cant et al., 2018; Mordensky et al., 2018; Navelot et al., 2018; Dúran et al., 2019; Farquharson et al., 2019; Heap et al., 2019a; Heap et al., 2020; Gibert et al., 2020; Heap et al., 2021; Kennedy et al., 2020; Nono et al., 2020; Kanakiya et al., 2021; Weydt et al., 2022; Scott et al., 2022; Kanakiya et al., 2022; Darmawan et al., 2022; Schaefer et al., 2023; Scott et al., 2023).

Fig. 11 allows to analyse the intricate effect of degree and type of alteration with rock type. Slightly altered dense rocks by alunite, namely lava (not specified) and andesite lava, demonstrate an increase in their porosity (2-18 %) and permeability (4E-12 m^2), and a reduction in density (2.66-2.49 g/cm^3) and ultrasonic wave velocity (Vp = 3.95-5.20 and Vs = 2.21-3.09 km/s) from their unaltered terms. Alunitic andesites from Merapi volcano, included in the compiled data, are described as less permeable than their porosity suggests (Heap et al., 2019a). Hydrothermal alteration led to a significant decrease in permeability, reducing it up to four orders of magnitude, while porosity remained within a narrow range. Permeability is primarily influenced by pore-coating, pore-filling, and microfracture filling, as microfractures contribute minimally to the overall porosity of a rock (Heap et al., 2019a). For mechanical parameters, UCS decreases for andesites to 94 MPa, but dense rocks either increase or maintain their stiffness (E_d = 28-61 GPa) concerning the unaltered rocks. Increasing alteration degree in dense rocks results in higher porosity and permeability, along with reductions in bulk density, ultrasonic wave velocity, strength, and stiffness. As an example, highly to fully alunitic lavas (andesitic or not specified) reach a porosity of 16 to 23 %, a permeability of 3E-16 m^2 to 4E-14 m^2, a density from 2.08 to 2.47 g/cm^3, a P-wave velocity of 3.09 to 4.03 km/s, a UCS from 47 to 19 MPa, and a dynamic Young's modulus from 28 to 16 GPa. For slight alunitic alteration, the influence of texture is evident, with vesicular lavas demonstrating much higher porosity (65%), ultrasonic velocities (Vp = 2.93 and Vs = 1.72 km/s), and stiffness (8 GPa) compared to the slightly altered massive lavas (Fig. S1 – Supplementary Data).

Compared to slightly alunitic massive lavas, tuffs with slight alunitic alteration and strongly exposed to sulphur action show a reduced permeability (4E-17 m^2) and porosity (7 %), despite the lower density (2.4 g/cm^3), ultrasonic wave velocity (Vp = 2.61 and Vs = 1.56 km/s), UCS (27 MPa) and stiffness (11 GPa). In addition to alunite, sulphur-bearing minerals are believed to fill open spaces within the rocks, contributing to their weakening and low density. Breccias are present either with a moderate or high degree of alteration. When moderately altered by alunite, breccias show a very low porosity (3 %), which is expected as these rocks are highly fractured, and secondary minerals tend to precipitate in their open spaces. But density decreases for a high degree of alteration, and porosity increases to 27 % as a probable result of dissolution. However, stiffness remains similar between breccias with moderate and high degrees of alteration. Kennedy et al. (2020) suggest that altered breccias within a volcano's conduit experience rapid variations in effective pressure. These fluctuations enable time-variable fluid movement, outgassing, and geophysical changes at the surface. When moderately altered, tuffs share identical values to breccias in P-wave velocity and density. However, tuffs can have a significant porosity (40%) when moderately affected by alunite, decreasing to 33 % when highly altered, probably due to minerals' precipitation. UCS values are very low (13 MPa) for highly altered tuffs and can reach the lowest results (3 MPa) for a complete alteration. For alunitic rocks with undefined alteration degrees, tuffs exhibit identical physical properties to moderately alunitic tuffs. Furthermore, unconsolidated pyroclasts have higher porosities (51 %) and permeabilities (3E-12 m^2) than pyroclastic rocks, evidencing the influence of compaction on the physical parameters.

In general, lavas exhibit a porosity increase of 1.5 to eight times and a weakening factor of 5.2 times with increasing alunitic alteration. On the other hand, breccias can increase porosity nine times, while tuffs only 1.3 times. In contrast to lavas, variations in physical and mechanical properties in fragmental rocks are influenced by the prevailing process (dissolution or precipitation) during increasing alteration, as described in the literature (Mielke et al., 2015; Mordensky et al., 2018; Kanakiya et al., 2021; Weydt et al., 2022). Furthermore, regardless of the degree of alunitic alteration, lava rocks exhibit greater stiffness and mechanical competence compared to fragmental rocks. However, this trend does not necessarily apply to all physical and dynamic properties.

Oxidation (Fig. 10) correlates with a porosity of 18% and results in denser rocks (2.68 g/cm^3), exhibiting higher seismic wave velocities (*V*p = 3.53 km/s and *V*s = 2.43 km/s) compared to alunitic facies. These findings align with the described effects of oxidation, wherein oxides and hydroxides, dense minerals (Fig. 6), occupy open spaces (pores and discontinuities) and replace the primary mineralogy (Abdel-Aal, 1978). While this review does not provide UCS values for oxidation, Callahan et al. (2019) observed that the presence of hematite (alongside chlorite and calcite) leads to a weakening of the rock compared to its unaltered state. This review focuses solely slightly oxidised andesites and ignimbrites (Weydt et al., 2022), among which the latter exhibits higher porosity (33%) and lower P-wave velocity (2.93 km/s) than oxidised andesites (n = 4 % and Vp = 4.14 km/s). Compared to unaltered andesites and the fresh group of ignimbrite and tuffs (Section 3), porosity is lower for oxidised ignimbrites and andesite lavas, with the latter reaching the lowest porosity (4 %) and the highest bulk density (2.71 g/cm^3). Oxidised ignimbrites have higher porosities (33 %) than the other hydrothermal alteration facies, but the highest bulk density (2.64 g/cm^3).

4.2.2 Argillic hydrothermal alteration

Argillic facies has different effects depending on which sub-facies it combines with and is highly heterogeneous as can be observed in Fig. 10. However, such heterogeneity is expected to be minimised by increasing the temperature of the system (Ladygin et al., 2000). Rocks in argillic facies have a porosity from 11% to 34 %, bulk density from 1.54 to 2.65 g/cm^3, P-wave velocity from 2.62 to 3.87 km/s, strength from 16 to 69 MPa (UCS) and 2 to 7 MPa (ITS), and elastic properties from 5 to 29 GPa (E_d) and 2 to 12 GPa (E_s). When clay minerals associate with oxides ("argillic + oxidation" facies), a slight increase in strength, stiffness, and porosity occurs compared to a rock in the argillic facies alone, while ultrasonic wave velocities and bulk densities remain similar. The most significant changes take place when silica minerals ("argillic + silicic + oxidation" sub-facies) and zeolites ("argillic + zeolitic" sub-facies) are assembled with clay minerals, leading to the lowest values of UCS (16-22 MPa) and highest values of porosity (32-34 %) of this type of alteration. The stiffness, density, and ultrasonic wave reduction also occur for the "argillic + silicic + oxidation" sub-facies. Conversely, transitioning to the propylitic facies results in rocks exhibiting higher strength, density, P-wave velocity, and lower porosity compared to those solely affected by clay minerals. According to Fig. 10, the combination of silicic and propylitic facies with other sub-facies can be responsible for the "poor quality" of the rocks (more porous and less resistant), equivalent to the effect of argillization.

The progressive increase in the degree of hydrothermal alteration that affects various rock types within the argillic facies (Fig. 12) exhibits similarities to alunitic alteration. When clay minerals alter dense rocks, intrusive rocks experience a slight increase in porosity (10-12%) and permeability (2E-16), accompanied by weakening (UCS = 101 MPa¸ E_d – 26-28 GPa). Additionally, there is a reduction in density (2.36 -2.52 g/cm^3) and P-wave velocity (3.46 - 4.12 km/s) compared to their equivalent unaltered counterpart. The variations from slight to high argillization do not appear significant for intrusive rocks, which are less competent under slight argillization. Andesite lavas span from slight to high argillic alteration. Similarly to intrusive rocks, their porosity and permeability are increased and reach higher values (19 %, 1E-13 m^2) for the highly altered term, with density (2.05 g/cm^3) and P-wave velocity (1.67 km/s) being reduced compared to unaltered and slightly altered andesites. Andesites experience a progressive weakening and loss in cohesion with the increase of argillic alteration, reaching UCS = 90 MPa when moderately to highly altered. Trachytes share a similar trend as andesitic lavas since they become more porous (32 %), less dense (1.65 g/cm^3), competent (UCS = 17 MPa), stiff (E_d = 3 GPa and E_s = 2 GPa), and cohesive (c = 3 MPa) when highly to fully altered by clay minerals. Compared to their unaltered homologous, trachytes increase their porosity three times and weaken seven times, a much higher difference than in andesites. This difference is attributed to the alkalis content, as feldspars are more prone to argillization. Furthermore, texture (trachytic) and microstructure (higher initial porosity than other lavas) can also contribute to the ease of alteration development. Conversely, alunitic facies appears to have a major weakening effect on andesites rather than argillic alteration. Rhyolite and basalt lavas are described in an undefined degree of alteration. Argillic basalts exhibit increased porosity and reduced density, P-wave velocity, and stiffness compared to unaltered basalts. Furthermore, transitioning from argillic to propylitic facies tends to increase the porosity of basalts by 7 %, while the opposite stands for rhyolite lavas, with a porosity reduction of 7%. Basalts reach their maximum value of porosity (26 %) when zeolites combine with clay minerals (Fig. S1). Argillic rhyolites have a porosity and stiffness similar to argillic basalts. However, since the degree of alteration is not defined, no clear conclusion can be drawn regarding the content in SiO_2, i.e. if evolved lavas are more prone to alteration. Compared to unaltered lava breccias, moderately argillic lava breccias display an increase in porosity to 43% and a decrease in bulk density to 1.66 g/cm^3. UCS is also reduced to 13 MPa. However, highly altered lavas breccias become less porous (18 %), denser (2.12 g/cm^3) and stronger (34 MPa) than when moderately altered. Increasing argillization on dense and fractured rocks like lava breccias does not have a linear progression. High argillization of lava breccias appears to promote the complete sealing of the fractures, enhancing the rock's quality. Furthermore, the complete infilling of fractures prevails over the replacement and precipitation of soft clay minerals (e.g. smectite), which enhances microstructural heterogeneity of a dense lithotype (Franzson et al., 2010; Heap et al., 2016; Peng et al., 2017; Xu et al., 2020; Heap et al., 2021; Heap et al., 2022b). Hydrothermal vein failure is critical in destabilising a larger volcanic rock volume (Mordensky et al., 2022). In this review, hydrothermal veins associate with advanced argillic alteration that originates kaolinite, albite, and minor smectite (Mordensky et al., 2018). Hydrothermal veins are similar to highly altered lava breccias in terms of porosity, permeability, P-wave velocity, bulk density, and stiffness, showing higher UCS (54 MPa) than lava breccias (34 MPa). Both lithotypes materialise the sealing of open spaces and discontinuities, which is common in volcanic systems. Sealing can result from the deposition of fragmented volcanic rocks or the precipitation of secondary hydrothermal minerals (e.g., Browne, 1978; Farquharson et al., 2015; McNamara et al., 2016; Kendrick et al., 2016; Cant et al., 2018).

For argillic fragmental rocks (Fig. 12), tuffs undergo significant alterations due to clay formation, leading to a notable reduction in porosity from 54 % in its unaltered state to 9 % when slightly argillized. With a higher degree of alteration, the porosity decreases further to 3%. This increase in argillization correlates with increased density, P-wave velocity, and stiffness of tuffs, attributed to the origin of secondary minerals, primarily clays. The trend observed in tuffs is similarly seen in the ignimbrite and tuffs group, where porosity decreases from 54% in its unaltered state to 49% and increases to 52% with a higher degree of alteration. While permeability initially increases from the pristine state, it slightly decreases with increasing degrees of alteration, potentially limiting fluid pathways due to intensified compaction with depth (Kanakiya et al., 2021), acting as potential fluid flow barriers. However, this trend is not universal for all fragmental rock. Highly argillic pyroclastics maintain their porosity, bulk density, and P-wave velocity compared to their unaltered counterparts. Despite retaining their competence, highly argillic pyroclastics still have a low mechanical quality (UCS

= 10 MPa; ITS = 1 MPa; E_d = 3 GPa; c = 2 MPa). Argillic tuffs and tuffites, altered to an undefined intensity, roughly maintain their porosity (34 %) compared to their unaltered equivalent, while becoming slightly denser (1.74 g/cm^3) and stronger (UCS = 32 MPa). Notably, some volcaniclastic formations maintain their original porosity and high permeability more than others due to a mineral assemblage resistant to mechanical compaction and hydrothermal alteration (Stimac et al. 2015; Scott et al., 2023). Furthermore, as alteration progresses and macropores are filled by secondary minerals, micropores are formed within alteration minerals, particularly low-temperature clays (Franzson et al., 2010), potentially sustaining porosity over increasing hydrothermal alteration.

The presence of zeolites tends to enhance the porosity of hyaloclastites and within the "ignimbrite + tuff" group (Fig. S1 – Supplementary Data). However, this observation is not consistently applicable to all tuffs and tuffites and cannot be generalised for fragmental rocks. From unaltered to moderately argillic debris flows, there is a slight decrease in porosity of nearly 10 %, with permeability decreasing to 6 E-15 m^2, density increasing to 1.99 g/cm^3, and P-wave velocity decreasing to 2.20 km/s, following a trend similar to that observed in tuffs.

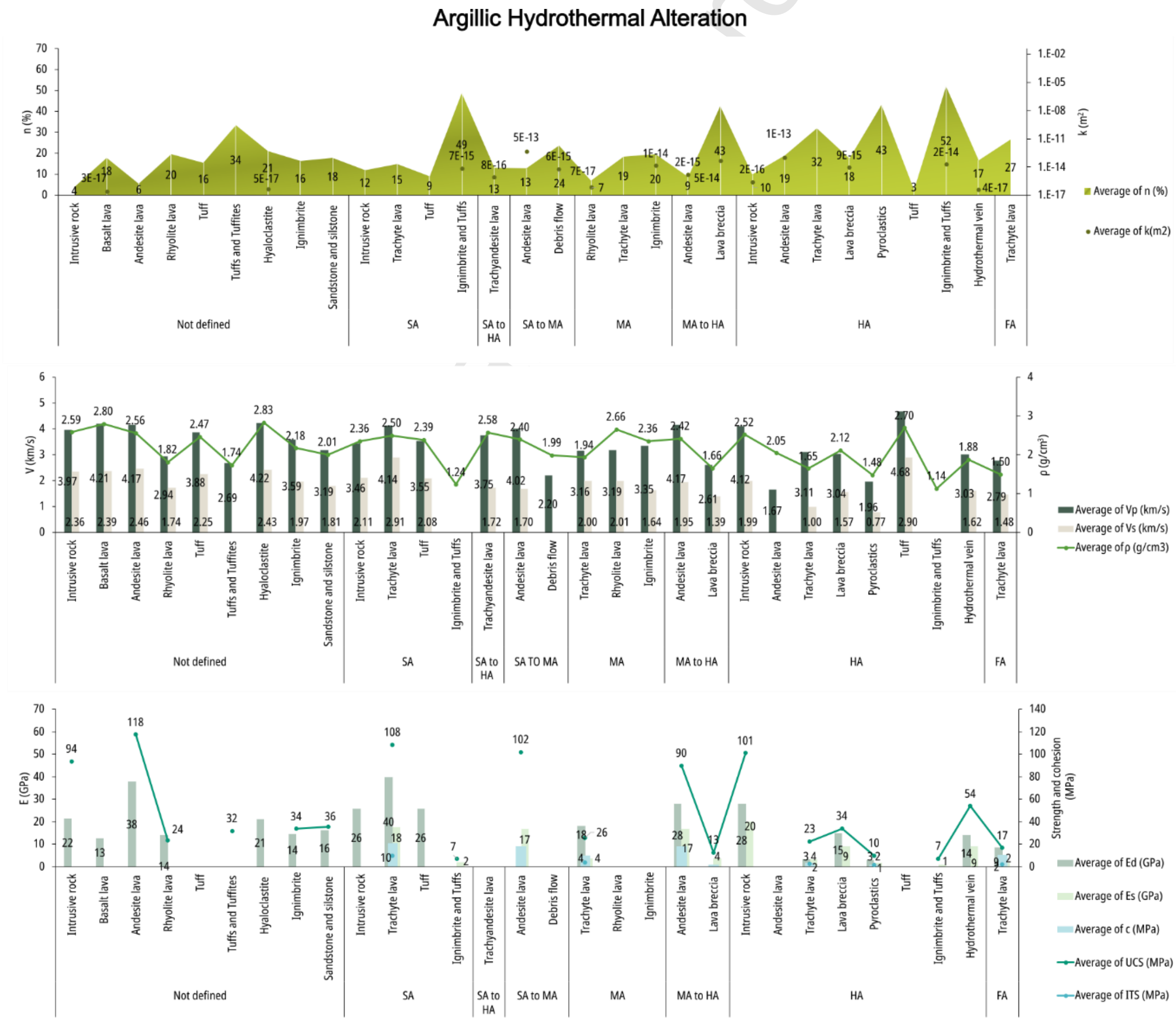

Fig. 12 Effect of argillic hydrothermal alteration facies on physical and mechanical properties along different hydrothermal degrees and per rock type (U – unaltered; SA – slightly altered; MA – moderately altered; HA – highly altered; FA – fully altered). Based on the compiled data (Table S1 – Supplementary Data; Franzson & Tulinius, 1999; Ladygin et al., 2000; Nasimov et al., 2005; Pola et al., 2012, Pola et al., 2014; Frolova et al., 2014; Mayer et al., 2015; Heap et al., 2015;

Siratovich et al., 2014; Wyering et al., 2014; Mayer et al., 2016; Siratovich et al., 2016; Cant et al., 2018; Mordensky et al., 2018; Navelot et al., 2018; Dúran et al., 2019; Farquharson et al., 2019; Heap et al., 2019a; Heap et al., 2020; Gibert et al., 2020; Heap et al., 2021; Kennedy et al., 2020; Nono et al., 2020; Kanakiya et al., 2021; Weydt et al., 2022; Scott et al., 2022; Kanakiya et al., 2022; Darmawan et al., 2022; Schaefer et al., 2023; Scott et al., 2023).

Sedimentary sandstone/siltstone (Wyering et al., 2014) with an alteration facies transiting from argillic to propylitic produces porosities (18 %) lower than "argillic + propylitic" tuffs, exhibiting a *Vp* of 3.19 km/s and a bulk density of 2.01 g/cm^3, that associated with intermediate elastic and strength properties (E_d~22 GPa; UCS = 43 MPa).

Generally, the impact of argillization on lavas has a linear trend with increasing alteration degree, increasing permeability and porosity, while strength is reduced. Higher alkalis content of lavas relate with a greater reduction in the competence and an increase in porosity when affected by clay minerals. Notwithstanding, the influence of argillic facies on lava breccias and fragmental rocks is opposite, tending to either enhance or maintain the competence of these lithotypes while decreasing or preserving their porosity. It is noteworthy that this non-uniform variation in physical and mechanical properties may partly arise from differences in the rock's composition (Frolova et al., 2014), although most fragmental rocks of the compiled data are rhyolitic. Regardless of the degree of alteration, dense rocks typically display higher competence than fragmental rocks.

4.2.3 Propylitic hydrothermal alteration

The coexistence of argillic and propylitic facies (Fig. 10) produces porosities of 20 % and a UCS inferior to that of the propylitic facies (alone or in combination with other sub-facies). The same applies to density and seismic wave velocities. The propylitic facies is described as having a variable effect on the physical and mechanical properties of the host rocks, as it may comprise softer (low-temperature propylites) or harder minerals (medium-high-temperature propylites) and show significant welding due to pressure and depth, especially in pyroclastic rocks. Notwithstanding, propylitic facies is generally associated with an increase in strength compared to argillic facies due to the secondary mineral assemblages formed (Fig. 10), whereas zeolites and clays weaken the rock (in agreement with Heap et al., 2012; Frolova et al., 2014; Heap et al., 2018), even when they are in the propylitic zone. UCS has a significant variation within the propylitic facies (Fig. 10), reaching the highest and lowest values. For the propylitic facies alone, UCS = 74 MPa is associated with significant stiffness (highest values of E_s and E_d), which is attributed to the presence of "stronger" secondary mineral assemblages (e.g., quartz, wairakite, calcite, epidote, albite). However, porosity, bulk density, and seismic wave velocities are intermediate compared to the other groups of hydrothermal alteration. It is confirmed that these mineral assemblages influence the mechanical behaviour more than the physical and dynamic properties. The presence of zeolites combined with the propylitic facies (Fig. 10) also produces this effect – UCS reaches one of the lowest values (UCS = 5 MPa), as well as bulk density (1.62 g/cm^3), while porosity is high (40%). From "argillic + zeolitic" sub-facies to "propylitic + zeolitic" sub-facies, porosity increases by 10 %, and strength reduces by 17 MPa. Notably, "argillic + zeolitc" facies comprise ignimbrites, tuffs, tuffites, hyaloclastites, and basalt lavas. Considering only tuffs and tuffites, the rocks are weaker for the argillic facies than the propylitic one. The increasing temperature effect on the tuffs has been previously assessed. The existence of thermally unstable zeolites in the rock matrix could cause a reduction in strength (Heap et al., 2012), and with increasing thermal stressing temperatures, the tuffs increase permeability and reduce their ultrasonic wave velocities and Young's modulus (Heap et al., 2014).

Carbonates (in "propylitic + carbonation" sub-facies; Fig. 10), which often replace the primary mineralogy and form hydrothermal veins, result in intermediate values of porosity (18 %) and UCS (47 MPa)bulk densities (3.23 g/cm^3) and P-wave velocities (3.23 km/s) of the propylitic facies. Calcite, which is not a dense and hard mineral (Fig. 6), can occupy fractures and pores, which could explain the moderate porosity and density. Albite increases the strength of the rocks within the propylitic facies. While this is not verified for the group "zeolitic + albitic", where zeolites predominate in propylitic facies, albite leads to the highest values of UCS, P-wave velocity, and bulk density.

In considering the effect of the degree of alteration and rock type (Fig. 13), propylitic andesite lavas have a consistent porosity compared to their unaltered counterparts. The maximum porosity of 16 % is observed in highly propylitic andesites, slightly inferior to the 19 % recorded for highly argillic andesites. When moderately to highly altered, andesite lavas have a strength of 125 MPa, representing 1.2 times reduction in UCS in respect to unaltered andesites, yet still exhibiting the highest strength among all altered andesitic lavas. However, stiffness remains similar from fresh to propylitic andesites, representing the highest value among altered andesitic lavas. Propylitic intrusive rocks, with an undefined pervasiveness of alteration, show lower porosity (2 %), higher density (2.96 g/cm^3) and similar P-wave velocity (4.17 km/s) and permeability (7E-17 m^2) than unaltered intrusive rocks. Conversely, their stiffness is significantly reduced from 39 GPa to 15 GPa. While physical properties are largely retained from the unaltered state to the propylitic facies, mechanical parameters are notably reduced. Propylitic basalts demonstrate lower porosity (9 %) and higher density (2.96 g/cm^3) than argillic basalts, attributed to the development of harder and denser minerals by the propylitic alteration.

In propylitic fragmental rocks (Fig. 13), moderately altered tuffs within "propylitic + carbonation" sub-facies associate with higher porosity (14 %), lower density (2.31 g/cm^3), P-wave velocity (.3.21 km/s), and stiffness (21 GPa) than argillic tuffs. Highly propylitic debris flow is more porous but less permeable than a slightly to moderately argillic debris flow. These differences are primarily attributed to the degree of alteration, with the type of alteration exerting a minor control in this lithology. In addition, debris flows are susceptible to changes in the pore network shape (Navelot et al., 2018), contributing to variable evolution with increasing alteration. The mechanical and physical values for argillic and propylitic hyaloclastites are similar for lithologies without a specified degree of alteration. Propylitic tuffs and tuffites (degree of alteration not specified) effectively demonstrate the effect of the hydrothermal sub-facies (Fig. S1), with albitic and silicic alterations enhancing the strength of these rocks, while argillic and carbonation tend to reduce their competence. Lower values are attained when zeolites are present.

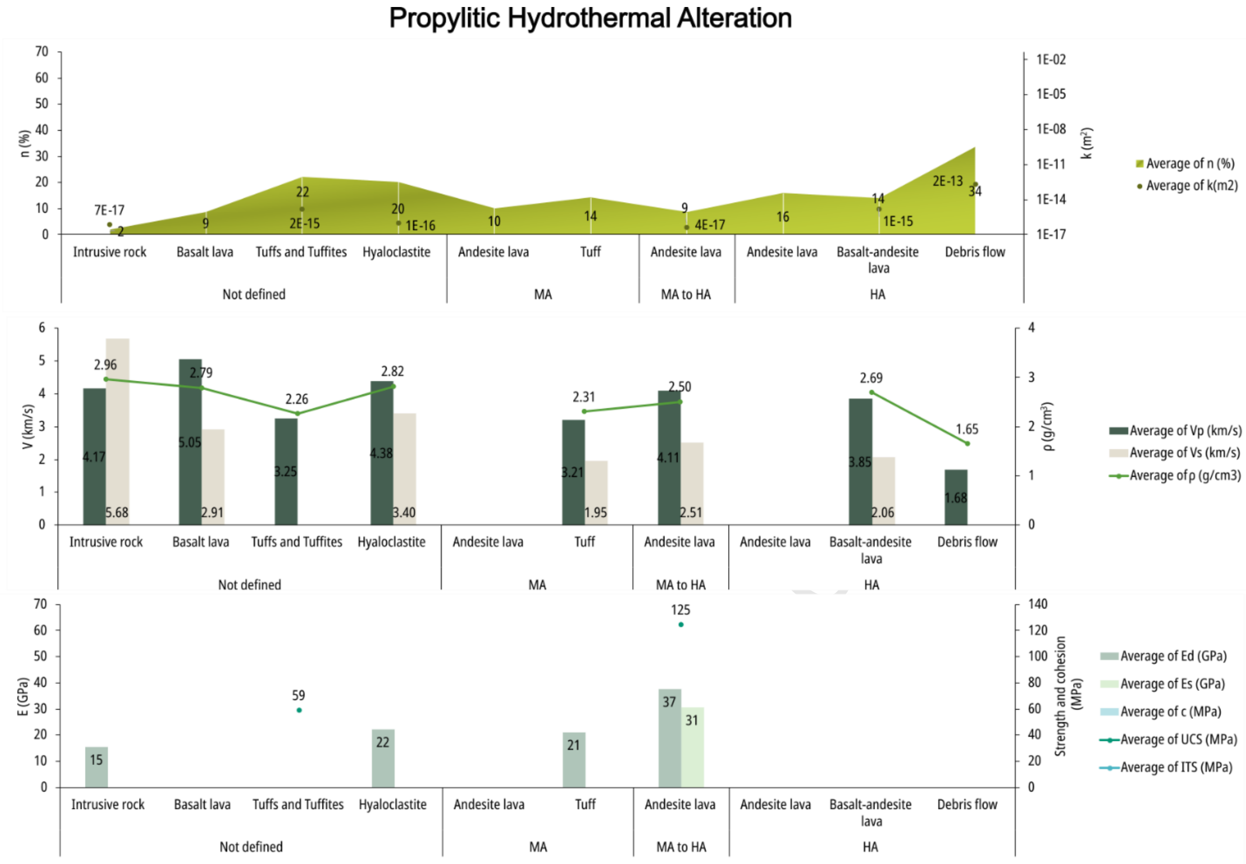

Fig. 13 Effect of propylitic hydrothermal alteration facies on physical and mechanical properties along different hydrothermal degrees and per rock type (U – unaltered; SA – slightly altered; MA – moderately altered; HA – highly altered; FA – fully altered). Based on the compiled data (Table S1 – Supplementary Data; Franzson & Tulinius, 1999; Ladygin et al., 2000; Nasimov et al., 2005; Pola et al., 2012, Pola et al., 2014; Frolova et al., 2014; Mayer et al., 2015; Heap et al., 2015; Siratovich et al., 2014; Wyering et al., 2014; Mayer et al., 2016; Siratovich et al., 2016; Cant et al., 2018; Mordensky et al., 2018; Navelot et al., 2018; Dúran et al., 2019; Farquharson et al., 2019; Heap et al., 2019a; Heap et al., 2020; Gibert et al., 2020; Heap et al., 2021; Kennedy et al., 2020; Nono et al., 2020; Kanakiya et al., 2021; Weydt et al., 2022; Scott et al., 2022; Kanakiya et al., 2022; Darmawan et al., 2022; Schaefer et al., 2023; Scott et al., 2023).

4.2.4 Silicic hydrothermal alteration

Generally, silicification (Fig. 10) produces the following average values: porosity varies from 11 % to 42 %, bulk density from 1.70 to 2.61 g/cm^3, P-wave velocity from 2.24 to 4.33. km/s, UCS from 7 to 113 MPa and E_s from 2 to 14 GPa. Overall, the silicic facies displays the highest value of porosity (42%) compared to all other facies, while strength, bulk density, and P-wave velocity values are often intermediate regarding argillic and propylitic facies. Silicic facies is characterised by silica minerals like opal, chalcedony, tridymite, and quartz. Advanced silicification is marked by crystalline (or recrystallised) quartz, typically found in hydrothermal veins and often associated with secondary adularia. These minerals constitute the "advanced silicic + potassic" sub-facies and are produced at higher temperatures and depths, with adularia probably originating from a boiling zone. Compared to other silicic facies, the advanced silicic and advanced silicic + potassic facies, with similar results for physical and mechanical properties, strengthen and stiffen altered rocks, increasing their density and P-wave velocity, while reducing porosity to the lowest values observed in the silicic facies. Rocks from these horizons have hard hydrothermal mineral assemblages that precipitate in the fractures, effectively sealing them and reducing porosity. The effects of silicification have been determined by Heap et al. (2020), who assessed the physical and mechanical properties of the Ohakuri ignimbrite deposit (rhyolitic ignimbrite and tuffs) (Taupo Volcanic Zone) for varying hydrothermal facies, both with the same degree (highly altered). The argillic facies produces rocks with a porosity of 49 %, a density of 1.24 g/cm^3 and a permeability of 7E-15 m^2. For the same lithotype, the advanced silicic facies enhances porosity (52 %) and permeability (1.85E-14 m^2) while reducing the density (1.14 g/cm^3). However, silicification increases the UCS (47 MPa) and stiffness (14 GPa) of the rocks compared to the same lithotypes subjected to argillic alteration (UCS = 7 Mpa; E_s = 1 GPa). Silicification affects mechanical properties, in contrast to smectite alteration, which does not seem to influence strength and stiffness, as observed by Heap et al. (2020).

For different rock types undergoing silicification (Fig. 14), the silicified lavas (n = 15 %; k = 1E-15 m^2; ρ = 2.69 g/cm^3; Vp = 3.93 km/s) represent highly altered lavas rich in crystalline quartz. Generally, their physical properties remain similar to those of unaltered lavas, except for a slightly higher porosity. Silicified lavas, along with hydrothermal veins and lava breccias, are often linked to the sealing of open spaces and discontinuities by quartz. These lithotypes are typically encountered in several volcanic settings (e.g., Browne, 1978; Farquharson et al., 2015; McNamara et al., 2016; Kendrick et al., 2016; Cant et al., 2018; Kennedy et al., 2020). Fully altered andesites ("silicic + argillic + alunitic" sub-facies) display higher porosity (42 %) than fully alunitic andesite lavas, evidencing the deleterious effect of clays and alunite when combined with silica.

For fragmental rocks (Fig. 14), silicified ignimbrite and tuffs (n = 34 %; k = 7E-16 m^2; ρ = 1.73 g/cm^3; UCS = 47 MPa) are less porous and permeable, and denser than their unaltered equivalent. The sealing of pores and fractures by silica possibly enhances their competence, as verified by several authors (Ladygin et al., 2000; Lutz et al., 2011; Nasimov et al., 2005; Frolova et al., 2014; Weydt et al., 2022). Highly silicified tuffs display a reduced porosity (4 %) and higher stiffness (38 GPa) than highly alunitic tuffs. Tuffs and tuffites group comprises both silicic and advanced silicic alteration (Frolova et al., 2014). Within this group, advanced silicification (recrystallised quartz ± adularia), typical of higher depths and temperatures, promotes reduced porosity, increased density, P-wave velocity and UCS than tuffs and tuffites from other silicic facies (with silica polymorphs), typical of lower temperatures (Fig. S1; in Fig. 14, the combined effect of these sub-facies is considered). It is verified that propylitic (+ albitic) and advanced silicic tuffs and tuffites are strengthened to UCS values in the order of those for unaltered dense rock (Fig. S1 – Supplementary Data).

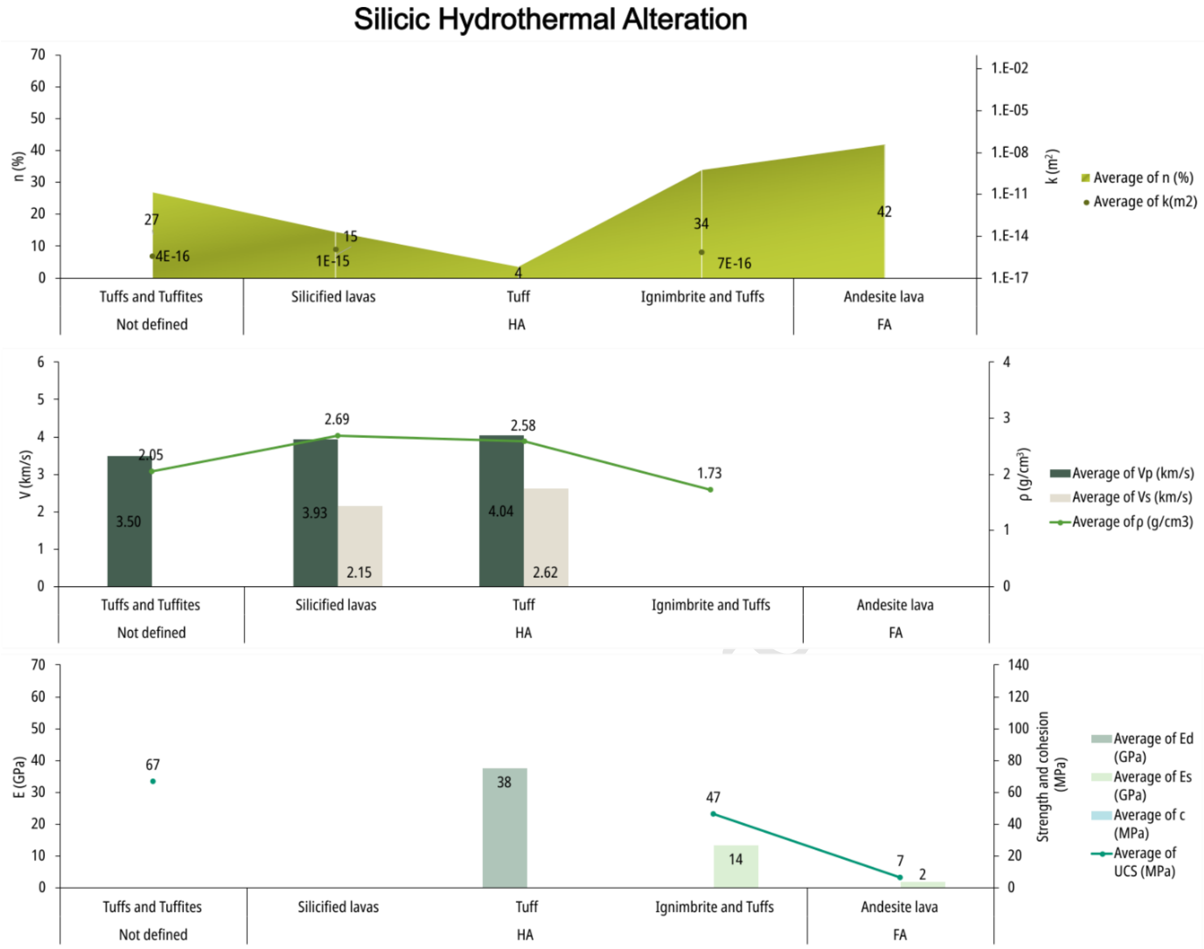

Fig. 14 Effect of silicic hydrothermal alteration facies on physical and mechanical properties along different hydrothermal degrees and per rock type (U – unaltered; SA – slightly altered; MA – moderately altered; HA – highly altered; FA – fully altered). Based on the compiled data (Table S1 – Supplementary Data; Franzson & Tulinius, 1999; Ladygin et al., 2000; Nasimov et al., 2005; Pola et al., 2012, Pola et al., 2014; Frolova et al., 2014; Mayer et al., 2015; Heap et al., 2015; Siratovich et al., 2014; Wyering et al., 2014; Mayer et al., 2016; Siratovich et al., 2016; Cant et al., 2018; Mordensky et al., 2018; Navelot et al., 2018; Dúran et al., 2019; Farquharson et al., 2019; Heap et al., 2019a; Heap et al., 2020; Gibert et al., 2020; Heap et al., 2021; Kennedy et al., 2020; Nono et al., 2020; Kanakiya et al., 2021; Weydt et al., 2022; Scott et al., 2022; Kanakiya et al., 2022; Darmawan et al., 2022; Schaefer et al., 2023; Scott et al., 2023).

Marble and skarn (Fig. 10) are metamorphic facies whose physical properties were determined by Weydt et al. (2022) for the rocks of the Los Humeros geothermal field. They are highly altered and have very low porosity (1-2 %) and intermediate density (2.64 and 2.72 g/cm^3 for skarn and marble, respectively). These results are in line with previous observations in the literature describing altered metamorphic rocks with less than 2 % porosity and negligible permeability (Lutz et al., 2011).

4.2.5 Correlations between physical and mechanical properties for hydrothermally altered rocks

Some correlations between physical and mechanical properties are presented in Fig. 15. Compared to Fig. 3 and Fig. 5, which depict unaltered rocks, Fig. 15 shows more scattered data and the variable effect of hydrothermal alteration type, which is also influenced by other factors (e.g., rock type and degree of alteration). Correlations are variable, resulting in either low (below 0.50) or high (above 0.80) R^2 values. Nevertheless, density and porosity maintain the negative linear correlation, with a lower R^2 than the correlation obtained for unaltered terms. P-wave velocity also preserves the positive linear correlation with bulk density but the correlation is poor for altered rocks. UCS and porosity also maintain the nonlinear correlation established for a good R^2 (0.81) but inferior to the one observed for the unaltered rock types (0.98). The linear positive correlations are maintained between ITS and UCS and E_s and UCS with the establishment of hydrothermal alteration. Wyering et al. (2014) state that some correlations (porosity vs density, UCS vs *E*) do not change with hydrothermal alteration, which is confirmed in this review. In their turn, Siratovich et al. (2014) and Weydt et al. (2022) consider physical and mechanical properties independent of the alteration mineralogy of the samples. The compiled data show that the hydrothermal facies contain many sub-facies that produce this variability, sometimes erasing the observed trends and producing lower R^2 than for unaltered/fresh rocks. Furthermore, the several sub-facies overlap, making distinguishing between the alunitic, argillic, and propylitic facies difficult.

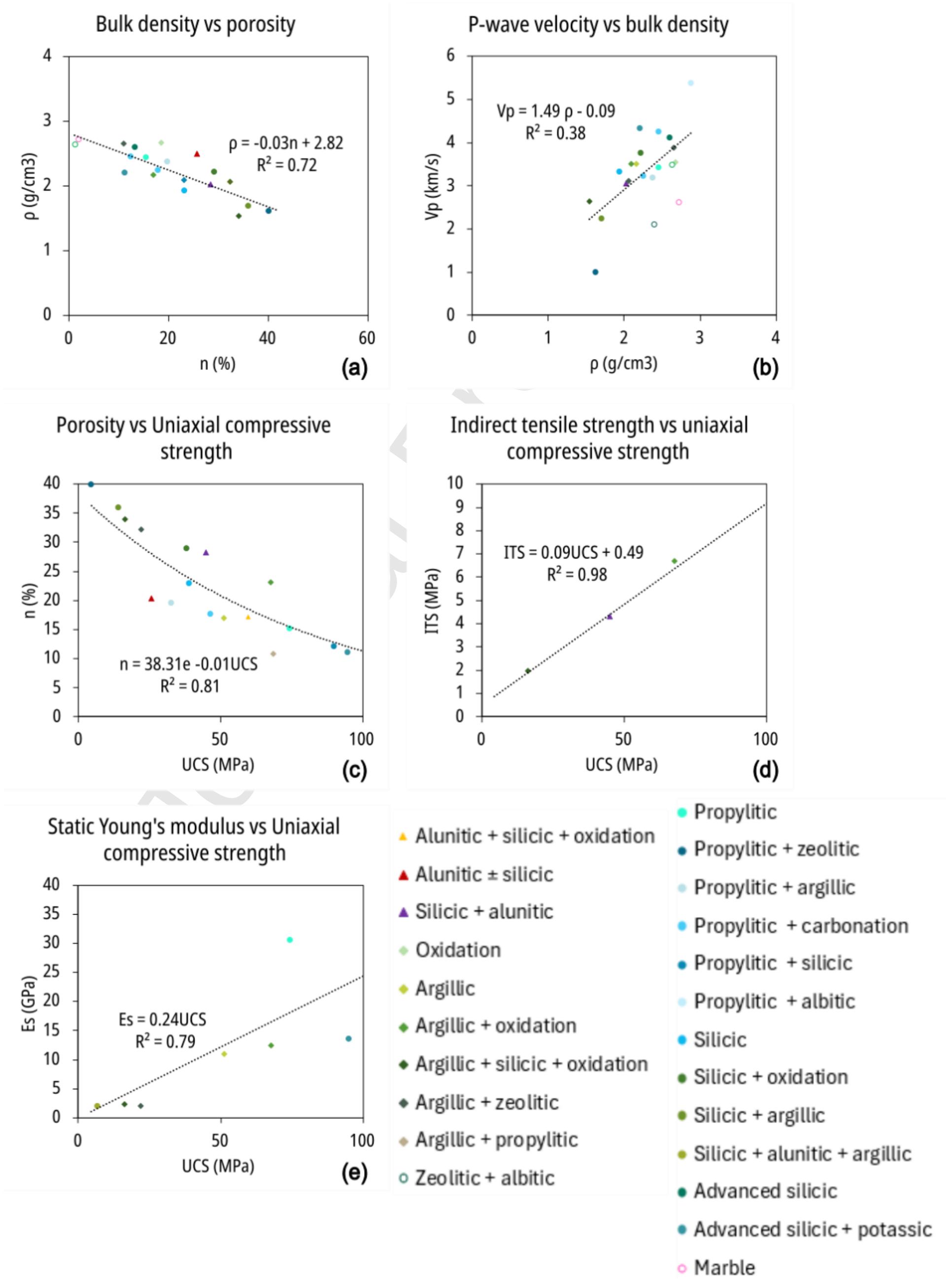

Fig. 15 Generalised correlation between physical and mechanical properties for distinct facies and sub-facies of hydrothermal alteration.

4.3 Summary and discussion of the effect of hydrothermal alteration degree and type on rock properties

Soft minerals, prevalent at lower temperatures (Fig. 6), were expected to partially weaken the host rock (e.g., Wyering et al., 2014; Frolova et al., 2014; Pola et al., 2014; Mordensky et al., 2018; Farquharson et al., 2019) and enhance microporosity within their structure (Franzson et al., 2010). Changes in porosity and permeability were expected to be variable (e.g., Mordensky et al., 2018; Villeneuve et al., 2019; Scott et al., 2023), with a loss of mechanical competence not necessarily implying an increase in porosity and vice versa for permeability. For example, Kanakiya et al. (2022) demonstrated that lavas with similar porosity can exhibit markedly different permeabilities, and Cant et al. (2018) showed that porosity and permeability variability arises from the nature of the pore space (pore-dominated, microfracture-dominated, or a combination of both). Various sub-facies emerge with pH and fluid temperature changes, significantly impacting rock behaviour within the main facies (e.g., argillic, propylitic, silicic). The interaction of the main facies with other alteration types, influenced by rock type and multiple hydrothermal events (Weydt et al., 2022), introduces data variability that disrupts established correlations under unaltered conditions. In addition to the degree and type of hydrothermal alteration, the influence of the host rock is expected to be shaped by the accumulation of damage and the degree of healing, as proposed by Callahan et al. (2019).

The degree of alteration determines the prevailing competing mechanism, whether net dissolution and mineralogy replacement or precipitation of secondary minerals. This observation is consistent with the findings of various authors (Mielke et al., 2015; Cant et al., 2018; Mordensky et al., 2018; Kennedy et al., 2020; Kanakiya et al., 2021; Weydt et al., 2022). For instance, Mielke et al. (2015) noted that progressive hydrothermal alteration reduces the porosity of sandstone and ash tuff, with contrasting effects on permeability: increasing for ash tuff but decreasing for sandstone. Moreover, both mineral dissolution and pore fracture-filling precipitation control mechanical properties throughout increasing hydrothermal alteration degree. Subsequently, the hydrothermal alteration degree may not consistently correlate with physical and mechanical properties. Some slightly altered samples exhibit higher strength and stiffness than highly altered equivalents, consistent with the findings of Sigurdsson et al. (2000) and Kanakiya et al. (2022).

The extent to which alteration develops cannot be dissociated from the type of hydrothermal alteration. For each facies of hydrothermal alteration, variable physical and mechanical properties evidence the overlap between the influence of rock type and hydrothermal alteration intensity.

The previous sections confirm that rock type is a primary controller of the change in physical and mechanical properties with different degrees and types of alteration, which is in line with the conclusions established by Mordesnky et al. (2018). Altered rocks inherit microstructural, chemical, and textural characteristics from their unaltered counterparts. Regardless of lithology, the microstructure plays a fundamental role in strength and alteration evolution, as highlighted by Pola et al. (2012), Pola et al. (2014), and Cant et al. (2018)

The prevalent influence of either porosity or alteration on strength remains unclear (Heap et al., 2022b). Additionally, the influence of rock type is particularly pronounced at shallower depths, consistent with the existing literature (Browne, 1978). Rocks from shallow and low-temperature sections of certain geothermal fields (e.g., Ngatamariki, Rotokawa, and Kawerau geothermal fields; TVZ; Wyering et al., 2014) exhibit higher porosity, lower saturated density, slower seismic wave velocity, and weaker properties compared to samples from deeper and higher-temperature sections of the fields (Wyering et al., 2014).

The pre-existence of fractures and their complete or partial filling significantly influences the evolution of physical and mechanical properties, independent of hydrothermal alteration facies—an observation consistent with the literature (Siratovich et al., 2014). The mechanical behaviour of fractures is known to be chemically dependent and decreases with acidity. Mohtarami et al. (2017) subjected pure andesite, porphyritic andesite, and tuff andesite to an acid attack and verified a selective chemical dissolution of the more reactive minerals. The degradation of fracture asperities is influenced by competing phenomena, such as pressure solution and free-face degradation. Then, despite the chemical dissolution, cohesion, and shear strength of rocks along fractures might be maintained.

In the context of rock failure mechanisms, the transition from a dilatant to compactant behaviour (Heap & Violay, 2021) is contingent upon factors such as lithology, texture, and hydrothermal alteration (Siratovich et al., 2016; Mordensky et al., 2018; Mordesnky et al., 2022; Schaefer et al., 2023). This transition holds critical significance in understanding the eruptive behaviour of a volcanic system (e.g. Kennedy et al., 2020). Clay minerals have been identified as catalysts for ductile behaviour (Siratovich et al., 2016; Mordesnky et al., 2018; Mordesnky et al., 2019). Altered rocks tend to transition to ductile deformation and likely compaction at lower confining pressures, although this is porosity-dependent (Siratovich et al., 2016; Mordensky et al., 2022). Altered lavas and fresh lava breccias from Mt. Ruapehu volcano exhibit brittle deformation under low confinement, unlike altered lava breccias, which display ductility under similar confinement conditions (Schaefer et al., 2023). Despite being dilatant, altered lavas tend to reach a lower peak stress or experience higher strains than their fresh counterparts (Siratovich et al., 2016). High-porosity rocks may undergo net porosity reduction despite a brittle failure mode (Siratovich et al., 2016; Mordensky et al., 2022). Cohesion, akin to strength, is influenced by rock type, texture, and the extent of hydrothermal alteration, with cohesion generally higher in lavas than in lava breccias or pyroclastic rocks and decreasing with increasing alteration, as observed by Schaefer et al. (2023). On the other hand, the intact rock parameter (Villeneuve & Heap, 2021), which has a clear relationship with the friction angle, demonstrates a weak correlation with porosity and no correlation with rock texture, type and degree of alteration (Schaefer et al., 2023).

Table 1 provides a comprehensive matrix summarising changes in physical and mechanical properties and focusing on well-documented rock groups (*n, ρ, k; Vp, UCS,* E_s).

Table 1 Overview matrix of the analysed compiled data. Green – highest values (and lowest porosity and permeability); Yellow – intermediate values; Red – lowest values (and highest porosity and permeability). U – unaltered; SA - slightly altered; HA - highly altered; FA - fully altered; arg - argillic; prop - propylitic; sil - silicic; adv. sil. - advanced silicic; oxi - oxidation; al – alunitic; zeo – zeolitic; pot – potassic; alb - albitic.

Host rock	Degree (min)	Degree (max)		Type	
Intrusive rock	U	SA	HA	Arg	Prop
n (%)	4	12	10	11	2

ρ (g/cm^3)	2.65	2.36	2.52	2.44	3.03 (prop + arg)
k (m^2)	4E-17		2E-16	2E-16	7E-17
Vp (km/s)	4.77	3.46	4.12	3.79	4.20
UCS (MPa)	170		101	94 (arg + prop)	
E_s (GPa)	39		20	20	
Lava rocks	U	U to SA	HA	Al ± sil	
n (%)	8	2	16	11	
ρ (g/cm^3)	2.69	2.66	2.47	2.58	
k (m^2)	3E-17		3E-16	3 E-16	
Vp (km/s)	4.76	5.20	4.03	4.53	
UCS (MPa)	121		33	33	
Andesite lava	U	HA to FA		Variable	Variable
n (%)	8	12 to 16		42 (sil + al + arg)	4 (oxi)
ρ (g/cm^3)	2.64	2.07		2.23 (al +sil + oxi)	2.71 (oxi)
k (m^2)	6E-15	4E-12		1E-12 (al +sil+ oxi)	4E-17 (prop)
Vp (km/s)	4.10	2.38		3.47 (al + sil)	4.32 (sil + al)
UCS (MPa)	161	13		7 (sil + al + arg)	125 (prop)
E_s (GPa)	30	12		2 (sil +al +arg)	31 (prop)
Trachyte lava	U	HA to FA		Arg + ox + sil	
n (%)	11	32		29	
ρ (g/cm^3)	2.38	1.50		1.58	
Vp (km/s)	4.39	2.79		2.95	
UCS (MPa)	117	17		20	
E_s (GPa)	18	2		3	
Basalt lava	U	-		Arg (± zeo)	Prop + arg
n (%)	10			26	9
ρ (g/cm^3)	2.95			2.78	2.79
k (m^2)				3E-17	
Vp (km/s)	4.31			3.96	5.05
Lava breccia	U	MA	HA	Arg	
n (%)	28	43	18	30	
ρ (g/cm^3)	1.95	1.66	2.12	1.89	
k (m^2)	5E-13	5E-14	9E-15	3E-14	
Vp (km/s)	2.87	2.61	3.04	2.83	
UCS (MPa)	25	13	34	23	
E_s (GPa)	7	4	9	6	
Pyroclastics	U	HA		Arg + sil + oxi	
n (%)	38	43		43	
ρ (g/cm^3)	1.53	1.48		1.48	
Vp (km/s)	1.77	1.96		1.96	
k (m^2)	2E-12				
UCS (MPa)		10		10	
E_s (GPa)		2		2	
Breccia	SA	HA		Al ± sil	
n (%)	3	27		19	
ρ (g/cm^3)	2.56	2.48		2.52	
k (m^2)		6E-16		6E-16	
Vp (km/s)	2.54	2.66		2.60	

UCS (MPa)		29		29	
Ignimbrite + Tuff	U	HA		Arg (± zeo)	Adv. sil + pot
n (%)	54	43		52	34
ρ (g/cm^3)	1.03	1.43		1.14	1.73
k (m^2)	2E-13	1E-14		2E-14	7E-16
UCS (MPa)		27		7	47
E_s (GPa)		7		1	14
Tuff ± Tuffite	U	HA	FA	Prop + zeo	Variable
n (%)	36	18	44	40	12 (adv. sil)
ρ (g/cm^3)	1.56	2.56	1.23	1.60	2.88 (prop + alb)
k (m^2)	2E-15	1E-15		4E-15	5E-16 (prop + arg)
Vp (km/s)	2.04	3.97	1.59	1.00	5.38 (prop + alb)
UCS (MPa)	15	13	3	5	175 (prop + alb)
Debris Flow	U	SA	HA	Prop	Prop + Alb
n (%)	33	24	34	34	24
ρ (g/cm^3)	1.74	1.99	1.65	1.65	1.99
k (m^2)	5E-13	6E-15	2E-13	2E-13	6E-15
Vp (km/s)	2.02	2.20	1.68	1.68	2.20

Dense rocks (intrusive and lavas) are described as more prone to failure and net dissolution, developing fractures (e.g., Kanakiya et al., 2021), but less susceptible to alteration given their low initial porosity (e.g., Lagat et al., 2009; Cant et al., 2018). Hydrothermal alteration generally affects dense rocks by increasing porosity and decreasing density and strength when affected by alunitic, argillic, and silicic alterations, while propylitic counteracts by reducing porosity and enhancing strength. Dense rocks generally exhibit increased porosity and permeability alongside a decrease in other physical and mechanical properties with variations in the degree of hydrothermal alteration. Nevertheless, when porosity and permeability increase together, it is often not at the same rate, as it depends on pore shape, pore connectivity and alteration-related change (Bubeck et al., 2017; Kanakiya et al., 2022). Scott et al. (2023) verified that a rapid porosity closure, in response to a low degree of alteration in a lava flow, results in a more rapid permeability decrease, which constrains the alteration extent. Furthermore, Farquharson et al. (2019) studied andesites from Mt. Ruapehu subjected to an acid attack over one day to four months. These authors concluded that prolonged exposure of andesite to sulphuric acid results in mineral dissolution that alters the texture and microstructure of the rocks. This process widens pore throats and enhances pore connectivity (permeability and porosity increase) and strength, resulting in a weakening effect. Nevertheless, enigmatic porosity and permeability relationships might arise from the lava texture and structure since compact lava flows display high pore interconnectivity. In contrast, lavas typical from the outer margins comprise numerous isolated vesicles (Scott et al., 2023 and references therein).

Intrusive rocks are described by Cant et al. (2018) as microfracture-dominated samples with low connected porosity and permeability, the latter significantly decreasing with increasing confining pressure. Intrusive rocks are characterised by pronounced changes in physical properties, experiencing increased porosity and decreased density that suggests mineral dissolution with increasing alteration. The strength and stiffness of intrusive rocks decrease notably under argillic alteration, with reduced quality when slightly altered than highly altered. Propylitic facies acts opposite to argillic alteration, promoting the precipitation of harder minerals in fractures, which enhances the density of a rock.

When highly to fully altered, andesites have a reduced density and P-wave velocity, with the type of alteration exerting a more significant effect on porosity and mechanical properties. Alunitic facies, combined with silica minerals and oxidation, greatly increases porosity and permeability of an andesitic lava. Its competence decreases when silicic facies associates with alunitic and argillic alteration. Propylitic facies increases the strength and stiffness of andesite lavas, while oxidation significantly reduces their porosity and increases their bulk density.

Trachytes are significantly influenced by a high degree of argillic alteration, resulting in increased porosity and reduced mechanical properties for highly and fully altered states due to mineral dissolution. Thus, the alkalis content of lava determines how physical and mechanical properties vary with increasing intensity of argillic alteration. The physical and dynamic properties of basalts depend on the type of alteration, enhanced by the propylitic facies, while becoming more porous and less dense when affected by the argillic alteration. Lava breccias exhibit an opposing pattern to trachyte lavas, becoming less porous and more resistant with a higher degree of argillic alteration. The cause is attributed to precipitation and the complete infilling of fractures by secondary minerals.

Fragmental rocks have varying behaviour with hydrothermal alteration, as verified before by Pola et al. (2012) and Pola et al. (2014). These studies analysed lavas and pyroclastic rocks, and highlighted a decrease strength with increasing alteration, while friction angle and cohesion did not follow any linear correlation with increasing alteration degree. Cant et al. (2018) also investigated tuffs from the Ngatamaraki geothermal field, finding that the type of pore space within these rocks could be pore-dominated, fracture-dominated, or contain both. High-connected porosity and permeability occur for the first type of samples, while the pore-dominated samples have low connected porosity and permeability. Mixed group samples exhibited a wide range of porosity values, with relatively high permeability, moderately affected by increasing confining pressure.

Fragmental rocks, regardless of the type of alteration, consistently display higher porosities, lower densities, reduced seismic velocities, and weaker strength than lavas. However, the variations in porosity and strength tend to be lower than in dense rocks, possibly due to a microstructure more resistant to mechanical compaction and hydrothermal alteration (Stimac et al., 2015; Cant et al., 2018). In addition, rocks with high initial porosity tend to maintain relatively high permeability even under high-temperature alteration facies (Scott et al., 2023).

Argillic, alunitic, propylitic and zeolitic alterations contribute to reduced strength, density, and increased porosity and permeability. Albitic alteration within propylitic facies and advanced silicification combined with potassic alteration result in lower porosity and higher strength in fragmental rocks. For these latter types of alteration, the formation of harder hydrothermal minerals prevails over dissolution mechanisms, which are more common in shallower alteration types and slight degrees of alteration. When highly altered, regardless of the type of alteration, fragmental rocks tend to experience significant reductions in porosity and permeability due to the complete sealing of open spaces and fractures.

The susceptibility of pyroclastic rocks and breccias to high degrees of argillic and alunitic alterations is notable. Within the "ignimbrite + tuff" group, alterations either enhance or maintain strength and porosity. Advanced silicic alterations can notably strengthen the rock, while argillic alteration generally maintains physical properties with low strength and stiffness across various degrees of hydrothermal alteration, consistent with existing literature (e.g., Franzson et al., 2010; Scott et al., 2023).

Conversely, the degree of alteration has a clear impact on tuffs, with highly altered terms being less porous, denser, and more competent than fully altered terms. The influence of propylitic alteration combined with zeolites tends to diminish the quality of these rocks. However, advanced silicification and propylitic facies featuring albite formation enhance the quality of tuffs and tuffites.

Debris flow is greatly influenced by a high propylitic alteration alone, resulting in increased porosity and significantly strength reduction. In contrast, the "propylitic + albitic" facies contributes to the strengthening and increased density of the host rock, similarly to the effects observed in tuffs and tuffites.

The significance of fragmental rocks extends beyond their variability with hydrothermal modification; they are also known to potentially impede fluid flow and seal the conduit of a volcano (e.g. Kennedy et al., 2010; Mordensky et al., 2018; Kennedy et al., 2020). This characteristic has implications for increasing pore pressure and possibly contributing to erratic explosive behaviour (e.g. Heap et al., 2019a). Additionally, fragmental rocks can create an unusually shallow brittle-ductile transition by acting as a barrier to local fluid flow (Kanakiya et al., 2021; Schaefer et al., 2023).

In summary, high-temperature hydrothermal alteration, such as the propylitic facies, has variable effects on rock properties, including porosity, permeability, strength, density, and seismic wave velocities, with significant modification by rock type and sub-facies. The degree of alteration generally plays a key role, with variable influence for dense and fragmental rocks. Silicic alteration introduces nuanced effect on porosity, and the "advanced silicic" and “propylitic + albitic” facies promote microfracture closure, contributing to strength recovery. The hydrothermal setting influences fault-proximal weakening or strengthening, as indicated by Callahan et al. (2019). Argillic alteration tends to increase porosity and reduces strength in dense and fragmental rocks, promoting ductile behaviour. Although trends can be established between the several physical and mechanical properties, a variability within each type of volcanic rock and over distinct scales exists.

5. Conclusions and future research

Hydrothermal alteration, which occurs when hot fluids circulate through rock, is more influenced by local conditions rather than large-scale geodynamic processes, although the latter play a major role in maintaining the hydrothermal activity. The formation of different types of altered rocks depends on a variety of factors, but pressure, temperature, host rock, and the chemical composition of the fluids appear to be the most important locally. While the formation of these rocks has been well studied, less attention has been paid to how the physical and mechanical properties of altered rocks vary. To fill this gap in knowledge, a data compilation was created to collect and analyse data on the properties of hydrothermally altered rocks. The *type of the rock* and its microstructure play an important role in determining the properties of altered rocks, as well as the pre-existence of discontinuities (faults, fractures, and microfractures). For example, lavas and intrusive rocks are generally denser, less porous, and stiffer than pyroclastic rocks, except where welding and compaction affect the structure of the volcaniclastic rocks. However, lavas are more likely to fracture and create permeability, whereas pyroclastic rocks may maintain low permeability but still be weaker due to their porosity and microstructure. Thus, determining the effect of hydrothermal alteration on the physical and mechanical properties of rocks is a complex task. Some conclusions can be drawn from the collected:

1. Dissolution and mineral replacement are the primary mechanisms affecting altered lavas and intrusive rocks by alunitic, argillic and shallow silicic hydrothermal alterations, rendering more porous and less competent dense rocks. On the contrary, pervasive propylitic alteration induces strengthening and stiffening. The composition of the lava (i.e. alkalis content) dictates the development of hydrothermal alteration.
2. Altered dense rocks display increased variations, especially in mechanical properties compared to altered fragmental rocks.
3. Lava breccia is more affected by the degree of alteration. When highly altered, lava breccias experience complete mineral precipitation and sealing of the pore network, thus strengthening the rock.
4. Fragmental and porous rocks have heterogeneous microstructures and compaction degrees, resulting in overlapping effects from both degree and type of hydrothermal alteration. Usually, alteration promotes mineral precipitation, leading to the strengthening and compaction of fragmental rocks. Argillic facies either contributes to or maintains the competence of fragmental rocks while decreasing or preserving physical properties. Nevertheless, permeability becomes more difficult to develop or preserve within high-temperature hydrothermal facies, despite the possibility of high porosity of these lithotypes. “Harder” hydrothermal facies, such as advanced silicic, tend to reduce porosity and permeability while strengthening pyroclastic rocks.
5. The impact of propylitic facies depends on its association with other hydrothermal sub-facies (argillic, oxidation, silicic, alunitic, zeolitic), introducing variability in the physical and mechanical properties of the host rocks. Propylites associated with zeolites or clays may exhibit weakness and increased porosity.
6. Rock type defines the textural, chemical, and microstructural features of host rocks, which are influenced by geological and hydrothermal settings. This conditioning affects the development and extent of hydrothermal alteration. However, correlations between mechanical and physical properties of altered rocks generally align with established trends for unaltered equivalents, albeit with a slightly reducing the quality of the correlation.

The sheer variability and unpredictability of the hydrothermal alteration, maintaining its ubiquitous character, promotes the quantification of the alteration degree as an important venue of research, which is crucial for estimating physical and mechanical properties. Darmawan et al. (2022) and Heap et al. (2022c) showed that whole-rock $\delta^{18}O$ can be used as an accurate geochemical proxy of hydrothermal alteration intensity, with the advantage of requiring only a small amount of material. Furthermore, chemical indexes can be developed and refined to estimate physical and mechanical properties by establishing dedicated equations. This is particularly useful for geothermal fields, where cuttings are often the only available material for analysis. A refinement and the broadening application of the alteration strength index (ASI) (Wyering et al., 2015) is suggested, as it estimates UCS based on mineralogy (primary and secondary mineralogy) - the dominant parameter - individual mineral hardness, porosity, and fracture number.

To gain a deeper understanding of the role and impact of hydrothermal alteration, another line of research is suggested. In fact, due to the geological complexity and variability, conducting hydrothermal alteration experiments in the laboratory could establish a solid foundation for this research topic, as promising results have been produced by Farquharson et al. (2019) and Nicolas et al. (2020). Subsequently, by comparing and correlating experimental data with geophysical and geochemical data from field-scale studies, the improvement of geothermal fields productivity, development of more reliable hazard assessments for active volcanoes and definition of the physical state of volcanic environments (fault structures, hydrothermal systems, and magma reservoirs) could be achieved.

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