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Lava flow-hosted reservoirs: a review

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Abstract: Lava flows form important fluid reservoirs and have been extensively exploited for water aquifers, geothermal energy, hydrocarbon production and, more recently, for carbon storage. Effusive subaerial mafic to intermediate lava flows account for vast rock volumes globally, and form reservoirs with properties dictated by well-known lava flow facies ranging from pāhoehoe through several transitional forms to ‘a’ā lava. These variations in flow type lead to critical differences in the pore structure, distribution, connectivity, strength and fracturing of individual lava flows, which, alongside lava flow package architectures, determine primary reservoir potential. Lava flow margins with vesicular, fracture and often autobreccia-hosted pore structures can have porosities commonly exceeding 40% and matrix permeabilities over 10^{-11} m^2 (>10 D) separated by much lower porosity and permeability flow interiors. Secondary post-emplacement physicochemical changes related to fracturing, meteoric, diagenetic and hydrothermal alteration can significantly modify reservoir potential through a complex interplay of mineral transformation, pore-clogging secondary minerals and dissolution, which must be carefully characterized and assessed during exploration and appraisal. Within this contribution, a review of selected global lava flow-hosted reservoir occurrences is presented, followed by a discussion of the factors that influence lava flow reservoir potential.

A lava flow forms when molten or partially molten magma erupts onto the surface of a planetary body and begins to spread and flow under the influence of gravity (Griffiths 2000). In terrestrial volcanism, upper crustal magmas typically comprise silicate melts (SiO_2 ranging from *c.* 40–75 wt%), with effusive lava flows dominated by the more mafic (low SiO_2 <52%) lower viscosity end of this compositional spectrum (Self *et al.* 1998; Giordano *et al.* 2008; Bryan and Ferrari 2013), albeit notable examples of more evolved lava flows such as rhyolite and dacite are well documented (Harris and Rowland 2015; Rossetti *et al.* 2019). Lava flows dominate the subaerial effusive component of most mafic volcanoes and lava fields, including many volcanic islands, whilst they may also form important components of more evolved volcanoes (Harris and Rowland 2015). Depending on eruption frequency and changing eruption and environmental conditions (such as water level), lava flows can occur in association with a wide range of other volcanic deposits (hyaloclastite, pyroclastic, volcaniclastic) and non-volcanic lithologies (siliciclastic or carbonate interlayers) which may act as associated reservoirs (e.g. Jerram *et al.* 1999; Sætre *et al.* 2018; Millett *et al.* 2021*a*). Although these mixed deposits, including also subvolcanic igneous intrusions, can form important reservoirs (Schutter 2003; Descovi *et al.* 2021; Galland *et al.* 2023), the focus in this contribution is restricted to effusive lava flows and the processes that directly influence their reservoir properties.

Lava flows have erupted regularly across geological time and in all tectonic settings including divergent, convergent, transform and intra-plate

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(including 'hotspot') settings. The most voluminous examples of lava flows are linked to the geologically infrequent eruption cycles of large igneous provinces (LIPs), often termed continental flood basalt (CFB) sequences when dominated by effusive subaerial basaltic volcanism (Coffin and Eldholm 1994; Bryan and Ferrari 2013); see Figure 1 and Table 1. In CFB sequences, individual lava flow units can cover tens of thousands of km^2 and reach volumes exceeding 1000 km^3 (Bryan *et al.* 2010; Self *et al.* 2021) resulting in often extensive intra-lava reservoirs spanning large regional extents (Reidel *et al.* 2002; Tolan *et al.* 2009). These lava flow sequences are typically several kilometres thick, sometimes reaching almost 10 km (Passey and Bell 2007; Self *et al.* 2021). In contrast, many volcanic systems, especially those forming modern rift- and subduction-related volcanoes can comprise much smaller <1 km^3 lava flows, which in turn form a smaller percentage of the cumulative volcanic deposits that may have significant pyroclastic, volcaniclastic and intrusive components leading to a typically greater reservoir complexity (e.g. Cinti *et al.* 2015; Toulier *et al.* 2019; Rossetti 2022). The wide global distribution of lava flows has inevitably resulted in their often-close proximity to human settlements and activities for which water, energy resources and, more recently, the disposal of CO_2 are critical (Benson *et al.* 2005). Robust characterization and understanding of lava flow reservoirs, and the features and parameters that may influence their utilization are, therefore, of widespread interest and application.

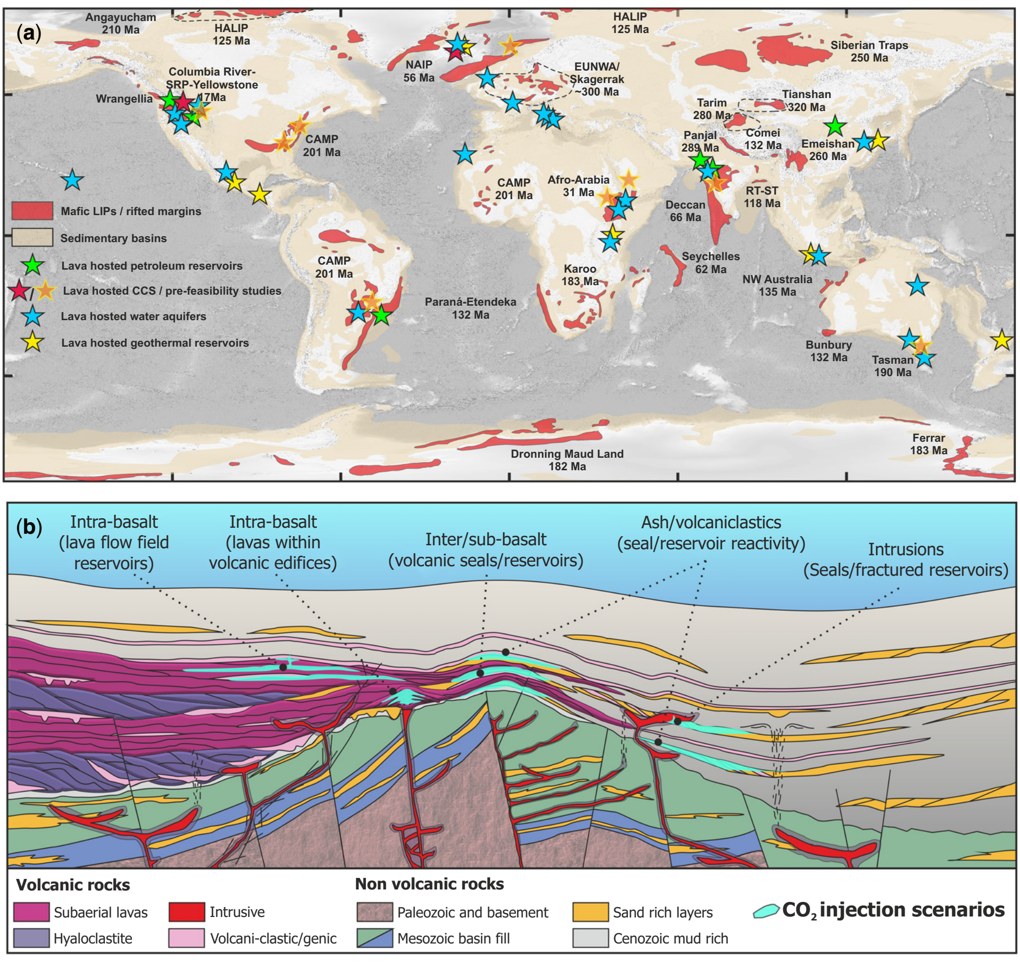

Fig. 1. (**a**) World map showing the locations of selected reservoirs hosted within lava flows or lava flow-bearing sequences. (**b**) Conceptual volcanic rifted margin model highlighting potential offshore CO_2 injection scenarios. Source: (a) mafic LIP distributions from Bryan and Ferrari (2013) and sedimentary basin outlines from Fugro Tellus (2013); (b) modified after Millett *et al.* (2022).

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Table 1. Compilation of global lava flow-hosted reservoirs utilized for different subsurface applications

Type of resource	Tectonic setting	Location	Age	Reservoir example	Lava flow reservoir component	References
Geothermal	Convergent (volcanic arc)	El Salvador	Neogene–Quaternary	Ahuachapán Geothermal Field	Andesite	Aunzo *et al.* (1989)
	Divergent margin	Iceland	Quaternary	Hengill Volcano	Basalt	Zakharova and Spichak (2012)
	Convergent (volcanic arc)	Japan	Neogene–Quaternary	Takigami geothermal system	Andesite to dacite	Furuya *et al.* (2000)
	Convergent (volcanic arc)	Java	Quaternary	Awibengkok geothermal system	Andesitic to basalt	Stimac *et al.* (2008)
	Convergent (volcanic arc)	Java	Quaternary	Darajat Geothermal Field	Andesite	Hadi *et al.* (2005)
	Continental rift zone	Kenya	Quaternary	Olkaria East Geothermal Field	Trachytic	Okoo (2013)
	Convergent (volcanic arc)	Lesser Antilles	Neogene–Quaternary	Bouillante field, Guadeloupe Island	Andesite	Navelot *et al.* (2018)
	Convergent (volcanic arc)	Mexico	Neogene–Quaternary	Los Humeros Volcanic Complex	Andesite	Weydt *et al.* (2022)
	Convergent (volcanic arc)	New Zealand	Quaternary	Rotokawa Geothermal Field	Andesite	Massiot *et al.* (2014)
Hydrocarbons	CFB	Brazil	Cretaceous	Badejo and Linguado (oil)	Basalt	Marins *et al.* (2022)
	Intra-continental rift	China	Cretaceous	Songliao Basin (gas)	Mixed	Wang and Chen (2015)
	CFB	India	Cretaceous–Paleogene	Padra and Gamij fields (oil)	Basalt	Kumar (2006)
	CFB	India	Cretaceous–Paleogene	Raageshwari Deep Gas Field (gas)	Basalt	Millett *et al.* (2021*b*)
	CFB	USA, Washington State	Neogene	Rattle Snake Ridge (gas)	Basalt	Reidel *et al.* (2002)
	Intra-plate (continental)	USA, Utah	Neogene	Rozel, West Rozel (oil)	Basalt	Kendell (1996)
Aquifers	Intra-plate (continental)	Australia	Quaternary	Undara	Basalt	Kiernan *et al.* (2003)
	Intra-plate (continental)	Australia	Neogene–Quaternary	Newer Volcanic Province, Victoria	Basalt	Kiernan *et al.* (2003)
	CFB	Brazil	Cretaceous	Serra Geral aquifer system	Basalt	Navarro *et al.* (2020)

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Table 1. *Continued.*

Type of resource	Tectonic setting	Location	Age	Reservoir example	Lava flow reservoir component	References
	Intra-plate (oceanic)	Canary Islands	Quaternary	El Hierro	Basalt	Luengo Oroz *et al.* (2014)
	Continental rift zone	Djibouti	Neogene–Quaternary	Coastal acquifer	Basalt	Ahmed *et al.* (2017)
	Continental rift zone	Ethiopia	Quaternary	Dangila district aquifer	Basalt	Fenta *et al.* (2020)
	Intra-plate (continental)	France	Quaternary	Chaîne des Puys aquifer	Basalt to trachybasalt	Bertrand *et al.* (2010)
	Intra-plate (oceanic)	Hawai'i	Quaternary	Hawai'i	Basalt	Oki *et al.* (1999)
	Divergent margin	Iceland	Quaternary	Reykjanes	Basalt	Sigurdsson and Einarsson (1988)
	CFB	India	Cretaceous/Paleogene	Deccan Traps	Basalt	Limaye (2010)
	Convergent (volcanic arc)	Italy	Neogene–Quaternary	Vicano–Cimino Volcanic District	Mixed composition (alkali)	Cinti *et al.* (2015)
	Convergent (volcanic arc)	Italy	Quaternary	Mt. Amiata	Trachydacite	La Felice *et al.* (2014)
	Convergent (volcanic arc)	Italy	Quaternary	Mt. Vulture	Mixed composition (alkali)	Parisi *et al.* (2011)
	Convergent (volcanic arc)	Java	Quaternary	Bromo-Tengger aquifer	Andesite	Toulier *et al.* (2019)
	Intraplate (continental)	Korea	Quaternary	Jeju	Basalt	Koh *et al.* (2017)
	Intraplate (continental rift)	Mexico	Paleogene–Neogene	Pachuca–Zumpango	Basalt to andesite	Huizar-Alvarez *et al.* (2003)
	CFB	Scotland	Paleogene	Isle of Skye	Basalt	MacDonald *et al.* (2017)
	Intraplate (continental rift)	Tanzania	Quaternary	Mount Meru	Nephelinite to phonolite	Tomašek *et al.* (2022)
	Intra-plate (continental)	Tazmania	Paleocene–Neogene	Thirlstane Basalt	Basalt	Kiernan *et al.* (2003)
	Intra-plate (continental)	USA, Idaho	Quaternary	Snake River Plain Aquifer	Basalt	Anderson and Liszewski (1997)
	Intra-plate (continental)	USA, Nevada	Paleogene–Neogene	Pahute Mesa	Rhyolite to dacite	Jackson *et al.* (2021)

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Table 1. *Continued.*

Type of resource	Tectonic setting	Location	Age	Reservoir example	Lava flow reservoir component	References
	CFB	USA, Washington State	Neogene	Columbia River Basalt Group	Basalt	Burns *et al.* (2012)
	Intra-plate (continental)	USA, Oregon	Neogene–Quaternary	Fort Rock Basin	Basalt	Hampton (1964)
Carbon storage pilot	Divergent margin	Iceland	Quaternary	Hellisheiði Power Station, Carbfix	Basalt	Matter *et al.* (2016)
	CFB	USA, Washington State	Neogene	Wallula	Basalt	McGrail *et al.* (2011)
Selected carbon storage potential areas	Intra-plate (continental)	Australia	Cretaceous	Gippsland basin	Basalt	Holford *et al.* (2021)
	CFB	Brazil	Cretaceous	Paraná Basin, Serra Geral Formation	Basalt	Carneiro *et al.* (2013)
	CFB	India	Cretaceous/Paleogene	Deccan Traps	Basalt	Shrivastava *et al.* (2016)
	Continental rift zone	Kenya	Neogene–Quaternary	Kenyan rift valley	Basalt	Okoko and Olaka (2021)
	CFB	Norway	Paleogene	North Atlantic Igneous Province	Basalt	Rosenqvist *et al.* (2023)
	CFB	Eastern USA	Triassic/Jurassic	Central Atlantic Magmatic Province	Basalt	Goldberg *et al.* (2009)
	Intra-plate (continental)	USA, Idaho	Quaternary	Snake River Plain	Basalt	Pollyea *et al.* (2014)
	Continental rift zone	Saudi Arabia	Paleogene–Neogene	Jizan Group	Basalt	Oelkers *et al.* (2022)

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Effective lava flow reservoirs result from an often-complex combination of both primary and secondary processes, which in turn define primary and secondary porosity types. Primary processes include all attributes relating to lava flow emplacement up to the point of solidification of the lava flow, and include vesicles and their distribution, inter-crystalline diktytaxitic voids, cooling contraction joints, inflation and flow-related fractures, and autobrecciation features (Saar and Manga 1999; Griffiths 2000; Lyle 2000; Schaefer and Kattenhorn 2004). Primary matrix porosity and permeability of lava flow margins can commonly reach >40% and $>10^{-11}$ m^2 (>10 D) respectively, whilst lava flow interiors can have very low matrix porosity and permeability <5% and $<10^{-16}$ m^2 (<0.1 mD), although exceptions occur (Franzson *et al.* 2001). Contractional cooling joints form ubiquitous features in igneous bodies, and form often consistently spaced and extensive networks of open fractures in primary lava flows, rendering flow interiors with low matrix permeability, initially highly permeable (Lamur *et al.* 2018). In turn, secondary processes include tectonic fracturing, meteoric weathering, subsurface diagenetic and hydrothermal alteration, mineralization and dissolution (Neuhoff *et al.* 1999; Heap and Kennedy 2016; Cant *et al.* 2018; Bischoff *et al.* 2021*b*; Macente *et al.* 2022). The influence of secondary processes on reservoir properties are diverse and can act both to destroy or enhance reservoir properties under different conditions, which are outlined, giving examples.

In this study, we first present a brief global review of the occurrence of selected lava flow-hosted reservoirs (n=40) including examples for groundwater, hydrocarbon, geothermal and CO_2 storage utilization (Table 1). This is followed by a discussion of the key controls that influence lava flow reservoir properties including magma rheology, lava flow types, lava flow architecture, pore structure end-members, secondary processes and burial, borehole appraisal techniques, and seismic properties of lava flows. Field outcrop and borehole examples of different lava flow facies are presented in support of the discussion alongside summaries from extensive compiled literature examples of relevant petrophysical data (porosity, permeability and velocity) and published models for lava flow pore structures in order to aid lava flow reservoir appraisal approaches.

Lava flow reservoir occurrence and applications

Water aquifers

Lava flow-hosted water reservoirs have been utilized from antiquity in the form of springs, have been accessed by drilling for over 100 years and, in many regions, host water resources upon which millions of people (Huizar-Alvarez *et al.* 2003; Fenta *et al.* 2020) and billions of dollars of industry and agriculture (Burns *et al.* 2012) depend. Groundwater aquifers hosted entirely or partly in lava flows can form highly effective reservoirs (Sigurdsson and Einarsson 1988; Kiernan *et al.* 2003; Burns *et al.* 2012); however, wells with high yields (e.g. >20 l s^{-1}) are not ubiquitous and low yields (e.g. <1 l s^{-1}) are also regularly encountered, especially for shallow wells (Fenta *et al.* 2020). Water produced from lava flow-hosted reservoirs clearly forms a critical global resource, and an expansive literature documents variations in water–host rock interactions, recharge and flow rate, etc. (Table 1). Due to the typically lower budgets available for water well drilling and the often-large number of required shallow boreholes (often many thousands), well data from which to undertake volcanological analyses are often limited, and the associated literature is often focused on production data and water chemistry studies. Several conceptual hydrogeological models of volcanic aquifers have been proposed based on different reservoir settings and geology including Hawai'i (USA; MacDonald *et al.* 1983), the Canary Islands (Spain; Custodio 1989), Mayotte (Comoros; Lachassagne *et al.* 2014) and Dangila (Ethiopia; Fenta *et al.* 2020). Key differences between the hydrological behaviour of pāhoehoe, transitional, and ʻaʻā lava flows have also been documented, highlighting the generally higher flow potential of brecciated lava margins (Oki *et al.* 1999; Tolan *et al.* 2009; Bertrand *et al.* 2010). As an example, lateral hydraulic conductivities for Columbia River Basalt Group lava flow top breccias can locally reach values of several thousand metres per day (up to 10^{-2} m s^{-1}), but can also reduce to *c.* 10^{-5} m s^{-1}, whereas vesicular flow tops can reach similar upper levels, but cover a wider range down to 10^{-12} m s^{-1}. Typically, flow interiors are of low permeability and reveal hydraulic conductivities ranging from 10^{-9} to 10^{-15} m s^{-1}, leading to vertical hydraulic conductivities commonly several orders of magnitude lower than for flow margin zones (Tolan *et al.* 2009, and references therein). Lava flows from the Chaine des Puys in France form part of the famous Volvic natural mineral water reservoirs (Rouquet *et al.* 2012), which as well as filtering the water, enrich it with various elements emphasized in marketing for the mineral water. High-quality drinking water is a common phenomenon related to lava flow-hosted reservoirs depending on the setting (e.g. Gunnarsdottir *et al.* 2016); however, this is not always the case. Parnell (2022) presents a compilation of volcanic-hosted aquifer systems, highlighting the impact of water–rock interactions in volcanic reservoirs on trace element enrichments such as arsenic (As), vanadium

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(V) and uranium (U), in some cases reaching levels harmful to humans. However, V, for example, is also a critical raw material for the energy transition, and it has recently been suggested that the extraction of V during water purification processes could potentially provide a resource going forward (Parnell 2022).

Hydrocarbons

Lava flows are also known to host hydrocarbon accumulations in several locations globally (Table 1) and include examples of commercial production of oil from within Lower Cretaceous lava flows offshore Brazil (Marins *et al.* 2022), gas from Late Cretaceous Deccan lava flows onshore India (Millett *et al.* 2021*b*), and a wide range of onshore volcanic reservoirs (including lava flows) from several basins across China such as the Songliao, Junggar and Bohai basins with reservoir ages ranging from Permian through to Neogene (Zou *et al.* 2010; Wang and Chen 2015). Additionally, where sedimentary reservoirs are interbedded with lava flows (e.g. Millett *et al.* 2021*a*), lava flows may have the potential to contribute to the overall reservoir volume. One clear advantage when interpreting well penetrations drilled for hydrocarbon exploration and development is the generally much higher budgets available for borehole analyses and characterization. This often results in a more comprehensive suite of geophysical downhole logs often including advanced logging sondes such as those measuring magnetic resonance, elemental spectroscopy, micro-resistivity and acoustic image logs, which can significantly aid volcanological characterization (e.g. Watton *et al.* 2014; Fornero *et al.* 2019; Millett *et al.* 2021*a*, *b*). The Raageshwari Deep Gas field lava flow reservoirs comprise deeply altered lava flow sequences with associated low permeability (typically $<2.3 \times 10^{-14}$ m^2, e.g. a few tens of millidarcies or less) requiring fracture stimulation for commercial production (Chowdhury *et al.* 2014). However, even in these low permeability sequences, it has been demonstrated that hydrocarbon storage and productive intervals are strongly linked to the original lava flow volcanological properties, with lava flow margins, and those revealing primary autobrecciation having the best reservoir properties (Millett *et al.* 2021*b*). This appears broadly consistent with results from the Badejo and Linguado oil fields offshore Brazil, where oil staining is linked to a combination of primary vesicular and rubbly porosity along with secondary fractures (Marins *et al.* 2022). Production data for these fields, however, revealed a steep decline from high early production rates, plateauing and remaining almost constant for the remainder of the production intervals, characteristics common for fractured reservoirs (Marins *et al.* 2022), and highlighting the dual-porosity nature of the lava flow reservoirs.

Geothermal

Globally, nearly 75% of productive and prospective geothermal power plants are associated with subduction zone volcanoes, albeit not all of these include lava flows as part of the productive reservoir (Moeck 2014; Stelling *et al.* 2016). A selection of volcanic reservoirs within which lava flows specifically form part of the reservoir sequence are summarized in Figure 1 and Table 1. Lava flow-hosted geothermal reservoirs occur in all tectonic settings and are often controlled by faulting and fracturing of hydrothermally altered lava sequences (Eidesgaard *et al.* 2019; Millett *et al.* 2020; Scott *et al.* 2023). Significant recent focus has been given to the mechanical properties of variably hydrothermally altered lava flows, and the impacts that this has on fracturing and related fluid flow in geothermal systems, features that are commonly integral to exploration approaches (Wyering *et al.* 2014; Heap and Kennedy 2016; Lamur *et al.* 2017; Mordensky *et al.* 2019). However, primary lava flow reservoir properties can also be important, for example, at Hengill Volcano, Iceland (Zakharova and Spichak 2012), highlighting the complex interplay between primary and secondary reservoir properties that may be encountered in lava-hosted geothermal settings (Table 1). This is also at least partly the case for andesitic lava flows with rubbly margins that occur within the Rotakawa Geothermal Field, New Zealand, which have been characterized by combining field outcrop analogue models with acoustic borehole images from boreholes (Massiot *et al.* 2014, 2015).

CO_2 storage

Climate change linked to anthropogenic greenhouse gas emissions presents one of the biggest challenges facing society over the coming decades and will require industrial-scale removal and safe subsurface storage of CO_2 as a fundamental part of mitigation efforts (Benson *et al.* 2005). Storage of CO_2 in geological formations as a fluid, in either structural or stratigraphic traps, presents leakage risks which must be monitored long term. However, mineral trapping of CO_2 in reactive reservoirs such as basalt has gained significant interest as an alternative over recent years due to the permanent storage method (Matter *et al.* 2007). CO_2 reacts with divalent cations such as Ca^{2+}, Mg^{2+} and Fe^{2+}, liberated from basalt and then precipitates as carbonate minerals, leading to stable mineral storage over geological timescales. Pilot studies at Carbfix in Iceland, and Walulla in Washington State, USA, have both demonstrated

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that CO_2 can be successfully injected into lava-bearing sequences (McGrail *et al.* 2011; Matter *et al.* 2016), and that potentially very rapid mineralization of >95% injected CO_2 within two years can occur (Matter *et al.* 2016). Extensive research has been undertaken to understand the impacts of reactive transport during injection of CO_2 and its impacts on evolving reservoir properties (Ratouis *et al.* 2022). Both of these examples have been undertaken onshore; however, significant recent interest has been given to the potential for expanding injection scenarios to the offshore realm where vast expanses of lava flow sequences occur (Goldberg *et al.* 2009; Planke *et al.* 2020; Holford *et al.* 2021; Rosenqvist *et al.* 2023). Clearly, the additional costs of injection in offshore areas, and particularly at distance from major CO_2 sources, come with limitations and constraints, which will need to be carefully assessed on a case-by-case basis going forward. However, appraisal of lava flow sequences for CO_2 storage is expanding around the world (Fig. 1) and may offer an important contribution to climate change mitigation going forward.

Other applications

In addition to the main applications outlined above, lava flow reservoirs have also been invoked as potentially viable candidates for natural gas storage (Reidel *et al.* 2002) and hydrogen storage (Bischoff *et al.* 2021*a*), whilst they also host important mineral deposits (du Bray 2017). Lava flow sequences were also extensively appraised and used for waste storage including nuclear waste in the USA; however, their applicability for safe storage has proven questionable in these settings due to aquifer contamination concerns (USDOE 1988; Ackerman *et al.* 2010).

Geological controls on lava flow reservoirs

Controls on magma rheology

Magmas produced in different tectonic settings have notable differences in terms of magma composition and associated volatile contents (Rogers 2015; Wallace *et al.* 2015), which in turn can have important implications for magma rheology and resulting lava flow properties. For example, magmas generated by large fractions of melting such as those produced at ocean ridges, so-called mid-ocean ridge basalts (MORB), typically lead to low alkaline (Na, K) tholeiitic basalt-dominated compositions depleted in volatiles (typically <0.4 wt%). Ocean island basalts (OIB), such as those erupted on Hawai'i, reveal a wider range of SiO_2 and alkali components compared to MORB, along with higher MgO, consistent with smaller degrees of melting beneath a thick 'lid' of oceanic lithosphere with deeper onset of melting, often inferred to relate to mantle thermal anomalies (Rogers 2015). Volatile contents in OIB overlap with MORB but span a wider range reaching up to *c.* 1.5 wt% (Wallace *et al.* 2015). In contrast, subduction-related magmas are often highly enriched in volatiles compared to MORB, with values of H_2O from 2 to 6 wt% and in continental subduction settings typically fractionating significantly prior to eruption (required to drive buoyancy in granitic crust), leading to ubiquitous andesitic volcanism.

Viscosity is the most important property of flowing lava that controls its behaviour during emplacement and ultimately lava morphology. Viscosity is defined as a fluid's internal resistance to flow and, therefore, affects the velocity of flow as well as flow thickness. In simple terms, on a near-planar surface of low gradient (e.g. <5°), eruption of low-viscosity magma will lead the development of higher-velocity, longer and thinner lava flows than a high-viscosity magma, everything else being equal (e.g. Kilburn 2004; Guest *et al.* 2012). Viscosity of magma is in turn dependent on a number of parameters: (i) temperature; (ii) composition of magma; (iii) volatile content; (iv) bubble (vesicle) content; and (v) phenocryst population (e.g. Griffiths 2000; Giordano *et al.* 2008; Hobiger *et al.* 2011; Mueller *et al.* 2011).

The relationship between viscosity and temperature is Arrhenian, such that viscosity increases exponentially with decreasing temperature. Conventionally, the viscosity of magmas is represented as the relationship between inverse temperature and log viscosity (Fig. 2). For a given magma composition, if $1/T(K)$ v. log viscosity approximates to linearity, then the liquid is near-Newtonian, meaning the relationship between stress and strain is constant (McBirney and Murase 1984). In addition to the temperature–viscosity relationship, Figure 2 shows that composition of lava strongly influences viscosity. Evolved, more acid magmas will have a higher viscosity at a given temperature than mafic magmas, and the range of absolute viscosity variation is up to 12 orders of magnitude. For reference, 10^2 Pa s is approximately the viscosity of golden syrup at 18°C and 10^{12} Pa s is that of glazing putty.

The fundamental structural unit of silicate melts is the SiO_2-tetrahedron. A pure SiO_2 glass will be dominated structurally by Si–O tetrahedra all of which share an oxygen anion (bridging oxygens) and therefore will have a robust and organized structure; such melts are described as being strongly polymerized. The addition of divalent (e.g. Mg^{2+}, Ca^{2+}) or large monovalent (e.g. Na^+, K^+) cations depolymerizes the melt by preventing the formation of bridging oxygens. In natural systems, the

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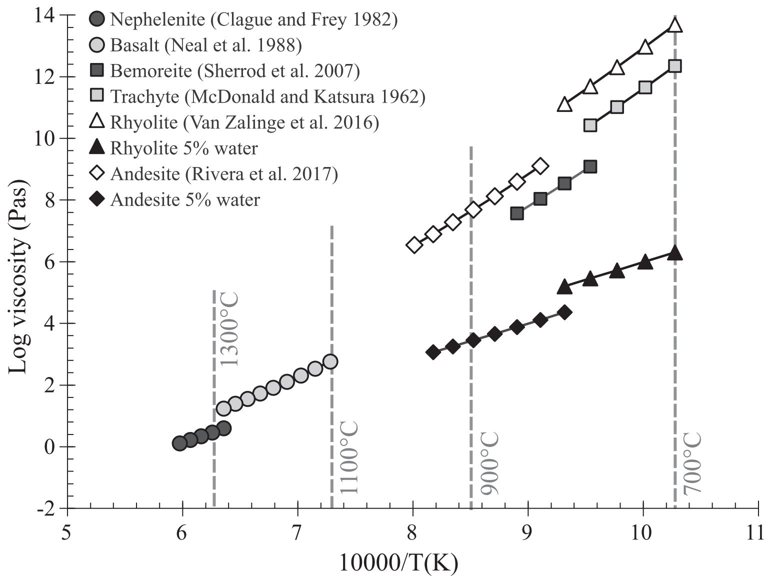

Fig. 2. Plot of log viscosity (Pa s) v. 10 000/$T(K)$ for nominally dry representative Hawaiian and dry and 'wet' (~5 wt% H_2O) Andean andesite and rhyolite samples. Vertical pecked lines are contours for absolute temperature in ° C. Each magma composition is plotted with a range of nominal liquidus temperatures based on the glass thermometer of Helz and Thornber (1987), assuming a flowing lava will cool with distance from source and time. Source: viscosity calculations performed using the algorithms of Giordano *et al.* (2008).

composition of lava and liquidus temperature is related, such that acid, polymerized melts will have lower liquidus temperatures than more mafic, depolymerized melts (Fig. 2). This combination results in the extreme viscosity variations illustrated in Figure 2.

Significantly, volatiles (H_2O, CO_2, F, Cl) have the same effect as alkali metal cations and strongly depolymerize magma (Fig. 2; Giordano *et al.* 2008; Hole *et al.* 2013). Where H_2O is an important component of magma, such as at subduction zones, conservative amounts of water (~5 wt%) will reduce the viscosity of, for example, an andesite, by more than four orders of magnitude at a given temperature. However, since the solubility of H_2O in magma is strongly dependent on pressure, once a water-saturated magma reaches subvolcanic depths, it will vesiculate (form bubbles) and volatile components come out of the solution. Removing H_2O from the silicate liquid by vesiculation increases viscosity dramatically (Fig. 2). Since vesicles are compressible, formation of bubbles can in turn decrease viscosity, but the effect of removing volatiles from the magma causes a far greater increase in viscosity than the decrease caused by bubble formation. Ultimately, the expansion of bubbles near the surface, along with increasing viscosity of the liquid caused by bubble formation, may result in explosive pyroclastic eruptions where the pressure build-up cannot be accommodated by outgassing (Mueller *et al.* 2005). Phenocrysts cause the viscosity of magma to increase for any given temperature, composition or volatile content; however, as with bubble formation, the magnitude of the effect of phenocrysts on viscosity is orders of magnitude less than the effect of temperature or volatile content (Mueller *et al.* 2011; Hole *et al.* 2013). In summary, more mafic magmas typically have viscosities several orders of magnitude lower than evolved counterparts, which leads to a greater propensity to erupt and flow as effusive lava flows rather than explosive pyroclastic eruptions. However, due to cooling, outgassing and crystallization, viscosity is time-dependent, leading to the development of substantial heterogeneities in lava flow rheology during flow and emplacement away from eruption sites, which in turn leads to different resulting lava flow facies discussed in the next section.

Lava flow types

There exists an expansive literature dealing with the emplacement dynamics and resulting characteristics of lava flows (MacDonald 1953; Walker 1971; Rowland and Walker 1990; Hon *et al.* 1994; Griffiths 2000; Kilburn 2004), with much of the pioneering studies of lava flow emplacement being linked to real-time observations and research on recent well-

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exposed lava flows conducted on Hawai'i (Cashman *et al.* 2014; Harris *et al.* 2017). Primary lava flow properties depend on a host of differing intrinsic and extrinsic conditions including magma rheology, volumetric flow rate, eruption environment and topography, to name a few (Cashman *et al.* 2014). Lava flows represent individual eruptive deposits often within a longer-lived eruption cycle, with lava flow lobes defined as an individual lava unit limited by a chilled upper and lower margin. Lava lobes can vary in thickness over four orders of magnitude from *c.* 0.1 m up to >100 m in the extreme (Self *et al.* 2021), with increasing lava flow thickness typically linked to the process of inflation (Hon *et al.* 1994).

Early work identified two dominant types of basaltic lava flows including pāhoehoe (lava flows with a smooth continuous crust) and ʻaʻā (lava flows with autobrecciated spiney/clinkery upper and lower crusts), based on a combination of surface and dissected cross-sectional differences (MacDonald 1953). A third type, block lava (similar to ʻaʻā but with flow margin breccias comprising large coherent blocks), was found typically associated with more evolved compositions (Finch 1933; MacDonald 1953). The terms pāhoehoe and ʻaʻā remain widely used today, and form end-members between which several transitional lava flow types have been defined, including rubbly, spiney, slabby, toothpaste and shark-skin pāhoehoe (Rowland and Walker 1987). The transition between pāhoehoe, transitional and ʻaʻā lava surface types relates to a complex interplay of factors but can be summarized as relating to a threshold value of apparent viscosity for a given shear rate such that when apparent viscosity increases (related to magma evolution, crystallinity, vesicle content, etc.), the shear rate (emplacement related) required to promote surface failure and the onset of crust tearing and brecciation reduces (Cashman *et al.* 2014). It follows that ʻaʻā lavas commonly contain greater crystallinity and are more degassed than pāhoehoe lava flows, with the transition often occurring with greater distance from the vent. Figure 3a highlights selected examples of lava flow surface types, with examples, modified after Voigt *et al.* (2021).

Based on variations in internal vesicle distributions, Wilmoth and Walker (1993) proposed that pāhoehoe can be split into spongy (S-type; highly vesicular throughout with highest abundances in centre of lobe) and pipe vesicle-bearing (P-type; including a massive poorly vesicular core with vesicular margins) types. The latter is the most common form of pāhoehoe, which can expand up to thick

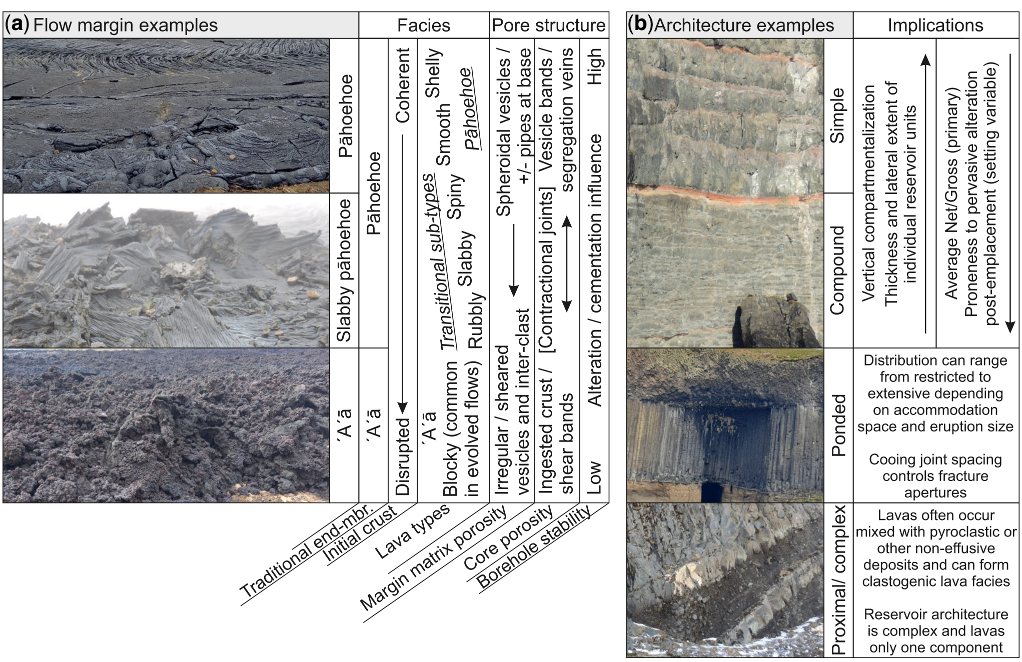

Fig. 3. Overview of selected lava flow architectural elements, facies styles and potential implications for reservoir property distributions. (**a**) Lava surface variations from the 2021 Fagradalsfjall eruption on Iceland. (**b**) Compound and simple lava flows from Svinoy, Faroe Islands, ponded lava from Isle of Staffa, Scotland, and clastogenic lava interlayered with basaltic pyroclastic deposits, Iceland. Source: modified after Voigt *et al.* (2021).

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inflated lavas with a typically asymmetrical distribution of vesicles (Self *et al.* 1998). In general, thin lobe-like pāhoehoe structures smaller than 0.5 m are referred to as lava toe lobes (Self *et al.* 1998). The ʻaʻā lava flows have also been subdivided using terms such as cauliflower, slabby, scoriaceous, clinker and blocky ʻaʻā (Lipman and Banks 1987; Kilburn 1990). For a comprehensive review of historical lava flow terminology usage, see Harris *et al.* (2017).

Where lava flows are emplaced into standing or flowing water, local hyaloclastites or pillow lava complexes can develop along the basal boundary of the flow and can develop laterally extensive intervals several metres thick. These flow margin or intraflow facies can form important aquifer components, as documented in the Columbia River Basalt Group (Reidel *et al.* 2002; Tolan *et al.* 2009). These and the wider field of subaqueous lava flow facies are not described in detail in this contribution and merit a separate contribution.

Lava flow architecture

A fundamental feature of lava flows is that they have the ability to transition between several different subtypes within a single erupted lava sequence, as is well documented for example in the pāhoehoe to ʻaʻā transitions that have attracted significant interest from a rheology and emplacement perspective on Hawaiʻi (Peterson and Tilling 1980; Rowland and Walker 1990; Kilburn 2004; Soule and Cashman 2005; Cashman *et al.* 2014). These transitions between different flow types, including through transitional forms can lead to complex lateral variations in flow types as exemplified by surface mapping of the recent Holuhraun eruption on Iceland (Voigt *et al.* 2021). These transitions can be preserved as relatively sharp boundaries occurring over a lateral extent of a few metres to tens of metres within individual lobes but may not always occur at the same position within different lobes of the same flow. These variations lead on to the importance of scale and architecture when appraising lava flows as reservoirs. Walker (1971) discussed the differences between simple lavas (those not divisible into flow units) and compound lavas (those divisible into multiple flow units) and highlighted the particular utility of the distinction for ancient, dissected lava sequences, whilst concluding that, in 3D, all lava flows are likely compound to some degree. Compound and simple lava flow terminology is independent of flow surface classifications, and as such can be constructed of either pāhoehoe, ʻaʻā or transitional forms (Walker 1971; Cashman *et al.* 2014). Compound (alternatively termed compound braided or hummocky pāhoehoe) and simple lava flow (alternatively termed massive tabular or sheet-lobe-dominated) classifications have been widely used for appraising LIP sequence architectures (Jerram 2002; Passey and Bell 2007; Self *et al.* 2021) and have been found especially useful for one-dimensional borehole appraisals with limited or no core (Nelson *et al.* 2009; Millett *et al.* 2016*a*, 2021*a*).

Ponded lava flows, emplaced into restricted accommodation space such as erosional valleys, canyons, or depressions formed by damming of earlier lava flows, can also form major rock volumes in flow fields (Lyle 2000; Single and Jerram 2004). Vent proximal lava flows may also reveal complex architectures and significant later variations between non-effusive pyroclastic products. In some cases, the products of more explosive mafic volcanism (Hawaiian fire fountaining or Strombolian eruptions) can lead to partial or complete homogenization of initially hot ejecta, forming agglutinate or clastogenic lava forms which look similar to lava flows but are internally composed almost entirely of welded pyroclasts (Greenfield *et al.* 2019). Figure 3b highlights examples of compound, simple, ponded and clastogenic lava flows from the North Atlantic Igneous Province. Several features such as flow channels, levees, lava tubes, lava lakes and rootless cone features can all form locally important features within lava flows, which can add to internal heterogeneity of lava flow sequences (Harris and Rowland 2015).

Pore structure end-members

The above description of lava flow facies and architecture is far from exhaustive but serves to highlight some of the key variations that may be expected in lava flow sequences, and which in turn serve to frame the variations in primary pore structure, reservoir properties and geometry of subsurface lava flow reservoirs. The two end-member lava flow facies (pāhoehoe and ʻaʻā), which bracket the range of typical possibilities, provide a useful starting point to appraise reservoir properties. Pāhoehoe lava flow pore structure is dominated by vesicles (exsolved gas bubbles ʻfrozen inʼ to the magma during cooling; Walker 1989) along with contraction cooling joint-, inflation- and flow-related fractures (Griffiths 2000; Schaefer and Kattenhorn 2004). Preserved vesicles in lava flows represent the culmination of a potentially complex history of volatile exsolution, bubble nucleation, growth, migration and coalescence within the liquid magma, both prior to and synchronous with cooling induced solidification (Sparks 1978; Walker 1989; Cashman *et al.* 1999). The resulting pore structure, connectivity and rock strength of vesicular volcanic rocks may be significantly different from that of clastic rocks, especially at high porosities (Saar and Manga 1999; Heap *et al.*

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2014; Heap and Violay 2021), with pore elongation associated with stretched vesicles influencing both strength (Bubeck *et al.* 2017) and permeability (Garboczi *et al.* 1995; Wright *et al.* 2009).

A common misconception regarding lava flows, which the authors have come across on multiple occasions, is that vesicles form only isolated, non-effective porosity. This appears partly linked to the fact that much of the literature relating to vesicular pore structures and magma/volcanic permeability has until relatively recently been published dominantly in the volcanological/hazards literature (e.g. Klug and Cashman 1996; Mueller *et al.* 2005). The case of ineffective porosity is undoubtedly true for many isolated vesicles within lava flow interiors and the transition into flow margins (Franzson *et al.* 2001; Couves *et al.* 2016). However, laboratory testing and theoretical models (Saar and Manga 1999; Mueller *et al.* 2005; Bai *et al.* 2010) clearly support high connectivity of vesicle networks above a percolation threshold of around *c.* 30% porosity in many cases (based on randomly distributed spheres), a value which is commonly reached in basaltic lava flow tops (Cashman and Kauahikaua 1997). Dense crystalline basalt associated with flow interiors will typically have permeability that is extremely low, i.e. $<10^{-16}$ m^2, suitable as effective seals, notwithstanding fractures which may be open or closed depending on setting (e.g. age, depth, stress state, alteration stage). Exceptions to this occur where clastogenic lava flows, those formed from the partial homogenization of fire fountaining deposits may maintain higher permeability within flow interiors (e.g. Greenfield *et al.* 2019; Fig. 4). Other examples include the compound lava documented from Öskjuhlíð, Iceland (Friðleifsson and Vilmundardóttir 1998; Franzson *et al.* 2001), which reveals an inverse relationship between porosity and permeability. Friðleifsson and Vilmundardóttir (1998) document textural evidence for inter-crystalline pores within the low-porosity, high-permeability samples, which appears consistent with a diktytaxitic texture that also yielded low-porosity and high-permeability analyses by Saar and Manga (1999) for samples of basaltic andesite from the Cascades Range.

A very common feature of ancient lava flows is for macroscopically isolated vesicles to be filled with secondary minerals, indicating microstructural controls (micro-fractures and inter-crystalline porosity) enabling saturation of pores, even at very low permeability. In detail, several studies have highlighted the variability of percolation threshold values for igneous rocks alongside porosity–permeability relationships for different vesicular rocks relating to differences in pore size, shape and distribution along with the impacts of shearing, cooling and fracturing (Wright *et al.* 2009; Farquharson *et al.* 2015; Kushnir *et al.* 2016; Lamur *et al.* 2017). For example, Kushnir *et al.* (2016) document the presence of two threshold porosities for andesitic to basaltic andesitic volcano sample permeabilities at *c.* 10.5% and *c.* 31% porosity, marking the transitions between domains where permeability is dominated variously by a combination of microcrack, diktytaxitic and vesicle pore structure controls (Fig. 4). Figure 4 presents a plot of porosity and permeability for global examples of lava flow sequences, measured at low pressure, highlighting the wide range in properties that can occur in nature.

Several authors have proposed porosity–permeability models for vesicular volcanic rocks, which are typically based on simplifications of the empirical Kozeny–Carman relationship (Carman 1937) in the form of a power-law relation but offset to higher porosities than for sedimentary rocks (Klug and Cashman 1996; Saar and Manga 1999). Mueller *et al.* (2005) presented two separate power-law trends for effusive compared with explosive volcanic rocks, with the latter models incorporating a critical porosity percolation threshold (Fig. 4), whilst modifications based on fractal pore-space geometry assumptions and Archies Law have also been proposed (Costa 2006). In the majority of experimental determinations of vesicular volcanic rock porosity and permeability, significant scatter is ubiquitous with permeability commonly spanning several orders of magnitude for a given porosity, and thus no general unified porosity–permeability relationship exists, although generalizations have been proposed (Navarro *et al.* 2020). In general, alteration of lava sequences appears to depress the permeability for a given porosity linked to pore throat clogging and is especially prevalent in older sequences which either are or have previously been deeply buried (Rossetti *et al.* 2019; Millett *et al.* 2021*b*). To highlight the potential impact of alteration, a trendline is plotted in Figure 4 based on the data compilation of Sigurðsson and Stefánsson (1994) covering lava samples spanning the smectite–zeolite through to epidote–actinolite alteration zones.

The matrix porosity and permeability of pāhoehoe lava flows is then highly dependent on the vesicle abundance and distribution, which vary considerably for different types and thicknesses of flow. The highest average primary porosities are likely linked to spongy pāhoehoe (e.g. Walker 1989; Wilmoth and Walker 1993), and the core–crust ratios of larger flows will have a first-order impact on the net-to-gross calculations of lava flow reservoirs (Yi *et al.* 2016). Typically, the percentage of crust relative to core broadly reduces with increasing flow thickness but significant variation can occur (Nelson *et al.* 2009; Millett *et al.* 2021*a*). In detail, features such as core–crust ratios, vesicle size distribution and coalescence may all be significantly influenced

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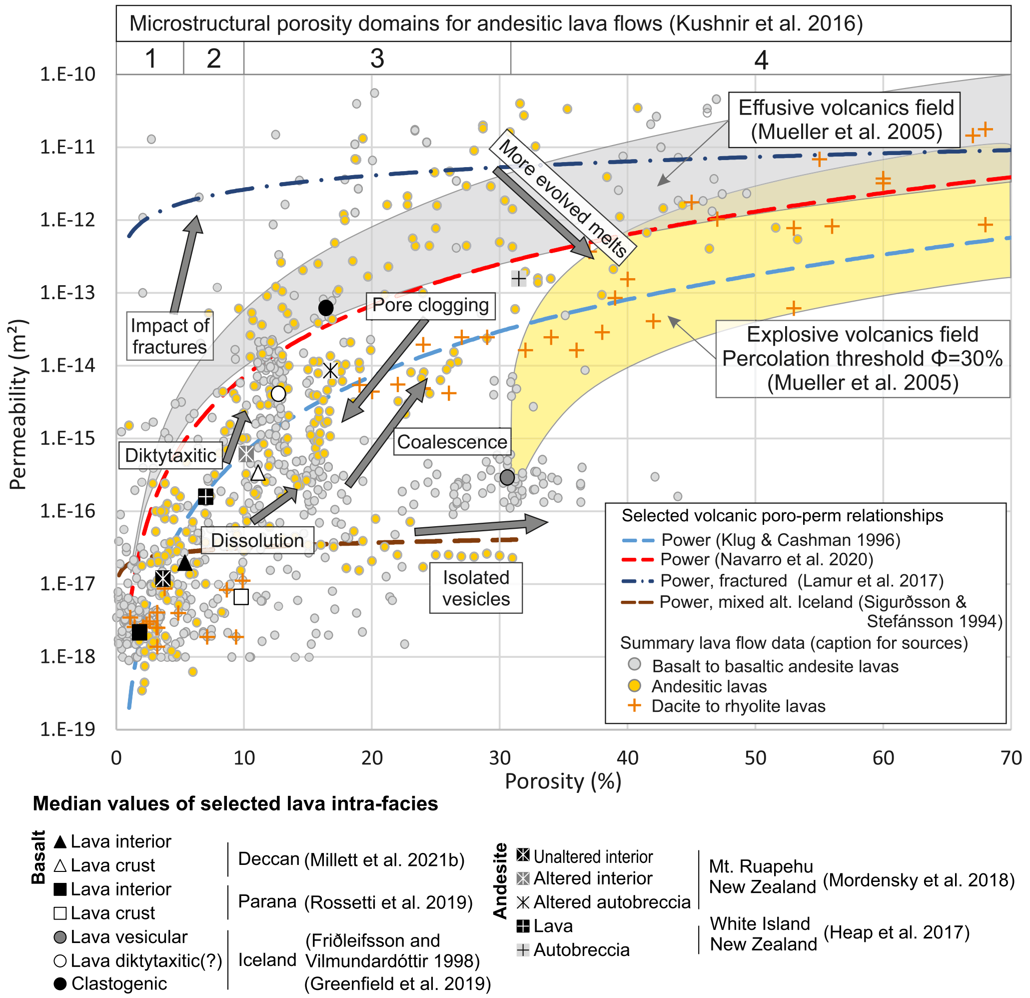

Fig. 4. Porosity v. permeability plotted for selected lava flows of mixed age, composition and alteration state along with selected literature models. The compilation of selected laboratory measurements on lava flows are grouped by composition including basalt to basaltic andesite (Sigurðsson and Stefánsson 1994; Friðleifsson and Vilmundardóttir 1998; Couves *et al.* 2016; Greenfield *et al.* 2019; Rossetti *et al.* 2019; Millett *et al.* 2021*b*; Marins *et al.* 2022), andesites (Bernard *et al.* 2007; Farquharson *et al.* 2015; Heap and Kennedy 2016; Kushnir *et al.* 2016; Heap *et al.* 2017; Cant *et al.* 2018; Mordensky *et al.* 2018), and examples of evolved dacitic to rhyolite composition flows (Rust and Cashman 2004; Rossetti *et al.* 2019) for comparison. Arrows show general relationships for key processes but are non-unique. As far as possible, ambient or near ambient pressure laboratory-measured effective porosity (gas pycnometer) and Klinkenberg-corrected gas permeability values have been plotted, but it should be noted that techniques vary between studies and readers are referred to the original publications for measurement details. Kushnir *et al.* (2016) domains include connected porosity–permeability microstructure relationships linked to (1) unknown, (2) microcrack- and diktytaxitic-controlled, (3) vesicle- and microcrack-controlled, and (4) vesicle controlled.

by distance to eruption source, and the efficiency of outgassing along lava flow pathways (Cashman *et al.* 1994). Other internal porosity features within lava flows may include diktytaxitic voids (irregular intercrystalline voids $<c.$ 0.2 mm; Saar and Manga 1999), and various vesicle segregation features that can complicate internal pore structures and vesicle distributions (Caroff *et al.* 2000; Nikkola *et al.* 2019). Based on oxygen isotopic analyses, Goff (1996) discussed the potential that vesicle cylinders formed in basalts with elevated water contents, potentially enhanced by subsurface addition of meteoric water. Other features associated with lavas flowing over water-saturated sediments such as spiracles,

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and the more explosive rootless cone formation (Reynolds *et al.* 2015), can impart significant vertical heterogeneities that may, for example, reduce the effectiveness of flow interiors to form effective seals upon burial.

The pore structure of ‘a‘ā lava flows has notable similarities and differences to the pāhoehoe features described above. As with pāhoehoe lava flows, ‘a‘ā lavas commonly reveal a three-part division with a flow top and base separated by a more massive, poorly vesicular flow interior; however, unlike pāhoehoe, ‘a‘ā lavas include an autobrecciated upper and lower flow margin breccia (Macdonald 1953). The ‘a‘ā lava interiors often display lower vesicle percentages compared to pāhoehoe lava (Cashman *et al.* 1999) whereas the autobreccia clasts, which can form diverse morphologies and porosities, commonly reveal abundant evidence for shearing and stretching of vesicles along with more irregular connected morphologies and rough interfaces linked to microlite presence (Cashman *et al.* 1999). Fully to partly ingested flow margin breccia clasts are commonly found associated with the flow interior to crust transitions of ‘a‘ā lavas (Crisp and Baloga 1994; Cashman *et al.* 1999). The addition of a well-connected interclast porosity network leads to initially highly permeable (over 10^{-11} m^2 or $>$10 D) flow margins, which are commonly identified as the most effective reservoir intervals both in younger and older lava reservoirs (Burns *et al.* 2012; Massiot *et al.* 2014; Millett *et al.* 2021*b*; Marins *et al.* 2022) and form, for example, the reservoir injection sites at the Wallula injection site (McGrail *et al.* 2011). In order to highlight these major differences in lava flow reservoir properties, Figure 5 presents a simplified schematic model of the pore structure in typical pāhoehoe and ‘a‘ā lava flows, along with emplacement examples, and typical core examples from the PTA2 borehole on Hawai’i (Jerram *et al.* 2019) using core-based terminology coined after Katz and Cashman (2003). Importantly, datasets like these are now becoming available where reservoir properties from core examples of lava flow facies (e.g. pāhoehoe, transitional and ‘a‘ā) can be examined along with their subsurface geophysical expressions (e.g. Jerram *et al.* 2019; Millett *et al.* 2021*b*; Marins *et al.* 2022).

Detailed studies characterizing the textural variations of transitional lava flows within ancient and recent eruptive deposits highlight the wide diversity of structures that occur in nature between the pāhoehoe and ‘a‘ā end-members (Keszthelyi 2002; Voigt *et al.* 2021). However, the documentation and discussion of impacts that these differences may have on reservoir sequences appear to be in their infancy from an applied perspective (Millett *et al.* 2021*b*; Marins *et al.* 2022). The influence of fracturing, both primary cooling/emplacement (Griffiths 2000; Schaefer and Kattenhorn 2004; Lamur *et al.* 2018; Vasseur and Wadsworth 2019), and secondary fracturing (Walker *et al.* 2013*a*, *b*; Heap and Kennedy 2016; Lamur *et al.* 2017) on permeability within lava flows can also be significant, potentially increasing permeability by several orders of magnitude. Appraisal of fracture spacing, timing and secondary mineral filling are therefore clearly important aspects of evaluating any lava flow reservoir sequence alongside original flow facies characterization.

Most lava flows therefore begin solidified life with a complex distribution of isolated matrix pores, connected matrix pores towards the margins, and often complex fracture $\pm$ autobreccia networks. The distribution of these features is, to a reasonable extent, predictable, enabling generic approximations of primary porosity and permeability for a given flow type (Fig. 5). A key point about these distributions is the proportion of permeable crust to low or impermeable interior, and that for most lava flows above a few metres thick both will typically be present. So, lava flows often represent reservoir–seal couplets which, when vertically stacked, impart a significant anisotropy onto any package of lavas that forms a reservoir interval (e.g. Oki *et al.* 1999; Reidel *et al.* 2002; Tolan *et al.* 2009; McGrail *et al.* 2011). These core–crust ratios can readily be appraised from subsurface wireline data when assessing lava flow reservoirs (Nelson *et al.* 2009; Millett *et al.* 2021*a*). Conventional porosity-dependent logs such as resistivity, neutron porosity, density and sonic, along with acoustic or electrical resistivity-based image logs, can all be used highly effectively for characterizing internal lava flow structures.

Secondary processes and burial

The primary porosity and permeability of lava flows form the blueprint for everything else that comes after, which is often where complexity can increase dramatically and non-uniquely. Even before burial, lava flows can quickly become highly altered due to subaerial exposure and meteoric weathering. Basaltic lava flows can be highly reactive under oxidizing conditions, a feature that is receiving much interest from the carbon storage industry (Matter *et al.* 2007) and, as such, alteration and pore clogging can rapidly alter initially good reservoir potential (Neuhoff *et al.* 1999; Millett *et al.* 2016*b*; Lee *et al.* 2021; Macente *et al.* 2022). Both eruptive frequency and palaeoclimate play an important role in surface weathering degree and efficiency prior to burial, with warmer climate and high rainfall promoting more rapid alteration, and long inter-eruptive hiatuses compounding these effects (Widdowson 1997; Jolley *et al.* 2012). Therefore, relatively rapid burial associated with high-frequency effusion events, effectively protecting lava flow margins from surface weathering, can be an important requirement

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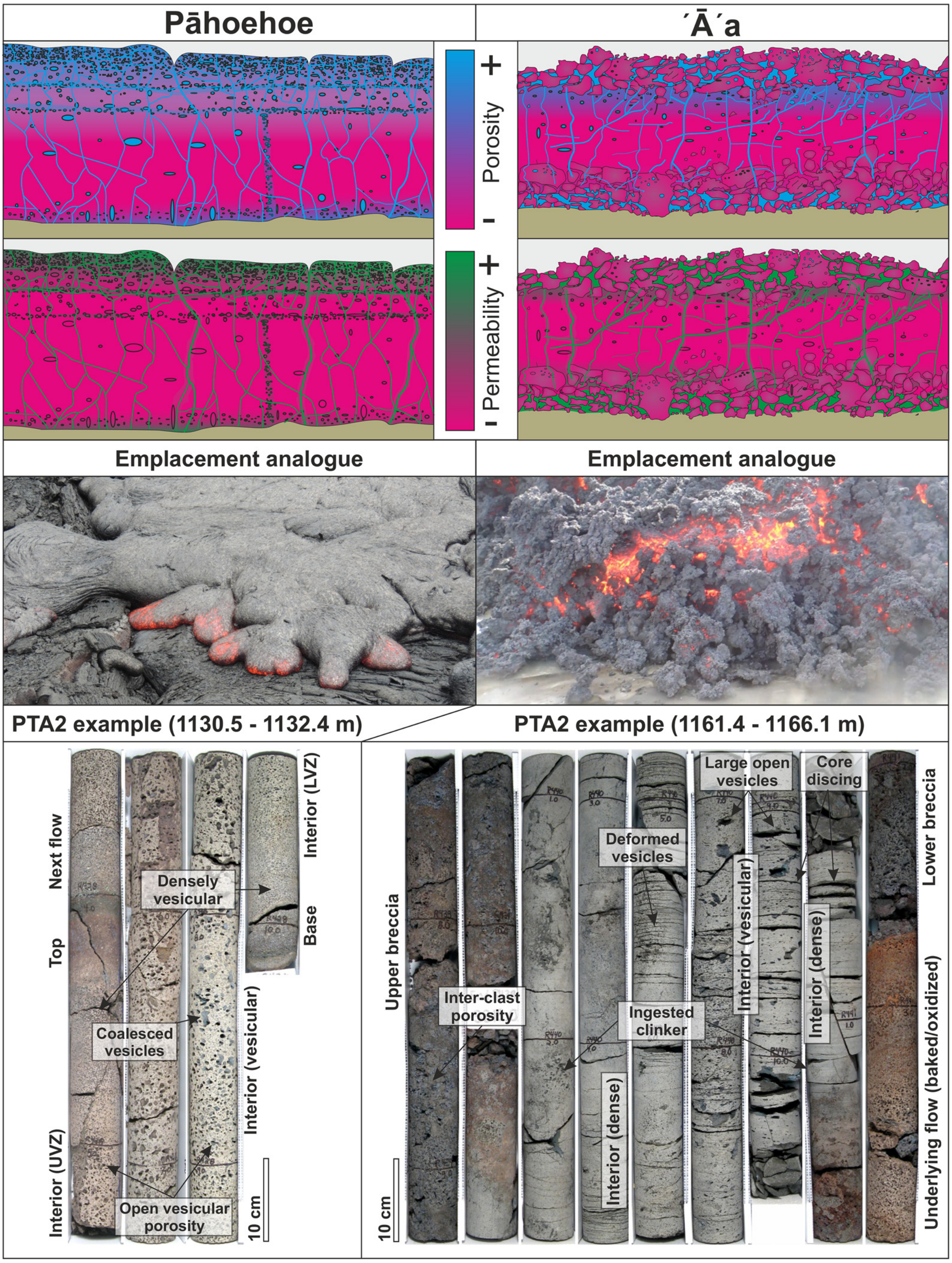

Fig. 5. Schematic sketches highlighting key differences between the pāhoehoe and ʻaʻā end-member lava flow morphologies with simplified conceptual distributions of porosity and permeability, emplacement examples from Hawaiʻi and Iceland, and core examples from the PTA2 borehole on Hawaiʻi. Source: Thomas and Haskins (2017), Jerram *et al.* (2019) and Pierdominici *et al.* (2020).

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in preserving good primary reservoir properties into the subsurface.

An intriguing feature of many lava flows is that they are initially intrinsically strong with porosities commonly >40% encased in a strong vesicular crystalline network that can withstand pressures associated with burial up to several kilometres prior to mechanical failure, a feature that separates them fundamentally from most sediments (Heap *et al.* 2014; Wang and Chen 2015; Millett *et al.* 2016*b*; Jerram *et al.* 2019). However, in lava flow samples with a lower porosity, and a poorly or largely unconnected vesicular pore network, matrix permeability is often low and associated with micro-fractures and intercrystalline pores, although exceptions with connected diktytaxitic textures occur. Unlike a connected vesicular pore network that can withstand elevated pressures, several studies have highlighted how the permeability of micro-fractured or fractured lava samples are highly stress-sensitive and likely reduce rapidly with greater burial depth (Lamur *et al.* 2017; Cant *et al.* 2018; Heap and Violay 2021). Autobrecciated lava flow margins, although potentially initially higher porosity than vesicular flow margins, clearly have lower strength and, as such, the evolution of reservoir properties with increasing compaction stress must be carefully assessed (e.g. Mordensky *et al.* 2018). Conversely, tectonic and burial processes can induce mechanical failure of lava flows accommodated through brittle failure and the introduction of fractures and faults (Walker *et al.* 2013*a*, *b*; Lamur *et al.* 2017). These structures typically form initially connected networks with secondary pore space and can potentially enhance reservoir performance, a feature often targeted in drilling strategies (Kumar *et al.* 2011). However, their effectiveness will also depend on their timing, age and degree of associated secondary mineralization.

In addition to stress-related burial influences, physicochemical processes of diagenesis and hydrothermal alteration typically produce textural and structural changes in primary mafic minerals, glass and feldspars, which can both degrade or enhance porosity and permeability within lava flow deposits (e.g. Sigurðsson *et al.* 2000; Sruoga and Rubinstein 2007; Kanakiya *et al.* 2017; Cant *et al.* 2018; Sun *et al.* 2018; Mordensky *et al.* 2019; Bischoff *et al.* 2021*b*; Macente *et al.* 2022; Scott *et al.* 2023). By their very nature, lava flows are deposited in volcanically active regions that often have high geothermal gradients and extensive hydrothermal fluid flow systems, which can impart fundamental changes to reservoir properties via alteration, dissolution of primary and secondary minerals, secondary mineralization, and changes to strength (Neuhoff *et al.* 1999; Kanakiya *et al.* 2017; Mordensky *et al.* 2018; Heap and Violay 2021; Scott *et al.* 2023). This can lead to highly complex pore structures in ancient and altered volcanic sequences (Zou *et al.* 2010; Rossetti *et al.* 2019; Marins *et al.* 2022). Both the presence and distribution of deformed authigenic clays can enhance rather than deteriorate permeability in faulted sandstones (Farrell *et al.* 2021). As such, the anisotropy of permeability within lava flow sequences, which naturally contain ubiquitous fracture networks capable of varying degrees and timings of slip, merits future study.

Much of what is known about alteration and secondary mineralization in modern and ancient lava fields comes from the geothermal industry, which utilizes secondary mineral assemblages such as zeolites associated with specific pressure/temperature conditions to characterize past and present geothermal conditions (e.g. Reyes 1990; Franzson *et al.* 2001; Weisenberger *et al.* 2020; Scott *et al.* 2023). In addition, the impact of hydrothermal alteration involving acidic CO_2-bearing fluids, and short-term heating on enhancing porosity and permeability in andesites in particular, is well documented (Kanakiya *et al.* 2017; Mordensky *et al.* 2019).

Early mapping of zeolite zones from field outcrops on Iceland led Walker (1960) to conclude that the palaeo-temperature of the exhumed system was independent of the lava flow stratigraphy. Similar conclusions have been drawn from ancient sequences on the Faroe Islands and Ireland among others, where zeolite zones were mapped notably with open porosity increasing in the upper portions of the preserved lava sequences of the Faroe Islands (Walker 1960; Jørgensen 2006). Whilst this may present an end-member case for systems which are able to equilibrate over long periods of time with a local heat source, it is questionable whether this is representative of examples where the heat source is transient or is removed, or in settings where the lava flow sequence is emplaced covering an area that spreads long distances from the active heat source, as can be the case for LIP sequences (e.g. Tolan *et al.* 2009; Self *et al.* 2021).

In many examples, the distribution of alteration within lava flows is not uniform as it is controlled by primary lava architecture, surface area, pore structure, and varies significantly for different compositions and different fluid–rock interaction conditions (Planke *et al.* 1999; Millett *et al.* 2016*a*, *b*; Rossetti *et al.* 2019; Scott *et al.* 2023). For example, in many cases, lava flow interiors, with low fracture-dominated porosity, can remain relatively fresh for long periods, after clogging of the fractures effectively stalls alteration reactions. Due to more open pore networks and greater surface areas, these reactions are able to progress further in flow tops (Franzson *et al.* 2001; Thien *et al.* 2015). Of particular relevance for large areal extent flow fields and thicker lava piles are the flow field architecture and

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initial hydrogeology, which will play a first-order role in dictating the pathways and impacts of hydrothermal fluids fed into these systems near to eruption sites from subsurface plumbing system intrusions.

In the Columbia River Basalt Group, USA, it is noted that there is a general trend of decreasing permeability of intra-flow aquifers with depth for individual wells based on extensive hydraulic testing. This feature is attributed to a combination of increasing effective stress and secondary mineral precipitation; however, exceptions with higher permeability at greater depths are also documented (USDOE 1988; Reidel *et al.* 2002). An important observation is that fractures within flow cores are observed to become highly mineralized at depth, whilst intra-flow reservoirs remain conductive, even if altered and at lower capacity. This highlights the development of the often encountered vertically layered sequences of seals (flow interiors) and reservoirs (flow margins; USDOE 1988).

A common observation from boreholes penetrating ancient lava flow sequences is that porosity occurrence and preservation are distinctly non-linear with depth, such that intervals with relatively fresh basalt and open porosity occur beneath and are interlayered with deeply altered and fully clogged intervals (e.g. Millett *et al.* 2016*a*; Jerram *et al.* 2019). Figure 6 presents an example from the ODP 642E borehole that penetrated a thick break-up-related lava flow sequence offshore mid-Norway (Planke 1994). Selected core examples are shown from different depths within the lava sequence. These display a complex and clearly not depth-systematic evolution of alteration and secondary mineralization, highlighting that reservoir properties within these sequences may be maintained to significant depths below the top volcanic surface (Harris and Higgins 2008). This feature is also identified in other deep boreholes in the NAIP (Millett *et al.* 2016*a*).

Secondary faulting, folding, erosional windows and intrusion emplacement can also have important impacts on lava flow reservoir architecture and properties after burial (Tolan *et al.* 2009; Walker *et al.* 2013*a*, *b*; Mordensky *et al.* 2018; Galland *et al.* 2023). Faulting and displacement of lava flow sequences are known to both vertically connect otherwise isolated reservoirs, and to lead to perched or compartmentalized aquifers by juxtaposing permeable with impermeable intra-flow layers forming structural barriers (Newcomb 1969). Dykes and other shallow intrusions can also form local barriers to flow, compartmentalizing or segmenting reservoir sequences (Newcomb 1969; Oki *et al.* 1999; Lachassagne *et al.* 2014). However, they are also identified as important fluid flow pathways (Schofield *et al.* 2020; Galland *et al.* 2023) which, when emplaced into lava sequences, may bypass sealing units such as mineralized flow interiors, making appraisal of intrusive impacts important. In addition, soil, volcaniclastic or ash layers, which may rapidly alter to form low permeability clay-bearing units during burial, can form stratigraphically constrained boundaries that, along with intrusions, can promote the development of perched lava-hosted aquifers (Oki *et al.* 1999).

Borehole appraisal of lava flows

An extensive literature exists focused on the interpretation of lava flow sequences from borehole data including from drill cuttings, core, sidewall core, remote geophysical data, or some combination of these (Broglia and Ellis 1990; Planke 1994; Keszthelyi 2002; Katz and Cashman 2003; Nelson *et al.* 2009; Watton *et al.* 2014; Millett *et al.* 2016*a*; Jerram *et al.* 2019; Quirie *et al.* 2019; Pierdominici *et al.* 2020; Millett *et al.* 2021*a*, *b*; Schofield *et al.* 2021; Marins *et al.* 2022). The characterization of porosity and permeability from borehole sequences of lava flows can, however, be challenging for a number of reasons. The neutron porosity log, which measures neutron absorption due to H within a formation, and is usually used to calculate porosity calibrated for a given matrix composition, is influenced by the presence of hydrous clays in altered volcanic rocks, typically leading to an overestimation of porosity (Broglia and Ellis 1990; Rosenqvist *et al.* 2023). In conventional borehole analyses, clay content can be assessed based on the natural gamma response in order to use density–neutron cross-plot approaches for porosity determinations. However, for basaltic volcanic rocks, gamma-ray values often remain constantly low even in altered and clay-rich formations, whilst primary changes in magma composition can also have a significant effect, complicating such approaches (Planke *et al.* 1999; Kumar 2006; Gupta *et al.* 2012; Millett *et al.* 2021*b*). Broglia and Ellis (1990) highlighted this challenge for ODP sites, including hole 642E, and presented a corrected total porosity by addressing both stand-off (lack of tool contact with the borehole wall), and the presence of hydrous alteration minerals calibrated from core, as plotted in Figure 6. The challenge is that for many wells, core is not available from which to calibrate the hydrous minerals, and they can be highly diverse.

Density-based porosity determination, utilizing the matrix density of volcanic rocks, is robust for fresh mineralogically uniform lava flow sequences, but suffers similar problems as the neutron log where matrix density is changed (typically reduced by the conversion to lower-density alteration minerals) at altered flow margins (Franzson *et al.* 2001), leading to an overestimation of porosities at flow margins (Rosenqvist *et al.* 2023). It should be noted that in high-temperature hydrothermal settings, more

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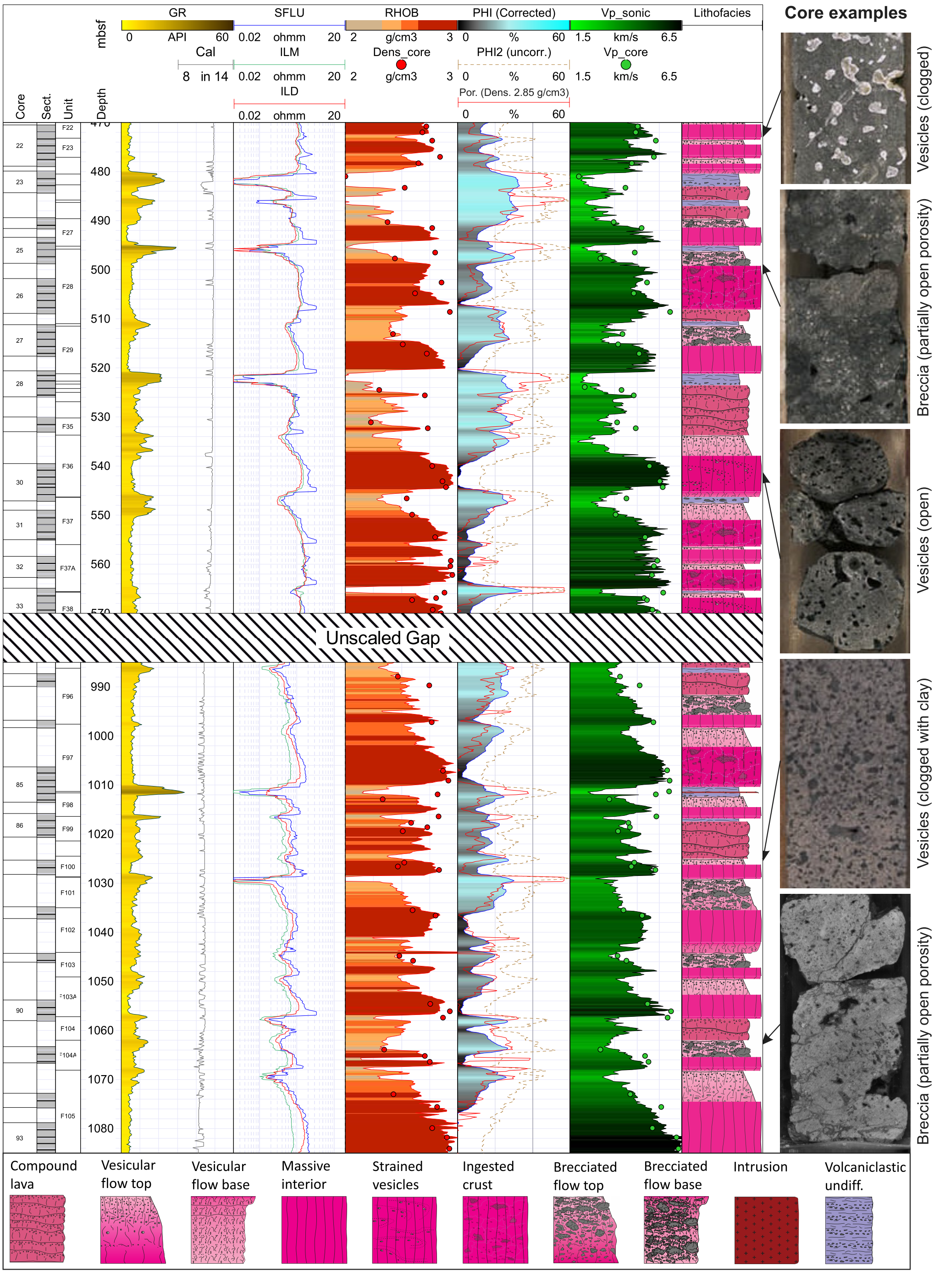

Fig. 6. Standard wireline log data through earliest Eocene basaltic lava flows in the ODP 642E borehole. Highlighted images are examples from the core revealing the complicated history of alteration and secondary mineral fills throughout the borehole. Source: volcanic facies modified after Planke (1994).

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dense secondary minerals can become stable at higher temperatures, potentially reversing this effect (e.g. Sigurðsson *et al.* 2000; Franzson *et al.* 2001). Core calibration can again be used to appraise the range of matrix density variations if available, and to derive multiple or dynamic models based on, for example, the correlation between matrix density and other wireline logs such as sonic. However, the literature treating this subject is to date limited, to our knowledge. Models based on velocity–porosity and derived permeability relations have been proposed (e.g. Navarro *et al.* 2020). However, as will be discussed in the next section, V_p–porosity relationships are often complex and lead to large uncertainties. Nuclear magnetic resonance logging can offer a robust solution for determining porosity and permeability of lava sequences (Chowdhury *et al.* 2014; Millett *et al.* 2021*b*) but may be influenced by the presence of magnetic minerals.

Electrical resistivity logs also form a powerful tool for appraising lava flow reservoirs, with the identification of invasion profiles giving an indirect measure of permeability where drilling fluid has a different salinity to formation fluids. However, in detail, the resistivity structure of volcanic rocks, and especially altered volcanic rocks can be highly complex. Wright *et al.* (2009) present a detailed summary of the impacts of different volcanic pore structures on electrical conductivity, highlighting that pore structure tortuosities decrease with increasing porosity for isotropic vesicular networks, but decrease with increasing deformation/stretching, such that application of a single Archies law fit to complex volcanic rocks is likely inappropriate. In addition to pore structure complexities, alteration mineralogy has a first-order impact on cation exchange capacity (CEC), and therefore resistivity, with common alteration and secondary minerals such as clays and zeolite having a marked effect (Weisenberger *et al.* 2020). In particular, geothermal wells on Iceland reveal an exponential decrease in CEC with depth, in line with increasing degrees and temperatures of alteration and secondary minerals. Therefore, differentiating between pore structure, mineralogy and fluid effects (if they are present) within lava flow sequences can be challenging and often requires additional focused studies on a case-by-case basis (Scott *et al.* 2023).

Seismic properties and reservoir monitoring

Several reservoir models for lava flow sequences have been published (Pollyea *et al.* 2014; Jayne *et al.* 2019; Ratouis *et al.* 2022) and have ranged from treating lava flow successions as relatively simple or layer cake units through to more volcanologically complex models. It is not a simple task to define what level of detail/gridding is adequate/appropriate for different lava flow reservoir settings, with the range spanning from thick tabular flood lava successions that may be relatively consistent over tens to hundreds of kilometres, to small-scale volcanoes and lava fields that may show huge variations within the space of 1 km. A fundamental and related component of characterizing lava flow sequences relates to their seismic properties, which have been studied extensively for decades (Planke 1994; Bücker *et al.* 1998; Bartetzko *et al.* 2005; Nelson *et al.* 2009). Lava flows reveal systematic and archetypal wireline responses that can be used to confidently infer facies type and information about porosity structures, even when no or limited core is available (Boldreel 2006; Nelson *et al.* 2009; Millett *et al.* 2021*a*). Figure 6 reveals textbook examples of simple and compound lava flows, with core observations enabling differentiation of pāhoehoe, ‘a’ā, and transitional forms where core recovery permits. The relationship between porosity and velocity, which underpins many modern approaches to rock physics modelling in conventional clastic and carbonate reservoir applications (Avseth *et al.* 2010), is, however, not straightforward for lava flows (Rossetti *et al.* 2019; Avseth *et al.* 2021). In Figure 7, a compilation of low pressure petrophysical data for lava flows from various global examples is compiled and compared with data fields for carbonate and sandstone from Avseth *et al.* (2010). Whereas clastic sedimentary rocks are typically regarded as approaching a critical porosity at *c.* 40% (sandstone), above which they become a suspension (Dvorkin and Nur 2002), vesicular basalt can exist as a coherent rock with porosities exceeding 70% (Mangan *et al.* 1993). The data reveal a wide spread of velocities for a given porosity, overlapping with both carbonates and sandstones. A rock physics modelling strategy is adapted (Avseth *et al.* 2021), utilizing physical bounds that interpolate between given critical porosity values and the effective mineralogical end-members representing lava flow matrix compositions. These diagnostic rock physics templates provide a framework for disentangling the complex interplay between multiple geological factors on elastic properties, including primary composition, secondary alteration, secondary mineralization and different pore structures. Hence, the rock physics link can reveal clear applications for better understanding and modelling lava flow reservoirs (Rossetti *et al.* 2019; Avseth *et al.* 2021). One important aspect of vesicular volcanic rocks, which is similar to what is seen in many carbonate reservoir rocks, is that the stiff matrix framework may make seismic monitoring of reservoirs undergoing fluid extraction or injection (fluid substitution effects) challenging to image (Avseth *et al.* 2021). This is clearly an area requiring new data and future

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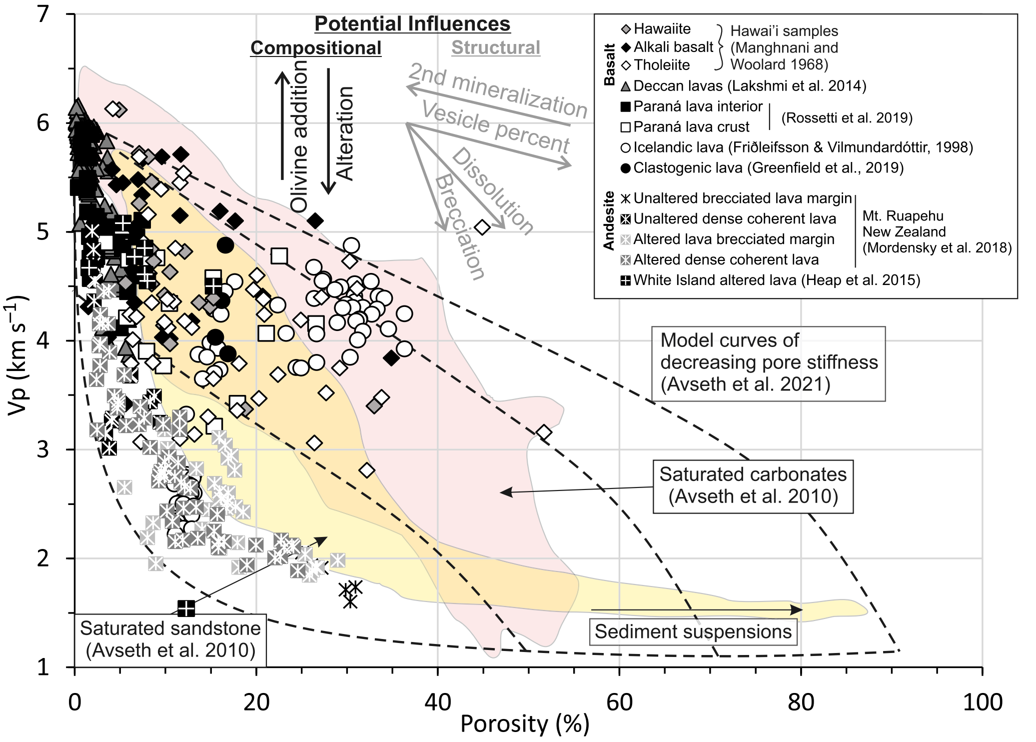

Fig. 7. P-wave velocity v. porosity for a range of field outcrop-based studies from different volcanic provinces. Hashin Strickman bounds are plotted along with different pore stiffness trends. Schematic arrows indicate common influences that can change sample properties. Note, the volcanic data are all measured dry at a low pressure, see original sources for details. Source: after Avseth *et al.* (2021) and modified after Rossetti *et al.* (2019).

development in order to develop and test safe monitoring and reservoir simulation approaches for both onshore and offshore applications.

Future outlook

Lava flow reservoirs have been utilized for centuries for fresh water and appear likely to continue to expand into an increasingly diverse range of uses going forward. The drinking water of millions of people and billions of dollars of agriculture depend on the careful monitoring and management of these resources, which will likely be influenced by future climate change, including changes in the volume, distribution and properties of run-off alongside likely increasing usage pressures. Additional and expanding utilization includes geothermal, petroleum and carbon storage applications, all of which are pivotal for the energy transition. Major differences exist between relatively young lava flows (e.g. Neogene/Quaternary; see Table 1), which host most documented lava flow reservoirs and commonly have excellent reservoir properties, compared with older and/or more altered lava flow reservoirs. Older and altered lava flows can also form effective reservoirs in some circumstances, whereas at the extreme end-member, alteration and secondary mineralization can transform previously porous and permeable lava flow reservoirs into impermeable rocks. Primary lava flow facies and intra-facies related to emplacement, including importantly the presence of flow margin breccias, flow thickness, core–crust ratios and fractures, all influence reservoir properties of individual lava flows. The presence of flow margin breccias, in particular, appears to enhance reservoir potential. However, more research is required on how these initially excellent reservoir properties evolve with increasing burial depth and changing compaction stresses relative to strong vesicular pore networks.

Beyond individual lava flows, the stacking patterns and architecture of lava flow sequences have important influences on primary reservoir property distributions at the larger scale. These in turn dictate how various fluids (hydrothermal, groundwater, petroleum) migrate, in turn, impacting the alteration, dissolution and secondary mineralization responsible for modifying lava flow reservoir properties. The same is true for modern injection scenarios

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where, for example, reactive transport and reservoir evolution due to injection of CO_2 has been the focus of much recent study. Clearly, improved methods and procedures for predicting and appraising lava flow reservoir properties, property distributions and alteration states are important for future utilizations. This requires improved integration of laboratory, borehole and field analogue data in order to build robust reservoir models for these often-complex systems with a specific focus on the important differences between initial reservoir properties and differing states of alteration, dissolution

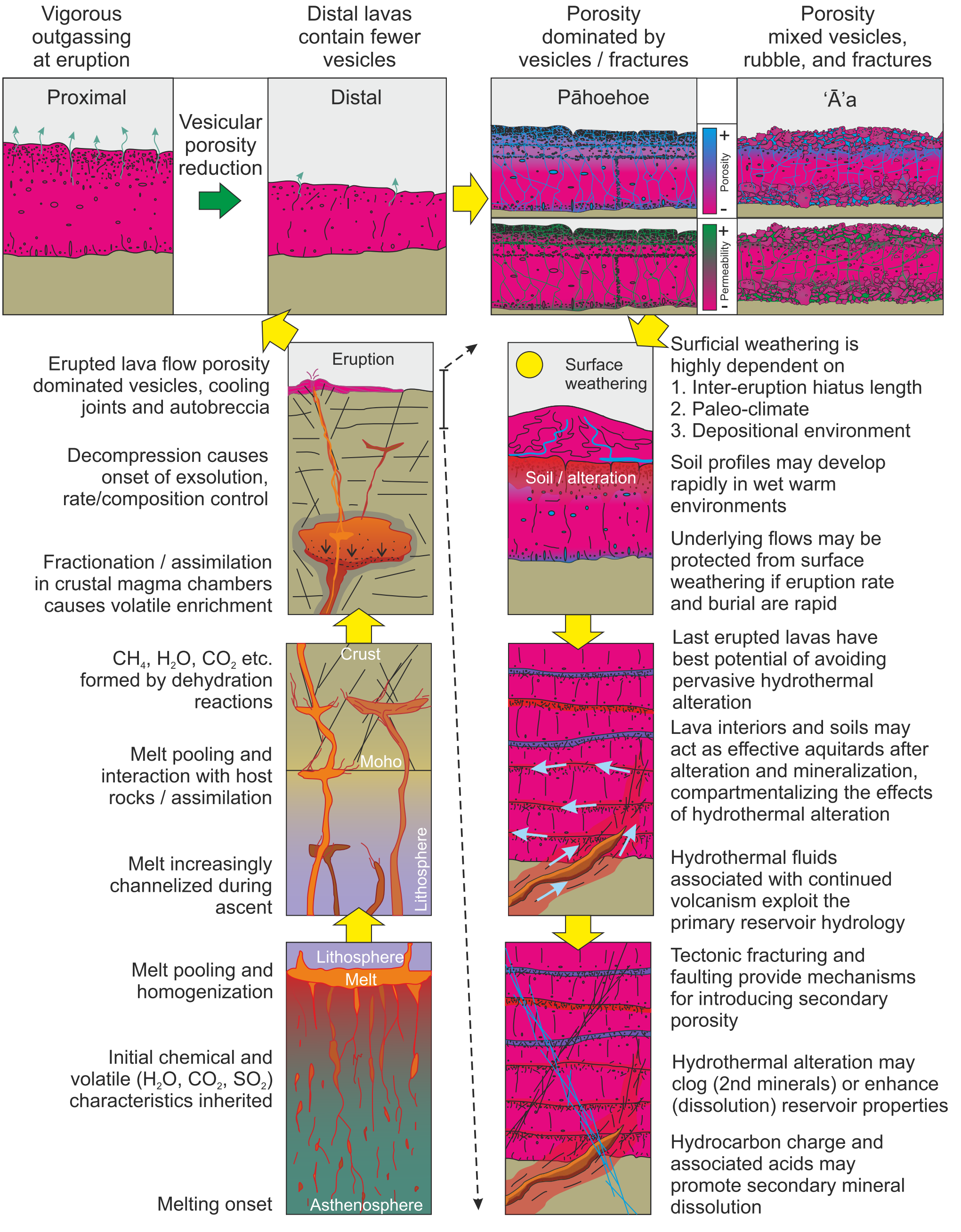

Fig. 8. Conceptual overview of the processes that contribute to and influence lava flow-hosted reservoirs.

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and secondary mineral clogging. In particular, the development of fit-for-purpose igneous rock physics templates, which can aid in sensitivity testing, imaging and monitoring of subsurface lava sequences, is needed going forward. While several of the applications discussed herein, including in particular carbon storage, have demonstrated efficiency in laboratory-controlled and small-scale pilot projects, their widespread adoption, and therefore impact, will critically depend on their implementation costs relative to alternative reservoirs. Robust appraisal of the risks and benefits of new geoenergy enterprises utilizing lava flow reservoirs requires improved understanding of the geological controls on reservoir properties and performance in the diverse settings where they occur. Clearly, these need to be balanced against the economic, social and environmental impacts of utilization going forward.

Summary

This contribution provides a condensed review of working lava flow reservoirs from around the globe, including examples utilized for water aquifers, geothermal energy, hydrocarbons and carbon storage. In addition, an appraisal of key factors that influence lava flow reservoir properties, focusing on the most common mafic to intermediate flow compositions is presented. The study draws on field outcrops, facies analyses, extensive published laboratory petrophysical data (porosity, permeability and velocity), theoretical models and borehole appraisal techniques. Figure 8 summarizes some of the main geological processes that can be considered when appraising a lava flow-hosted reservoir sequence from melting and magma properties, melt migration, eruption, surface weathering and subsequent burial. Based on this review, a number of conclusions can be made.

- Lava flow reservoirs are complex but incorporate a combination of volcanic properties that are well understood and for which petrophysical data are becoming rapidly more available.
- High porosity and permeability in pāhoehoe lava flow top facies are related to the partial coalescence of vesicles along with fractures.
- In addition to vesicles and fractures, ‘a’ā lava flows, along with several transitional varieties, incorporate autobreccia within their flow margins, which can significantly increase permeability, making these styles of lava flow a key target for exploration.
- Volcanic basins incorporate processes associated with magmatism that often expose lava flow reservoirs to conditions rarely experienced in non-volcanic basins, such as high-temperature hydrothermal circulation, which has the potential to change the reservoir properties significantly either negatively by clogging pores, or also positively by dissolution.
- Permeability at greater confining pressures remains near constant for vesicular rocks due to strong framework strength, a feature significantly different from clastic rocks but similar to some carbonates, although alteration can reduce lava flow strength substantially.
- Cooling joints and fracturing associated with lava flow emplacement (inflation and flow) form critical additional primary porosity and permeability. Like flow margins, these pores can become clogged and sealing in older deeply buried lava flow sequences. However, due to smaller relative porosity and surface areas, they often appear to become filled more effectively during burial.
- Rock physics approaches, which are in extensive use for conventional reservoirs, are in their infancy in terms of application to volcanic rocks but show promise and require significant focus going forward.
- A holistic approach to understanding lava flow reservoirs is required in order to better understand and begin to predict reservoir potential in different basins and settings.

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formal analysis (equal), investigation (equal), visualization (supporting), writing – original draft (supporting), writing – review & editing (supporting); **SP**: conceptualization (supporting), methodology (supporting), writing – review & editing (supporting); **DH**: conceptualization (supporting), methodology (supporting), writing – review & editing (supporting); **DAJ**: conceptualization (equal), funding acquisition (equal), project administration (equal), supervision (supporting), writing – review & editing (supporting); **SP**: conceptualization (equal), data curation (supporting), formal analysis (supporting), funding acquisition (equal), methodology (supporting), software (supporting), writing – review & editing (supporting).

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Data availability Data sharing is not applicable to this article as no datasets were generated during the current study.

References

Ackerman, D.J., Rousseau, J.P., Rattray, G.W. and Fisher, J.C. 2010. *Steady-State and Transient Models of Groundwater Flow and Advective Transport, Eastern Snake River Plain Aquifer, Idaho National Laboratory and Vicinity, Idaho*. US Department of the Interior, US Geological Survey.

Ahmed, A.H., Rayaleh, W.E., Zghibi, A. and Ouddane, B. 2017. Assessment of chemical quality of groundwater in coastal volcano-sedimentary aquifer of Djibouti, Horn of Africa. *Journal of African Earth Sciences*, **131**, 284–300, https://doi.org/10.1016/j.jafrearsci.2017.04.010

Anderson, S.R. and Liszewski, M.J. 1997. *Stratigraphy of the Unsaturated Zone and the Snake River Plain Aquifer at and Near the Idaho National Engineering Laboratory, Idaho*. US Department of the Interior, US Geological Survey.

Aunzo, Z., Bodvarsson, G.S., Laky, C., Lippmann, M.J., Steingrimsson, B., Truesdell, A.H. and Witherspoon, P.A. 1989. *The Ahuachapan Geothermal field, El Salvador: Reservoir Analysis (No. LBL-26612-Vol. 1)*. Lawrence Berkeley Lab., CA, USA.

Avseth, P., Mukerji, T. and Mavko, G. 2010. *Quantitative Seismic Interpretation: Applying Rock Physics Tools to Reduce Interpretation Risk*. Cambridge University Press.

Avseth, P., Millett, J., Jerram, D., Planke, S. and Healy, D. 2021. Rock physics analysis of volcanic lava flows and hyaloclastites. Paper presented at the 82nd EAGE Annual Conference and Exhibition, Amsterdam, The Netherlands, EAGE Publications BV.

Bai, L., Baker, D.R. and Hill, R.J. 2010. Permeability of vesicular Stromboli basaltic glass: Lattice Boltzmann simulations and laboratory measurements. *Journal of Geophysical Research: Solid Earth*, **115**, https://doi.org/10.1029/2009JB007047

Bartetzko, A., Delius, H. and Pechnig, R. 2005. Effect of compositional and structural variations on log responses of igneous and metamorphic rocks. I: mafic rocks. *Geological Society, London, Special Publications*, **240**, 255–278, https://doi.org/10.1144/GSL.SP.2005.240.01

Benson, S., Cook, P. *et al*. 2005. Underground geological storage. *In*: Metz, B., Davidson, O., Coninck, H. and Loos, M.L.M. (eds) *IPCC Special Report on Carbon Dioxide Capture and Storage*, 1st edn. Cambridge University Press, 195–276.

Bernard, M.L., Zamora, M., Géraud, Y. and Boudon, G. 2007. Transport properties of pyroclastic rocks from Montagne Pelée volcano (Martinique, Lesser Antilles). *Journal of Geophysical Research: Solid Earth*, **112**, https://doi.org/10.1029/2006JB004385

Bertrand, G., Celle-Jeanton, H., Huneau, F., Loock, S. and Renac, C. 2010. Identification of different groundwater flowpaths within volcanic aquifers using natural tracers for the evaluation of the influence of lava flows morphology (Argnat basin, Chaîne des Puys, France). *Journal of Hydrology*, **391**, 223–234, https://doi.org/10.1016/j.jhydrol.2010.07.021

Bischoff, A., Adam, L. *et al*. 2021*a*. Underground hydrogen storage in sedimentary and volcanic rock reservoirs: foundational research and future challenges for New Zealand. EGU General Assembly Conference Abstracts, EGU21-3496.

Bischoff, A., Fensom, J., Tang, H., Rosetti, M., and Nicol, A. 2021*b*. Processes controlling volcanic and epiclastic reservoir formation in a buried polygenetic stratocone. *Geological Society, London, Special Publications*, **520**, 285–310, https://doi.org/10.1144/SP520-2021-137

Boldreel, L.O. 2006. Wireline log-based stratigraphy of flood basalts from the Lopra-1/1A well, Faroe Islands. *Geological Survey of Denmark and Greenland Bulletin*, **9**, 7–22, https://doi.org/10.34194/geusb.v9.4855

Broglia, C. and Ellis, D. 1990. Effect of alteration, formation absorption, and standoff on the response of the thermal neutron porosity log in gabbros and basalts: examples from Deep Sea Drilling Project-Ocean Drilling Program Sites. *Journal of Geophysical Research: Solid Earth*, **95**, 9171–9188, https://doi.org/10.1029/JB095iB06p09171

Bryan, S.E. and Ferrari, L. 2013. Large igneous provinces and silicic large igneous provinces: progress in our understanding over the last 25 years. *GSA Bulletin*, **125**, 1053–1078, https://doi.org/10.1130/B30820.1

Bryan, S.E., Peate, I.U., Peate, D.W., Jerram, D.A., Mawby, M.R., Marsh, J.S. and Miller, J.A. 2010. The largest volcanic eruptions on Earth. *Earth-Science Reviews*, **102**, 207–229, https://doi.org/10.1016/j.earscirev.2010.07.001

Bubeck, A., Walker, R.J., Healy, D., Dobbs, M. and Holwell, D.A. 2017. Pore geometry as a control on rock strength. *Earth and Planetary Science Letters*, **457**, 38–48, https://doi.org/10.1016/j.epsl.2016.09.050

Bücker, C.J., Cashman, K.V. and Planke, S. 1998. Physical and magnetic characterization of aa and pahoehoe flows: Hole 990A. *Proceedings of the ODP, Scientific Results*, **163**, 41–49.

Burns, E.R., Snyder, D.T., Haynes, J.V. and Waibel, M.S. 2012. *Groundwater Status and Trends for the*

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Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho. US Department of the Interior, US Geological Survey.

Cant, J.L., Siratovich, P.A., Cole, J.W., Villeneuve, M.C. and Kennedy, B.M. 2018. Matrix permeability of reservoir rocks, Ngatamariki geothermal field, Taupo Volcanic Zone, New Zealand. *Geothermal Energy*, **6**, 1–28, https://doi.org/10.1186/s40517-017-0088-6

Carman, P.C. 1937. Fluid flow through granular beds. *Chemical Engineering Research and Design*, **75**, S32–S48, https://doi.org/10.1016/S0263-8762(97)80003-2

Carneiro, P., Dullius, J., Lagabue, R., Machado, C., Ketzer, J.M. and Einloft, S. 2013. Basalt carbonation and its potential use in CO_2 storage. *Technology in Metallurgy, Materials and Mining*, **10**, 43–49.

Caroff, M., Maury, R.C., Cotten, J. and Clément, J.P. 2000. Segregation structures in vapor-differentiated basaltic flows. *Bulletin of Volcanology*, **62**, 171–187, https://doi.org/10.1007/s004450000077

Cashman, K.V. and Kauahikaua, J.P. 1997. Reevaluation of vesicle distributions in basaltic lava flows. *Geology*, **25**, 419–422, https://doi.org/10.1130/0091-7613(1997)025<0419:ROVDIB>2.3.CO;2

Cashman, K.V., Mangan, M.T. and Newman, S. 1994. Surface degassing and modifications to vesicle size distributions in active basalt flows. *Journal of Volcanology and Geothermal Research*, **61**, 45–68, https://doi.org/10.1016/0377-0273(94)00015-8

Cashman, K.V., Thornber, C. and Kauahikaua, J.P. 1999. Cooling and crystallization of lava in open channels, and the transition of pāhoehoe lava to ‘a'ā. *Bulletin of Volcanology*, **61**, 306–323, https://doi.org/10.1007/s004450050299

Cashman, K.V., Mangan, M.T. and Poland, M. 2014. A century of studying effusive eruptions in Hawai'i. Characteristics of Hawaiian volcanoes. *US Geological Survey Professional Paper*, **1801**, 357–394, https://doi.org/10.3133/pp18019

Chowdhury, M., Guha, R. *et al*. 2014. Characterization of volcanic reservoir-New integrated approach: a case study from Raageshwari Deep Gas Field, Rajasthan, India. International Petroleum Technology Conference, OnePetro, Doha, Qatar.

Cinti, D., Poncia, P.P., Brusca, L., Tassi, F., Quattrocchi, F. and Vaselli, O. 2015. Spatial distribution of arsenic, uranium and vanadium in the volcanic-sedimentary aquifers of the Vicano–Cimino Volcanic District (Central Italy). *Journal of Geochemical Exploration*, **152**, 123–133, https://doi.org/10.1016/j.gexplo.2015.02.008

Clague, D.A. and Frey, F.A. 1982. Petrology and trace element geochemistry of the Honolulu Volcanics, Oahu: implications for the oceanic mantle below Hawaii. *Journal of Petrology*, **23**, 447–504, https://doi.org/10.1093/petrology/23.3.447

Coffin, M.F. and Eldholm, O. 1994. Large igneous provinces: crustal structure, dimensions, and external consequences. *Reviews of Geophysics*, **32**, 1–36, https://doi.org/10.1029/93RG02508

Costa, A. 2006. Permeability–porosity relationship: a reexamination of the Kozeny–Carman equation based on a fractal pore-space geometry assumption. *Geophysical Research Letters*, **33**, L02318, https://doi.org/10.1029/2005GL025134

Couves, C., Roberts, R., Racey, A., Troth, I. and Best, A. 2016. Use of X-ray computed tomography to quantify the petrophysical properties of volcanic rocks: a case study from Tenerife, Canary Islands. *Journal of Petroleum Geology*, **39**, 79–94, https://doi.org/10.1111/jpg.12629

Crisp, J. and Baloga, S. 1994. Influence of crystallization and entrainment of cooler material on the emplacement of basaltic aa lava flows. *Journal of Geophysical Research: Solid Earth*, **99**, 11819–11831, https://doi.org/10.1029/94JB00134

Custodio, E. 1989. Groundwater characteristics and problems in volcanic rock terrains. *In*: *Isotope Techniques in the Study of the Hydrology of Fractured and Fissured Rocks*. International Atomic Energy Agency (IAEA).

Descovi, P.L., Ade, M.V.B., De Oliveira Avellar, G., Bermúdez, S.L.B. and Vieira, F.P. 2021. Volcanic reservoirs: historic and current context. *Pesquisas em Geociências*, **48**, e104451–e104451, https://doi.org/10.22456/1807-9806.104451

du Bray, E.A. 2017. Geochemical characteristics of igneous rocks associated with epithermal mineral deposits – a review. *Ore Geology Reviews*, **80**, 767–783, https://doi.org/10.1016/j.oregeorev.2016.08.023

Dvorkin, J. and Nur, A. 2002. Critical-porosity models. *AAPG Memoirs*, **76**, 33–42, https://doi.org/10.1306/M76870C4

Eidesgaard, Ó.R., Schovsbo, N.H., Boldreel, L.O. and Ólavsdóttir, J. 2019. Shallow geothermal energy system in fractured basalt: a case study from Kollafjørður, Faroe Islands, NE-Atlantic Ocean. *Geothermics*, **82**, 296–314, https://doi.org/10.1016/j.geothermics.2019.07.005

Farquharson, J., Heap, M.J., Varley, N.R., Baud, P. and Reuschlé, T. 2015. Permeability and porosity relationships of edifice-forming andesites: a combined field and laboratory study. *Journal of Volcanology and Geothermal Research*, **297**, 52–68, https://doi.org/10.1016/j.jvolgeores.2015.03.016

Farrell, N.J.C., Debenham, N. *et al.* 2021. The effect of authigenic clays on fault zone permeability. *Journal of Geophysical Research: Solid Earth*, **126**, e2021JB022615, https://doi.org/10.1029/2021JB022615

Fenta, M.C., Anteneh, Z.L., Szanyi, J. and Walker, D. 2020. Hydrogeological framework of the volcanic aquifers and groundwater quality in Dangila Town and the surrounding area, Northwest Ethiopia. *Groundwater for Sustainable Development*, **11**, 100408, https://doi.org/10.1016/j.gsd.2020.100408

Finch, R.H. 1933. Block lava. *Journal of Geology*, **41**, 769–770, https://doi.org/10.1086/624096

Fornero, S.A., Marins, G.M., Lobo, J.T., Freire, A.F.M. and de Lima, E.F. 2019. Characterization of subaerial volcanic facies using acoustic image logs: lithofacies and log-facies of a lava-flow deposit in the Brazilian pre-salt, deepwater of Santos Basin. *Marine and Petroleum Geology*, **99**, 156–174, https://doi.org/10.1016/j.marpetgeo.2018.09.029

Franzson, H., Gudlaugsson, S.T. and Fridleifsson, G.O. 2001. Petrophysical properties of Icelandic rocks. Sixth Nordic Symposium on Petrophysics, Trondheim, Norway, Nordic Petroleum Technology Series VI.

Friðleifsson, G.Ó. and Vilmundardóttir, E.G. 1998. Reservoir parameters TCP-project: a thin-section

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study of the Öskuhlíð samples, Orkustofnun, Reykjavik, Iceland, OS-98041.

Fugro Tellus 2013. Sedimentary Basins of the World, available at http://www.datapages.com/AssociatedWebsites/GISOpenFiles/FugroTellusSedimentaryBasinsoftheWorldMap.aspx [last accessed July 2013].

Furuya, S., Aoki, M., Gotoh, H. and Takenaka, T. 2000. Takigami geothermal system, northeastern Kyushu, Japan. *Geothermics*, **29**, 191–211, https://doi.org/10.1016/S0375-6505(99)00059-0

Galland, O., Villar, H.J. *et al*. 2023. The long-term legacy of subvolcanic intrusions on fluid migration in sedimentary basins: the Cerro Alquitrán case study, northern Neuquén Basin, Argentina. *Basin Research*, **35**, 1840–1855, https://doi.org/10.1111/bre.12782

Garboczi, E.J., Snyder, K.A., Douglas, J.F. and Thorpe, M.F. 1995. Geometrical percolation threshold of overlapping ellipsoids. *Physical Review E*, **52**, 819–828, https://doi.org/10.1103/PhysRevE.52.819

Giordano, D., Russell, J.K. and Dingwell, D.B. 2008. Viscosity of magmatic liquids: a model. *Earth and Planetary Science Letters*, **271**, 133–134, https://doi.org/10.1016/j.epsl.2008.03.038

Goff, F. 1996. Vesicle cylinders in vapor-differentiated basalt flows. *Journal of Volcanology and Geothermal Research*, **71**, 167–185, https://doi.org/10.1016/0377-0273(95)00073-9

Goldberg, D.S., Kent, D.V. and Olsen, P.E. 2009. Potential on-shore and off-shore reservoirs for CO_2 sequestration in Central Atlantic magmatic province basalts. *Proceedings of the National Academy of Sciences*, **107**, 1327–1332, https://doi.org/10.1073/pnas.0913721107

Greenfield, L., Millett, J.M. *et al*. 2019. The 3D facies architecture and petrophysical properties of hyaloclastite delta deposits: an integrated photogrammetry and petrophysical study from southern Iceland. *Basin Research*, **32**, 1081–1104, https://doi.org/10.1111/bre.12415

Griffiths, R.W. 2000. The dynamics of lava flows. *Annual Review of Fluid Mechanics*, **32**, 477–518, https://doi.org/10.1146/annurev.fluid.32.1.477

Guest, J.E., Duncan, A.M., Stofan, E.R. and Anderson, S.W. 2012. Effect of slope development on pāhoehoe lava fields: Evidence from Mount Etna. *Journal of Volcanology and Geothermal Research*, **219–220**, 52–62, https://doi.org/10.1016/j.jvolgeores.2012.01.006

Gunnarsdottir, M.J., Gardarsson, S.M., Jonsson, G.S. and Bartram, J. 2016. Chemical quality and regulatory compliance of drinking water in Iceland. *International Journal of Hygiene and Environmental Health*, **219**, 724–733, https://doi.org/10.1016/j.ijheh.2016.09.011

Gupta, S.D., Chatterjee, R. and Farooqui, M.Y. 2012. Formation evaluation of fractured basement, Cambay Basin, India. *Journal of Geophysics and Engineering*, **9**, 162–175, https://doi.org/10.1088/1742-2132/9/2/162

Hadi, J., Harrison, C., Keller, J. and Rejeki, S. 2005. Overview of Darajat reservoir characterization: a volcanic hosted reservoir. Proceedings World Geothermal Congress 2005, 24–29 April 2005, Antalya, Turkey, 24–29.

Hampton, E.R. 1964. *Geologic Factors That Control the Occurrence and Availability of Ground Water in the Fort Rock Basin, Lake County, Oregon*. US Government Printing Office, **383-B**, https://doi.org/10.3133/pp383B

Harris, A.J. and Rowland, S.K. 2015. Lava flows and rheology. *In*: Sigurdsson, H. (ed.) *The Encyclopedia of Volcanoes*, 2nd edn. Elsevier, 321–3442, https://doi.org/10.1016/B978-0-12-385938-9.00017-1

Harris, A.J., Rowland, S.K., Villeneuve, N. and Thordarson, T. 2017. Pāhoehoe, ‘a ‘ā, and block lava: an illustrated history of the nomenclature. *Bulletin of Volcanology*, **79**, 7, https://doi.org/10.1007/s00445-016-1075-7

Harris, R.N. and Higgins, S.M. 2008. A permeability estimate in 56 Ma crust at ODP Hole 642E, Vøring plateau Norwegian Sea. *Earth and Planetary Science Letters*, **267**, 378–385, https://doi.org/10.1016/j.epsl.2007.11.055

Heap, M.J. and Kennedy, B.M. 2016. Exploring the scale-dependent permeability of fractured andesite. *Earth and Planetary Science Letters*, **447**, 139–150, https://doi.org/10.1016/j.epsl.2016.05.004

Heap, M.J. and Violay, M.E. 2021. The mechanical behaviour and failure modes of volcanic rocks: a review. *Bulletin of Volcanology*, **83**, 33, https://doi.org/10.1007/s00445-021-01447-2

Heap, M.J., Xu, T. and Chen, C.F. 2014. The influence of porosity and vesicle size on the brittle strength of volcanic rocks and magma. *Bulletin of Volcanology*, **76**, 856, https://doi.org/10.1007/s00445-014-0856-0

Heap, M.J., Kennedy, B.M. *et al*. 2015. Mechanical behaviour and failure modes in the Whakaari (White Island volcano) hydrothermal system, New Zealand. *Journal of Volcanology and Geothermal Research*, **295**, 26–42, https://doi.org/10.1016/j.jvolgeores.2015.02.012

Heap, M.J., Kennedy, B.M. *et al*. 2017. A multidisciplinary approach to quantify the permeability of the Whakaari/White Island volcanic hydrothermal system (Taupo Volcanic Zone, New Zealand). *Journal of Volcanology and Geothermal Research*, **332**, 88–108, https://doi.org/10.1016/j.jvolgeores.2016.12.004

Helz, R.T. and Thornber, C.R. 1987. Geothermometry of Kilauea Iki lava lake, Hawaii. *Bulletin of Volcanology*, **49**, 651–668, https://doi.org/10.1007/BF01080357

Hobiger, M., Sonder, I., Büttner, R. and Zimanowski, B. 2011. Viscosity characteristics of selected volcanic rock melts. *Journal of Volcanology and Geothermal Research*, **200**, 27–34, https://doi.org/10.1016/j.jvolgeores.2010.11.020

Hole, M., Jolley, D., Hartley, A., Leleu, S., John, N. and Ball, M. 2013. Lava–sediment interactions in an Old Red Sandstone basin, NE Scotland. *Journal of the Geological Society, London*, **170**, 641–655, https://doi.org/10.1144/jgs2012-107

Holford, S., Schofield, N., Bunch, M., Bischoff, A. and Swierczek, E. 2021. Storing CO_2 in buried volcanoes. *The APPEA Journal*, **61**, 626–631, https://doi.org/10.1071/AJ20056

Hon, K.E.N., Kauahikaua, J.I.M., Denlinger, R. and Mackay, K. 1994. Emplacement and inflation of pāhoehoe sheet flows: observations and measurements of active lava flows on Kilauea Volcano, Hawaii. *Geological Society of America Bulletin*, **106**, 351–370, https://doi.org/10.1130/0016-7606(1994)106<0351:EAIOPS>2.3.CO;2

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Huizar-Alvarez, R., Hernández, G., Carrillo-Martinez, M., Carrillo-Rivera, J., Hergt, T. and Ángeles, G. 2003. Geologic structure and groundwater flow in the Pachuca–Zumpango sub-basin, central Mexico. *Environmental Geology*, **43**, 385–399, https://doi.org/10.1007/s00254-002-0654-4

Jackson, T.R., Fenelon, J.M. and Paylor, R.L. 2021. *Groundwater flow conceptualization of the Pahute Mesa–Oasis Valley Groundwater Basin, Nevada – a synthesis of geologic, hydrologic, hydraulic-property, and tritium data*. US Geological Survey, Scientific Investigations Report, **2020-5134**., https://doi.org/10.3133/sir20205134

Jayne, R.S., Wu, H. and Pollyea, R.M. 2019. Geologic CO_2 sequestration and permeability uncertainty in a highly heterogeneous reservoir. *International Journal of Greenhouse Gas Control*, **83**, 128–139, https://doi.org/10.1016/j.ijggc.2019.02.001

Jerram, D.A. 2002. Volcanology and facies architecture of flood basalts. *Geological Society of America Special Papers*, **362**, 119–132, https://doi.org/10.1130/0-8137-2362-0.119

Jerram, D.A., Mountney, N. and Harald Stollhofen, H. 1999. Facies architecture of the Etjo Sandstone Formation and its interaction with the basal Etendeka flood basalts of NW Namibia: implications for offshore analogues. *Geological Society, London, Special Publications*, **153**, 367–380, https://doi.org/10.1144/GSL.SP.1999.153.01.22.

Jerram, D.A., Millett, J.M. *et al*. 2019. Understanding volcanic facies in the subsurface: a combined core, wireline logging and image log data-set from the PTA2 and KMA1 boreholes, Big Island, Hawai'i. *Scientific Drilling*, **25**, 15–33, https://doi.org/10.5194/sd-25-15-2019

Jolley, D.W., Passey, S.R., Hole, M. and Millett, J. 2012. Large-scale magmatic pulses drive plant ecosystem dynamics. *Journal of the Geological Society, London*, **169**, 703–711, https://doi.org/10.1144/jgs2012-012

Jørgensen, O. 2006. The regional distribution of zeolites in the basalts of the Faroe Islands and the significance of zeolites as palaeotemperature indicators. *GEUS Bulletin*, **9**, 123–156, https://doi.org/10.34194/geusb.v9.4865

Kanakiya, S., Adam, L., Esteban, L., Rowe, M.C. and Shane, P. 2017. Dissolution and secondary mineral precipitation in basalts due to reactions with carbonic acid. *Journal of Geophysical Research: Solid Earth*, **122**, 4312–4327, https://doi.org/10.1002/2017JB 014019

Katz, M.G. and Cashman, K.V. 2003. Hawaiian lava flows in the third dimension: Identification and interpretation of pāhoehoe and ʻaʻā distribution in the KP-1 and SOH-4 cores. *Geochemistry, Geophysics, Geosystems*, **4**, 8705, https://doi.org/10.1029/2001GC000209

Kendell, C.F. 1996. West Rozel Point. *Utah Geological Association Publication*, **22**.

Keszthelyi, L. 2002. Classification of mafic lava flows from ODP Leg 183. *Proceedings of the Ocean Drilling, Program, Scientific Results*, **183**, http://www-odp.tamu.edu/publications/183_SR/012/012.htm

Kiernan, K., Wood, C. and Middleton, G. 2003. Aquifer structure and contamination risk in lava flows: insights from Iceland and Australia. *Environmental Geology*, **43**, 852–865, https://doi.org/10.1007/s00254-002-0707-8

Kilburn, C. 1990. Surfaces of aa flow-fields on Mount Etna, Sicily: morphology, rheology, crystallization and scaling phenomena. *In*: Fink, J.H. (ed.) *Lava Flows and Domes. IAVCEI Proceedings in Volcanology*. Springer, Berlin, **2**, 129–156, https://doi.org/10.1007/978-3-642-74379-5_6

Kilburn, C.R.J. 2004. Fracturing as a quantitative indicator of lava flow dynamics. *Journal of Volcanology and Geothermal Research*, **132**, 209–224, https://doi.org/10.1016/S0377-0273(03)00346-9

Klug, C. and Cashman, K.V. 1996. Permeability development in vesiculating magmas: implications for fragmentation. *Bulletin of Volcanology*, **58**, 87–100, https://doi.org/10.1007/s004450050128

Koh, D.C., Genereux, D.P., Koh, G.W. and Ko, K.S. 2017. Relationship of groundwater geochemistry and flow to volcanic stratigraphy in basaltic aquifers affected by magmatic CO_2, Jeju Island, Korea. *Chemical Geology*, **467**, 143–158, https://doi.org/10.1016/j.chemgeo.2017.08.009

Kumar, A. 2006. Formation evaluation of unconventional basaltic Deccan Trap basement reservoir of Gamij field, Cambay Basin India. 6th International Conference and Exposition on Petroleum Geophysics Organized by Society of Petroleum Geophysicist, India, 534–538.

Kumar, S., Mohan, D., Ahmed, A. and Dhannawat, B.S. 2011. Fracture characterisation and its significance in production from unconventional fractured Deccan Trap Reservoir, Padra Field, Cambay Basin, India. Paper presented at the 2nd South Asian Geoscience Conference and Exhibition, GEOIndia 2011, 12–14 January 2011, Greater Noida, New Delhi, India.

Kushnir, A.R., Martel, C. *et al*. 2016. Probing permeability and microstructure: Unravelling the role of a low-permeability dome on the explosivity of Merapi (Indonesia). *Journal of Volcanology and Geothermal Research*, **316**, 56–71, https://doi.org/10.1016/j.jvolgeores.2016.02.012

La Felice, S., Montanari, D., Battaglia, S., Bertini, G. and Gianelli, G. 2014. Fracture permeability and water–rock interaction in a shallow volcanic groundwater reservoir and the concern of its interaction with the deep geothermal reservoir of Mt. Amiata, Italy. *Journal of Volcanology and Geothermal Research*, **284**, 95–105, https://doi.org/10.1016/j.jvolgeores.2014.07.017

Lachassagne, P., Aunay, B., Frissant, N., Maud, G. and Malard, A. 2014. High-resolution conceptual hydrogeological model of complex basaltic volcanic islands: a Mayotte, Comoros, case study. *Terra Nova*, **26**, 307–321, https://doi.org/10.1111/ter.12102

Lakshmi, K.P., Kumar, P.S., Vijayakumar, K., Ravinder, S., Seshunarayana, T. and Sen, M.K. 2014. Petrophysical properties of the Deccan basalts exposed in the Western Ghats escarpment around Mahabaleshwar and Koyna, India. *Journal of Asian Earth Sciences*, **84**, 176–187, https://doi.org/10.1016/j.jseaes.2013.08.028

Lamur, A., Kendrick, J.E., Eggertsson, G.H., Wall, R.J., Ashworth, J.D. and Lavallée, Y. 2017. The permeability of fractured rocks in pressurised volcanic and geothermal systems. *Scientific Reports*, **7**, 6173, https://doi.org/10.1038/s41598-017-05460-4

Lamur, A., Lavallée, Y., Iddon, F.E., Hornby, A.J., Kendrick, J.E., Von Aulock, F.W. and Wadsworth, F.B.

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2018. Disclosing the temperature of columnar jointing in lavas. *Nature Communications*, **9**, 1432, https://doi.org/10.1038/s41467-018-03842-4

Lee, E.Y., Tejada, M.L.G. *et al*. 2021. Petrophysical property modifications by alteration in a volcanic sequence at IODP Site U1513, Naturaliste Plateau. *Journal of Geophysical Research: Solid Earth*, **126**, e2020JB021061, https://doi.org/10.1029/2020JB021061

Limaye, S.D. 2010. Review: groundwater development and management in the Deccan Traps (basalts) of western India. *Hydrogeology Journal*, **18**, 543–558, https://doi.org/10.1007/s10040-009-0566-4

Lipman, P.W. and Banks, N.G. 1987. A'a flow dynamics, Mauna Loa 1984. *US Geological Survey Professional Paper*, **1350**, 1527–1567.

Luengo Oroz, N., Bellomo, S. and D'Alessandro, W. 2014. High vanadium concentrations in groundwater at el Hierro (Canary Islands, Spain). Paper presented at the 10th International Hydrogeological Congress, Aristotele University of Thessaloniki, Greece.

Lyle, P. 2000. The eruption environment of multi-tiered columnar basalt lava flows. *Journal of the Geological Society, London*, **157**, 715–722, https://doi.org/10.1144/jgs.157.4.71

MacDonald, A.M., O Dochartaigh, B.E. and Smedley, P.L. 2017. *Baseline groundwater chemistry in Scotland's aquifers*. British Geological Survey, Open Report, **OR/17/030**, https://nora.nerc.ac.uk/id/eprint/519084/1/OR17030.pdf

Macdonald, G.A. 1953. Pāhoehoe, aa, and block lava. *American Journal of Science*, **251**, 169–191, https://doi.org/10.2475/ajs.251.3.169

Macdonald, G.A. and Katsura, T. 1962. Relationship of petrographic suites in Hawaii. *The Crust of the Pacific Basin*, **6**, 87–195.

Macdonald, G.A., Abbott, A. and Peterson, F.L. 1983. *Volcanoes in the Sea: The Geology of Hawaii*. University of Hawaii Press.

Macente, A., Dobson, K.J., MacDonald, J., Wadsworth, F.B. and Vasseur, J. 2022. The Evolution of paleo-porosity in basalts: reversing pore-filling mechanisms using x-ray computed tomography. *Transport in Porous Media*, **145**, 697–717, https://doi.org/10.1007/s11242-022-01869-2

Mangan, M.T., Cashman, K.V. and Newman, S. 1993. Vesiculation of basaltic magma during eruption. *Geology*, **21**, 157–160, https://doi.org/10.1130/0091-7613(1993)021<0157:VOBMDE>2.3.CO;2

Manghnani, M.H. and Woollard, G.P. 1968. Elastic wave velocities in Hawaiian rocks at pressures to ten kilobars. *AGU Geophysical Monograph*, **12**, 501–516, https://doi.org/10.1029/GM012p0501

Marins, G.M., Parizek-Silva, Y. *et al*. 2022. Characterization of volcanic reservoirs: insights from the Badejo and Linguado oil field, Campos Basin, Brazil. *Marine and Petroleum Geology*, **146**, 105950, https://doi.org/10.1016/j.marpetgeo.2022.10595

Massiot, C., McNamara, D.D., Nicol, A., Archibald, G. and Townend, J. 2014. Fracture geometries and processes in andesites at Mt Ruapehu, New Zealand: implications for the fracture modelling of the Rotokawa Geothermal Field. Paper presented at the 34th GOCAD Meeting, France.

Massiot, C., McNamara, D.D., Nicol, A. and Townend, J. 2015. Fracture width and spacing distributions from borehole televiewer logs and cores in the Rotokawa Geothermal Field, New Zealand. Paper presented at the World Geothermal Congress 2015, Melbourne, Australia, International Geothermal Association.

Matter, J.M., Takahashi, T. and Goldberg, D. 2007. Experimental evaluation of in situ CO_2-water-rock reactions during CO_2 injection in basaltic rocks: implications for geological CO_2 sequestration. *Geochemistry, Geophysics, Geosystems*, **8**, Q02001, https://doi.org/10.1029/2006GC001427

Matter, J.M., Stute, M. *et al*. 2016. Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. *Science (New York, NY)*, **352**, 1312–1314, https://doi.org/10.1126/science.aad8132

McBirney, A. and Murase, T. 1984. Rheological properties of magmas. *Annual Review of Earth and Planetary Sciences*, **12**, 337–357, https://doi.org/10.1146/annurev.ea.12.050184.002005

McGrail, B., Spane, F., Sullivan, E., Bacon, D. and Hund, G. 2011. The Wallula basalt sequestration pilot project. *Energy Procedia*, **4**, 5653–5660, https://doi.org/10.1016/j.egypro.2011.02.557

Millett, J.M., Hole, M.J., Jolley, D.W., Schofield, N. and Campbell, E. 2016*a*. Frontier exploration and the North Atlantic Igneous Province: new insights from a 2.6 km offshore volcanic sequence in the NE Faroe–Shetland Basin. *Journal of the Geological Society, London*, **173**, 320–336, https://doi.org/10.1144/0016-76492015-069

Millett, J.M., Wilkins, A.D. *et al*. 2016*b*. The geology of offshore drilling through basalt sequences: understanding operational complications to improve efficiency. *Marine and Petroleum Geology*, **77**, 1177–1192, https://doi.org/10.1016/j.marpetgeo.2016.08.010

Millett, J.M., Planke, S. *et al*. 2020. Sub-surface geology and velocity structure of the Krafla high temperature geothermal field, Iceland: integrated ditch cuttings, wireline and zero offset vertical seismic profile analysis. *Journal of Volcanology and Geothermal Research*, **391**, 106342, https://doi.org/10.1016/j.jvolgeores.2018.03.024

Millett, J.M., Jerram, D.A. *et al*. 2021*a*. The Rosebank Field, NE Atlantic: volcanic characterisation of an inter-lava hydrocarbon discovery. *Basin Research*, **33**, 2883–2913, https://doi.org/10.1111/bre.12585

Millett, J.M., Jerram, D.A. *et al*. 2021*b*. Volcanic facies architecture of early bimodal volcanism of the NW Deccan Traps: volcanic reservoirs of the Raageshwari Deep Gas Field, Barmer Basin, India. *Basin Research*, **33**, 3348–3377, https://doi.org/10.1111/bre.12605

Millett, J.M., Manton, B.M. *et al*. 2022. Basin structure and prospectivity of the NE Atlantic volcanic rifted margin: cross-border examples from the Faroe–Shetland, Møre and Southern Vøring basins. *Geological Society, London, Special Publications*, **495**, 99–138, https://doi.org/10.1144/SP495-2019-12

Moeck, I.S. 2014. Catalog of geothermal play types based on geologic controls. *Renewable and Sustainable Energy Reviews*, **37**, 867–882, https://doi.org/10.1016/j.rser.2014.05.032

Mordensky, S.P., Villeneuve, M.C., Kennedy, B.M., Heap, M.J., Gravley, D., Farquharson, J.I. and Reuschlé, T. 2018. Physical and mechanical property relationships

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of a shallow intrusion and volcanic host rock, Pinnacle Ridge, Mt. Ruapehu, New Zealand. *Journal of Volcanology and Geothermal Research*, **359**, 1–20, https://doi.org/10.1016/j.jvolgeores.2018.05.020

Mordensky, S.P., Kennedy, B.M. *et al*. 2019. Increasing the permeability of hydrothermally altered andesite by transitory heating. *Geochemistry, Geophysics, Geosystems*, **20**, 5251–5269, https://doi.org/10.1029/2019GC008409

Mueller, S., Melnik, O., Spieler, O., Scheu, B. and Dingwell, D.B. 2005. Permeability and degassing of dome lavas undergoing rapid decompression: an experimental determination. *Bulletin of Volcanology*, **67**, 526–538, https://doi.org/10.1007/s00445-004-0392-4

Mueller, S., Llewellin, E.W. and Mäder, H.M. 2011. The effect of particle shape on suspension viscosity and implications for magmatic flows. *Geophysical Research Letters*, **38**, L13316, https://doi.org/10.1029/2011GL047167

Navarro, J., Teramoto, E.H., Engelbrecht, B.Z. and Kiang, C.H. 2020. Assessing hydrofacies and hydraulic properties of basaltic aquifers derived from geophysical logging. *Brazilian Journal of Geology*, **50**, https://doi.org/10.1590/2317-4889202020200013

Navelot, V., Géraud, Y. *et al*. 2018. Petrophysical properties of volcanic rocks and impacts of hydrothermal alteration in the Guadeloupe Archipelago (West Indies). *Journal of Volcanology and Geothermal Research*, **360**, 1–21, https://doi.org/10.1016/j.jvolgeores.2018.07.004

Neal, C.A., Duggan, T.J., Wolfe, E.W. and Brandt, E.L. 1988. Lava samples, temperatures, and compositions. *US Geological Survey Professional Paper*, **1463**, 99–126.

Nelson, C.E., Jerram, D.E. and Hobbs, R.W. 2009. Flood basalt facies from borehole data: implications for prospectivity and volcanology in volcanic rifted margins. *Petroleum Geoscience*, **15**, 313–324, https://doi.org/10.1144/1354-079309-842

Neuhoff, P.S., Fridriksson, T., Arnorsson, S. and Bird, D.K. 1999. Porosity evolution and mineral paragenesis during low-grade metamorphism of basaltic lavas at Teigarhorn, eastern Iceland. *American Journal of Science*, **299**, 467–501, https://doi.org/10.2475/ajs.299.6.467

Newcomb, R.C. 1969. *Effect of Tectonic Structure on the Occurrence of Ground Water in the Basalt of the Columbia River Group of The Dalles Area, Oregon and Washington*. US Government Printing Office, **383-E**.

Nikkola, P., Thordarson, T., Rämö, O.T. and Hikkilä, P. 2019. Formation of segregation structures in Hafnarhraun pāhoehoe lobe, SW Iceland: a window into crystal–melt separation in basaltic magma. *Bulletin of Volcanology*, **81**, 70, https://doi.org/10.1007/s00445-019-1330-9

Oelkers, E.H., Arkadakskiy, S. *et al*. 2022. The subsurface carbonation potential of basaltic rocks from the Jizan region of Southwest Saudi Arabia. *International Journal of Greenhouse Gas Control*, **120**, 103772, https://doi.org/10.1016/j.ijggc.2022.103772

Oki, D.S., Gingerich, S.B. and Whitehead, R.L. 1999. Hawaii. *In*: Miller, J.A., Whitehead, R.L., Oki, D.S., Gingerich, S.B. and Olcott, P.G. (eds) *Ground Water Atlas of the United States, Segment 13, Alaska, Hawaii, Puerto Rico, and the U.S. Virgin Islands*. U.S. Geological Survey Hydrologic Investigations Atlas, **730**, N12–N22, N36.

Okoko, G.O. and Olaka, L.A. 2021. Can East African rift basalts sequester CO_2? Case study of the Kenya rift. *Scientific African*, **13**, e00924, https://doi.org/10.1016/j.sciaf.2021.e00924

Okoo, J.A. 2013. Borehole geology and hydrothermal alteration mineralogy of well OW-39A, Olkaria geothermal project, Naivasha, Kenya. Geothermal Training Programme Reports 2013, Orkustofnun, Grensasvegur, 9.

Parisi, S., Paternoster, M., Perri, F. and Mongelli, G. 2011. Source and mobility of minor and trace elements in a volcanic aquifer system: Mt. Vulture (southern Italy). *Journal of Geochemical Exploration*, **110**, 233–244, https://doi.org/10.1016/j.gexplo.2011.06.010

Parnell, J. 2022. Vanadium for green energy: increasing demand but with health implications in volcanic terrains. *GeoHealth*, **6**, e2021GH000579, https://doi.org/10.1029/2021GH000579

Passey, S.R. and Bell, B.R. 2007. Morphologies and emplacement mechanisms of the lava flows of the Faroe Islands Basalt Group, Faroe Islands, NE Atlantic Ocean. *Bulletin of Volcanology*, **70**, 139–156, https://doi.org/10.1007/s00445-007-0125-6

Peterson, D.W. and Tilling, R.I. 1980. Transition of basaltic lava from pāhoehoe to aa, Kilauea Volcano, Hawaii: field observations and key factors. *Journal of Volcanology and Geothermal Research*, **7**, 271–293, https://doi.org/10.1016/0377-0273(80)90033-5

Pierdominici, S., Millett, J.M. *et al*. 2020. Stress field interactions between overlapping shield volcanoes: borehole breakout evidence from the Island of Hawai'i, USA. *Journal of Geophysical Research: Solid Earth*, **125**, e2020JB019768, https://doi.org/10.1029/2020JB019768

Planke, S. 1994. Geophysical response of flood basalts from analysis of wire line logs: Ocean Drilling Program Site 642, Vøring volcanic margin. *Journal of Geophysical Research: Solid Earth*, **99**, 9279–9296, https://doi.org/10.1029/94JB00496

Planke, S., Cerney, B., Bücker, C.J. and Nilsen, O. 1999. Alteration effects on petrophysical properties of subaerial flood basalts: Site 990, Southeast Greenland margin. Proceedings of the Ocean Drilling Program, Scientific Results, **163**, 17–28.

Planke, S., Bellwald, B. *et al*. 2020. Permanent carbon sequestration potential in offshore basalt sequences on the NW European continental margins. European Association of Geoscientists and Engineers, Conference Proceedings, 82nd EAGE Annual Conference and Exhibition, Amsterdam, Netherlands.

Pollyea, R.M., Fairley, J.P., Podgorney, R.K. and Mcling, T.L. 2014. Physical constraints on geologic CO_2 sequestration in low-volume basalt formations. *GSA Bulletin*, **126**, 344–351, https://doi.org/10.1130/B30874.1

Quirie, A.K., Schofield, N. *et al*. 2019. The Rattray Volcanics: Mid-Jurassic fissure volcanism in the UK Central North Sea. *Journal of the Geological Society, London*, **176**, 462–481, https://doi.org/10.1144/jgs2018-151

Ratouis, T.M., Snæbjörnsdóttir, S.Ó., Voigt, M.J., Sigfússon, B., Gunnarsson, G., Aradóttir, E.S. and Hjörleifsdóttir, V. 2022. Carbfix 2: a transport model of

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long-term CO_2 and H_2S injection into basaltic rocks at Hellisheidi, SW-Iceland. *International Journal of Greenhouse Gas Control*, **114**, 103586, https://doi.org/10.1016/j.ijggc.2022.103586

Reidel, S.P., Spane, F.A. and Johnson, V.G. 2002. *Natural Gas Storage in Basalt Aquifers of the Columbia Basin, Pacific Northwest USA: A Guide to Site Characterization (No. PNNL-13962)*. Pacific Northwest National Lab. (PNNL), Richland, WA, United States.

Reyes, A.G. 1990. Petrology of Philippine geothermal systems and the application of alteration mineralogy to their assessment. *Journal of Volcanology and Geothermal Research*, **43**, 279–309, https://doi.org/10.1016/0377-0273(90)90057-M

Reynolds, P., Brown, R.J., Thordarson, T., Llewellin, E.W. and Fielding, K. 2015. Rootless cone eruption processes informed by dissected tephra deposits and conduits. *Bulletin of Volcanology*, **77**, 72, https://doi.org/10.1007/s00445-015-0958-3

Rivera, M., Martin, H., Le Pennec, J.L., Thouret, J.C., Gourgaud, A. and Gerbe, M.C. 2017. Petro-geochemical constraints on the source and evolution of magmas at El Misti volcano (Peru). *Lithos*, **268**, 240–259, https://doi.org/10.1016/j.lithos.2016.11.009

Rogers, N. 2015. The composition and origin of magmas. *In*: Sigurdsson, H. (ed.) *The Encyclopedia of Volcanoes*, 2nd edn. Academic Press, 93–112, https://doi.org/10.1016/B978-0-12-385938-9.00004-3

Rosenqvist, M.P., Meakins, M.W., Planke, S., Millett, J.M., Kjøll, H.J., Voigt, M.J. and Jamtveit, B. 2023. Reservoir properties and reactivity of the Faroe Islands Basalt Group: investigating the potential for CO_2 storage in the North Atlantic Igneous Province. *International Journal of Greenhouse Gas Control*, **123**, 103838, https://doi.org/10.1016/j.ijggc.2023.103838

Rossetti, M.M. 2022. *Three-dimensional architecture and petrophysical properties of a basaltic-trachytic polygenetic volcano, Lyttelton Volcanic Complex, Banks Peninsula, New Zealand*. PhD thesis, University of Canterbury.

Rossetti, L.M., Healy, D., Hole, M.J., Millett, J.M., de Lima, E.F., Jerram, D.A. and Rossetti, M.M. 2019. Evaluating petrophysical properties of volcano-sedimentary sequences: a case study in the Paraná-Etendeka Large Igneous Province. *Marine and Petroleum Geology*, **102**, 638–656, https://doi.org/10.1016/j.marpetgeo.2019.01.028

Rouquet, S., Boivin, P., Lachassagne, P. and Ledoux, E. 2012. A 3-D genetic approach to high-resolution geological modelling of the volcanic infill of a paleovalley system. Application to the Volvic catchment (Chaîne des Puys, France). *Bulletin de la Société Géologique de France*, **183**, 395–407, https://doi.org/10.2113/gssgfbull.183.5.395

Rowland, S.K. and Walker, G.P. 1987. Toothpaste lava: characteristics and origin of a lava structural type transitional between pahoehoe and aa. *Bulletin of Volcanology*, **49**, 631–641, https://doi.org/10.1007/BF01079968

Rowland, S.K. and Walker, G.P. 1990. Pahoehoe and aa in Hawaii: volumetric flow rate controls the lava structure. *Bulletin of Volcanology*, **52**, 615–628, https://doi.org/10.1007/BF00301212

Rust, A.C. and Cashman, K.V. 2004. Permeability of vesicular silicic magma: inertial and hysteresis effects. *Earth and Planetary Science Letters*, **228**, 93–107, https://doi.org/10.1016/j.epsl.2004.09.025

Saar, M.O. and Manga, M. 1999. Permeability–porosity relationship in vesicular basalts. *Geophysical Research Letters*, **26**, 111–114, https://doi.org/10.1029/1998GL900256

Sætre, C., Hellevanga, H., Dennehy, C., Dypvik, H. and Clark, S. 2018. A diagenetic study of intrabasaltic siliciclastics sandstones from the Rosebank field. *Marine and Petroleum Geology*, **98**, 335–355, https://doi.org/10.1016/j.marpetgeo.2018.08.026

Schaefer, C.J. and Kattenhorn, S.A. 2004. Characterization and evolution of fractures in low-volume pahoehoe lava flows, eastern Snake River Plain, Idaho. *Geological Society of America Bulletin*, **116**, 322–336, https://doi.org/10.1130/B25335.1

Schofield, N., Holford, S., Edwards, A., Mark, N. and Pugliese, S. 2020. Overpressure transmission through interconnected igneous intrusions. *AAPG Bulletin*, **104**, 285–303, https://doi.org/10.1306/05091918193

Schofield, N., Newton, R., Thackrey, S., Watson, D., Jolley, D. and Morley, C. 2021. Linking surface and subsurface volcanic stratigraphy in the Turkana Depression of the East African Rift system. *Journal of the Geological Society, London*, **178**, jgs2020-110, https://doi.org/10.1144/jgs2020-1

Schutter, S.R. 2003. Hydrocarbon occurrence and exploration in and around igneous rocks. *Geological Society, London, Special Publications*, **214**, 7–33, https://doi.org/10.1144/GSL.SP.2003.214.01.02

Scott, S.W., Lévy, L. *et al*. 2023. Valgarður: a database of the petrophysical, mineralogical, and chemical properties of Icelandic rocks. *Earth System Science Data*, **15**, 1165–1195, https://doi.org/10.5194/essd-2022-279

Self, S., Keszthelyi, L. and Thordarson, T. 1998. The importance of pāhoehoe. *Annual Review of Earth and Planetary Sciences*, **26**, 81–110, https://doi.org/10.1146/annurev.earth.26.1.81

Self, S., Mittal, T. and Jay, A.E. 2021. Thickness characteristics of pāhoehoe lavas in the Deccan Province, Western Ghats, India, and in continental flood basalt provinces elsewhere. *Frontiers in Earth Science*, **8**, 630604, https://doi.org/10.3389/feart.2020.630604

Sherrod, D.R., Murai, T. and Tagami, T. 2007. New K–Ar ages for calculating end-of-shield extrusion rates at West Maui volcano, Hawaiian island chain. *Bulletin of Volcanology*, **69**, 627–642, https://doi.org/10.1007/s00445-006-0099-9

Shrivastava, J.P., Rani, N. and Pathak, V. 2016. Geochemical modeling and experimental studies on mineral carbonation of primary silicates for long-term immobilization of CO_2 in basalt from the eastern Deccan volcanic province. *Journal of Indian Geophysical Union, Special Volume*, **1**, 42–58.

Sigurdsson, F. and Einarsson, K. 1988. Groundwater, resources of Iceland: availability and demand. *Jökull*, **38**, 35–54, https://doi.org/10.33799/jokull1988.38.035

Sigurðsson, Ó. and Stefánsson, V. 1994. Forðafræðistuðlar, Mælingará bergsýnum [Reservoir parameters, Measurements on rock samples], Orkustofnun, Reykjavik, Iceland, OS-94049/JHD28B, https://gogn.orkustofnun.is/Skyrslur/OS-1994/OS-94049.pdf [last accessed 22 September 2023].

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Sigurðsson, O., Gudmundsson, A., Fridleifsson, G.O., Franzson, H., Gudlaugsson, S.P. and Stefansson, V. 2000. Database on igneous rock properties in Icelandic geothermal systems: status and unexpected results. Proceedings World Geothermal Congress, International Geothermal Association, Tohoku, Japan.

Single, R.T. and Jerram, D.A. 2004. The 3D facies architecture of flood basalt provinces and their internal heterogeneity: examples from the Palaeogene Skye Lava Field. *Journal of the Geological Society, London*, **161**, 911–926, https://doi.org/10.1144/0016-764903-13

Soule, S.A. and Cashman, K.V. 2005. Shear rate dependence of the pāhoehoe-to-'a'ā transition; analog experiments. *Geology*, **33**, 361–364, https://doi.org/10.1130/G21269.1

Sparks, R.S.J. 1978. The dynamics of bubble formation and growth in magmas: a review and analysis. *Journal of Volcanology and Geothermal Research*, **3**, 1–37, https://doi.org/10.1016/0377-0273(78)90002-1

Sruoga, P. and Rubinstein, N. 2007. Processes controlling porosity and permeability in volcanic reservoirs from the Austral and Neuquén basins, Argentina. *AAPG Bulletin*, **91**, 115–129, https://doi.org/10.1306/08290605173

Stelling, P., Shevenell, L., Hinz, N., Coolbaugh, M., Melosh, G. and Cumming, W. 2016. Geothermal systems in volcanic arcs: volcanic characteristics and surface manifestations as indicators of geothermal potential and favorability worldwide. *Journal of Volcanology and Geothermal Research*, **324**, 57–72, https://doi.org/10.1016/j.jvolgeores.2016.05.018

Stimac, J., Nordquist, G., Suminar, A. and Sirad-Azwar, L. 2008. An overview of the Awibengkok geothermal system, Indonesia. *Geothermics*, **37**, 300–331, https://doi.org/10.1016/j.geothermics.2008.04.004

Sun, X., Cao, S., Pan, X., Hou, X., Gao, H. and Li, J. 2018. Characteristics and prediction of weathered volcanic rock reservoirs: a case study of Carboniferous rocks in Zhongguai paleouplift of Junggar Basin, China. *Interpretation*, **6**, T431–T447, https://doi.org/10.1190/INT-2017-0159.1

Thien, B.M., Kosakowski, G. and Kulik, D.A. 2015. Differential alteration of basaltic lava flows and hyaloclastites in Icelandic hydrothermal systems. *Geothermal Energy*, **3**, 1–32, https://doi.org/10.1186/s40517-015-0031-7

Thomas, D.M. and Haskins, E. 2017. Reconsidering Hawaii's hydrogeologic conditions in light of recent exploration results. Paper presented at the 113th Annual Meeting, Geological Society of America, Honolulu, HI, 49, https://doi.org/10.1130/abs/2017CD-292772

Tolan, T., Lindsey, K. and Porcello, J. 2009. A summary of Columbia River Basalt Group geology and its influence on the hydrogeology of the Columbia River basalt aquifer system: Columbia basin ground water management area of Adams, Franklin, Grant, and Lincoln counties: Columbia Basin. Ground Water Management Area (GWMA), http://www.cbgwma.org/pdf/GWMA_Groundwater%20Level%20Declines_%20TEXT_June%202009.pdf

Tomašek, I., Mouri, H. *et al*. 2022. Naturally occurring potentially toxic elements in groundwater from the volcanic landscape around Mount Meru, Arusha, Tanzania and their potential health hazard. *Science of the Total Environment*, **807**, 150487, https://doi.org/10.1016/j.scitotenv.2021.150487

Toulier, A., Baud, B. *et al*. 2019. Multidisciplinary study with quantitative analysis of isotopic data for the assessment of recharge and functioning of volcanic aquifers: case of Bromo-Tengger volcano, Indonesia. *Journal of Hydrology: Regional Studies*, **26**, 100634, https://doi.org/10.1016/j.ejrh.2019.100634

USDOE 1988. *Environmental Assessment: Reference Repository Location, Hanford Site, Washington (US)*. USDOE, United States, https://doi.org/10.2172/5416408

Van Zalinge, M.E., Sparks, R.S.J., Cooper, F.J. and Condon, D.J. 2016. Early Miocene large-volume ignimbrites of the Oxaya Formation, Central Andes. *Journal of the Geological Society, London*, **173**, 716–733, https://doi.org/10.1144/jgs2015-123

Vasseur, J. and Wadsworth, F.B. 2019. The permeability of columnar jointed lava. *Journal of Geophysical Research: Solid Earth*, **124**, 11,305–11,315, https://doi.org/10.1029/2019JB018118

Voigt, J.R., Hamilton, C.W., Scheidt, S.P., Münzer, U., Höskuldsson, Á., Jónsdottir, I. and Thordarson, T. 2021. Geomorphological characterization of the 2014–2015 Holuhraun lava flow-field in Iceland. *Journal of Volcanology and Geothermal Research*, **419**, 107278, https://doi.org/10.1016/j.jvolgeores.2021.107278

Walker, G.P.L. 1960. The amygdale minerals in the Tertiary lavas of Ireland. III. Regional distribution. *Mineralogical Magazine and Journal of the Mineralogical Society*, **32**, 503–527, https://doi.org/10.1180/minmag.1960.032.250.01

Walker, G.P.L. 1971. Compound and simple lava flows and flood basalts. *Bulletin Volcanologique*, **35**, 579–590, https://doi.org/10.1007/BF02596829

Walker, G.P. 1989. Spongy pahoehoe in Hawaii: a study of vesicle-distribution patterns in basalt and their significance. *Bulletin of Volcanology*, **51**, 199–209, https://doi.org/10.1007/BF01067956

Walker, R.J., Holdsworth, R.E., Armitage, P.J. and Faulkner, D.R. 2013*a*. Fault zone permeability structure evolution in basalts. *Geology*, **41**, 59–62, https://doi.org/10.1130/G33508.1

Walker, R.J., Holdsworth, R.E., Imber, J., Faulkner, D.R. and Armitage, P.J. 2013*b*. Fault zone architecture and fluid flow in interlayered basaltic volcaniclastic-crystalline sequences. *Journal of Structural Geology*, **51**, 92–104, https://doi.org/10.1016/j.jsg.2013.03.004

Wallace, P.J., Plank, T., Edmonds, M. and Hauri, E.H. 2015. Volatiles in magmas. *In*: Sigurdsson, H. (ed.) *The Encyclopedia of Volcanoes*, 2nd edn. Elsevier, 163–183.

Wang, P. and Chen, S. 2015. Cretaceous volcanic reservoirs and their exploration in the Songliao Basin, northeast China volcanic reservoirs and their exploration. *AAPG Bulletin*, **99**, 499–523, https://doi.org/10.1306/09041413095

Watton, T.J., Cannon, S., Brown, R.J., Jerram, D.A. and Waichel, B.L. 2014. Using formation micro-imaging, wireline logs and onshore analogues to distinguish volcanic lithofacies in boreholes: examples from Palaeogene successions in the Faroe–Shetland Basin, NE

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Atlantic. *Geological Society, London, Special Publications*, **397**, 173–192, https://doi.org/10.1144/SP397.7

Weisenberger, T.B., Ingimarsson, H., Hersir, G.P. and Flóvenz, Ó.G. 2020. Cation-exchange capacity distribution within hydrothermal systems and its relation to the alteration mineralogy and electrical resistivity. *Energies*, **13**, 5730, https://doi.org/10.3390/en13215730

Weydt, L.M., Bär, K. and Sass, I. 2022. Petrophysical characterization of the Los Humeros geothermal field (Mexico): from outcrop to parametrization of a 3D geological model. *Geothermal Energy*, **10**, 1–48, https://doi.org/10.1186/s40517-022-00212-8

Widdowson, M. 1997. Tertiary palaeosurfaces of the SW Deccan, Western India: implications for passive margin uplift. *Geological Society, London, Special Publications*, **120**, 221–248, https://doi.org/10.1144/GSL.SP.1997.120.01.1

Wilmoth, R.A. and Walker, G.P. 1993. P-type and S-type pahoehoe: a study of vesicle distribution patterns in Hawaiian lava flows. *Journal of Volcanology and Geothermal Research*, **55**, 129–142, https://doi.org/10.1016/0377-0273(93)90094-8

Wright, H.M., Cashman, K.V., Gottesfeld, E.H. and Roberts, J.J. 2009. Pore structure of volcanic clasts: measurements of permeability and electrical conductivity. *Earth and Planetary Science Letters*, **280**, 93–104, https://doi.org/10.1016/j.epsl.2009.01.023

Wyering, L.D., Villeneuve, M.C., Wallis, I.C., Siratovich, P.A., Kennedy, B.M., Gravley, D.M. and Cant, J.L. 2014. Mechanical and physical properties of hydrothermally altered rocks, Taupo Volcanic Zone, New Zealand. *Journal of Volcanology and Geothermal Research*, **288**, 76–93, https://doi.org/10.1016/j.jvolgeores.2014.10.008

Yi, J., Wang, P., Gao, Y., Yao, R., Zhao, R. and Chen, C. 2016. Vesicle distribution in basalt lava flow units in the Mesozoic rift basins of northeast China and its application in gas reservoir prediction. *Canadian Journal of Earth Sciences*, **53**, 59–70, https://doi.org/10.1139/cjes-2015-0004

Zakharova, O.K. and Spichak, V.V. 2012. Geothermal fields of Hengill volcano, Iceland. *Journal of Volcanology and Seismology*, **6**, 1–14, https://doi.org/10.1134/S074204631201006X

Zou, C., Zhu, R. *et al*. 2010. Geologic characteristics of volcanic hydrocarbon reservoirs and exploration directions in China. *Acta Geologica Sinica-English Edition*, **84**, 194–205, https://doi.org/10.1111/j.1755-6724.2010.00181.x