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Fracture aperture: A review on fundamental concepts, estimation methods, applications, and research gaps

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ABSTRACT

Among all rock-fracture parameters, fracture aperture plays an especially crucial role in a range of engineering applications, such as controlling reservoir behavior during production and storage, drilling management, and groundwater recharge and exploitation. However, major challenges persist in the accurate measurement, inference and modelling of fracture aperture. In this work, we offer an overview on the definition, research history, and applied significance of fracture aperture, and we review previous studies on fracture aperture presenting a data compilation illustrating how aperture varies against other fracture parameters, based on analyses of 48 datasets. The analysis of the integrated dataset yields correlations between fracture aperture and other fracture and geomechanical parameters (e.g., Young's modulus, Poisson ratio, spacing, length, height). In the current body of literature, data exist that were mainly collected through experimental, field and modelling studies and analyzed in different ways to derive insights in the association between aperture and other selected parameters. There exist various methods to measure rock-fracture aperture, whose determination is important particularly for the collection of data required to build discrete fracture network models, for the purpose of investigating fluid flow and geomechanical behavior in underground and surface conditions. Examples of these measurement methods include: the study of outcrops and cores, analysis of conventional and advanced well-log data to understand fracture networks in near-bore region; development of artificial intelligence algorithms to constrain or predict fracture aperture based on other known surface or subsurface data. In general, fracture aperture demonstrates significant correlations with a number of other fracture parameters, such as fracture length, fracture density and tectonic stresses, and with related geological variables. Some of these attributes can be readily constrained by means of cost-effective approaches and surface or subsurface studies including outcrop investigations, seismic data, well-log and core analyses. Finally, based on the current state of knowledge, avenues for future work are outlined.

1. Introduction

Rock fractures are local mechanical breaks in the lithological frameworks of rock volumes. They occur in different types of geological materials in the upper part of the Earth's crust, because of mechanical failures driven by natural geological stresses, such as tectonic forces, lithostatic pressure changes, thermal stresses, and fluid pressure (Hussein et al., 2010; Temizel et al., 2016; Garavand & Podgornov, 2018; Al-Fatlawi et al., 2019a; Al-Fatlawi et al., 2019b). In addition, fracturing can be induced by anthropogenic activities, such as drilling, hydraulic fracturing or withdrawal of pore fluid that partially supports the weight of overburden pressure.

In general, there exist two main categories of rock fractures: faults and joints, depending on the presence or absence, respectively, of relative rock displacement along the fracture plane (Mitcham, 1963; Gudmundsson, 2011). Along joints, which lack appreciable displacement,

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separation of fracture planes can occur due to extension, folding, internal stress release during uplift or cooling, or when the pore pressure overcomes the smallest principal stress. Joints with similar orientation and morphology can be categorized into one 'set', whereas a joint 'system' is composed of a combination of two or more joint sets. By contrast, faults exhibit relative displacement from a few millimetres to several kilometres, caused by compressional or tensional forces on the geological volume. Faults are usually classified according to dip angle and the type of relative displacement, perpendicular or parallel to the dip direction of the plane. Faults can have a strong impact on subsurface fluid flow, by variably acting as flow barriers or conduits that can affect hydrocarbon appraisal and production and exploitation of geothermal resources (e.g., see Zaal et al., 2021; Kettermann et al., 2020; Ogilvie Steven et al., 2020).

In the present work, the focus is exclusively on joints, that is, fractures that are purely tensile. The term fracture is applied accordingly in the following sections.

The aim of this review article is to provide an overview of approaches to the characterization of fracture aperture in subsurface geological media, in view of the importance of this parameter for a number of applications, as outlined in the next section. To meet the stated aim of the article, specific objectives are: (i) to provide an overview of previous studies on fracture aperture, (ii) to discuss correlations determined between fracture aperture and other fracture parameters, and (iii) to suggest recommendations for future work in this field.

1.1. *Engineering applications*

Knowledge of the geometrical, (geo)mechanical and flow properties of a fracture is critical for a range of engineering applications, including: (i) the exploration and production of conventional and unconventional hydrocarbon resources (Hinsby et al., 1996; Keller et al., 1999; Pirker et al., 2008; Tran, 2009; Bear et al., 2012; Van Stappen et al., 2018), since more than 60% of global proven oil reserves and 40% of global gas reserves are hosted in fractured carbonate reservoirs (Schlumberger Market Analysis, 2007), and considering that understanding host-rock fracture networks is necessary for predicting the effects of hydraulic fracturing (Heath, 1982; Azad et al., 2021); (ii) the eploitation of geothermal systems (Glaas et al., 2021), (iii) mining (Barton et al., 1995; Guo et al., 2012); (iv) geological carbon sequestration (Klimczak et al., 2010; Annewandter et al., 2013; Ghoochaninejad et al., 2018), (v) the planning of radioactive waste repositories (Neretnieks, 1990); (vi) the prediction of pollutant dispersion in fractured rocks (Kulatilake et al., 2006; Dardashti and Ajalloeian, 2015; Deng et al., 2015); (vii) hydrogeological studies on groundwater recharge and exploitation (Younger and Elliot, 1995; Masciopinto, 2005; Mazumder et al., 2006; Huy et al., 2010); (viii) civil engineering (Bažant and Verdure, 2007); (ix) the design of composite materials through combination of two materials with different physical and chemical properties (Camanho et al., 2004); and (x) tunnel engineering (Fernandez and Moon, 2010).

There are many studies in the literature reporting geological and geomechanical data linked to all these applications. However, depending on the application of interest, these may or may not contain data on fracture aperture, which may be measured directly or inferred through modelling. As a result, the expected correlations between geological, geometrical, and geomechanical characteristics and fracture aperture may vary quite significantly between studies, leading to a lack of consensus on how to best infer fracture aperture data when modelling a network of fractures.

1.2. *Fracture characterization*

Where fractures act as the main, or even sole, type of flow pathway, the analysis and modelling of fracture networks underpins the decision-making of geologists and engineers dealing with resource recovery, injection, waste isolation, and aquifer remediation. However, to overcome the difficulty of data collection, presentation and modelling for a 3D natural fracture systems, stochastic approaches have emerged (Dershowitz and Einstein, 1988) as a solution to complexities relating to the percolation of finite-sized fracture populations (Balberg and Binenbaum, 1983; Robinson, 1983, 1984) and fluid flow in fracture networks (Long et al., 1982; Andersson et al., 1984; Long et al., 1985; Andersson and Dverstorp, 1987; Long and Billaux, 1987). With this regard, fracture modelling approaches, such as the Discrete Fracture Network (DFN) approach, provide a platform with which to better understand the static and dynamic behavior of fracture networks. DFN explicitly represents the stochastic models of fracture architecture within the mathematical framework of numerical simulation and engineering calculations. This includes presentation of geometrical properties, such as length, height, spacing, orientation, and aperture, of each individual fracture while also capturing topological relationships between individual fractures and fracture sets. Input data to a typical DFN model can be collected from field studies, well logs, core analysis and geomechanical simulations. The DFN technique is applicable for simulation of flow and solute transport in a fractured rock mass and offers promising applications in hydraulic fluid transport (Cacas et al., 1990), carbon sequestration modelling (Guohai et al., 2003; Pashin et al., 2004), and fractured reservoir characterization (Dershowitz et al., 1996).

However, the employed fracture models are constrained based on a range of input variables that may be difficult to determine, including geometrical and geomechanical attributes of fractures. Moreover, the coupling of these variables, such as temperature and confining pressure, with the fracturing process is sometime considered as a major challenge in modelling of fracture networks (Jäger et al., 2008; Wong, 2008).

There exists a range of common approaches for the characterization of fracture parameters at multiple scales (Fig. 1). For example, well logs and core samples mainly provide a one-dimensional (1D) characterization of fracture properties, while outcrop analogues allow two-dimensional (2D) (e.g., see Aghaei et al., 2020) or even pseudo-three-dimensional (3D) mapping of fracture systems. Advanced petrophysical logs are capable of producing a graphical image from the borehole wall, for example recording responses of the formation to electrical and acoustic pulses. This provides the possibility of measuring in-situ fracture plane orientation, intensity (number of fractures per unit length) and spacing in the near-bore region. Note that fracture intensity can be described in one, two and three dimensions (Dershowitz and Herda, 1992). For instance, linear fracture intensity, known as P10 (L^{-1}), is defined as the number of fractures per unit length whereas the volumetric fracture density, known as P32 (L^{-1}) describes the area of fracture per unit volume. Sonic imaging tools, which usually run in the oil base mud systems, are effectively unable to measure fracture parameters (de Jesus et al., 2016), and have lower resolution than electrical image logs. Open fractures present a conductive appearance on the electrical images, because their opening is filled with conductive drilling mud in Water Based Mud (WBM) systems (Aghli et al., 2020a, b).

1.3. *Fracture aperture*

A particularly important attribute of rock fractures, which is however very difficult to estimate, is the amount of fracture opening, also known as aperture (see pore-scale view in Fig. 1). Fracture aperture controls the hydro-mechanical properties of fracture networks in rock masses (Fossen, 2010). Mechanically, the aperture is defined as the physical separation of the fracture walls. Hydraulic aperture is also defined as the equivalent open part of the aperture through which fluid can flow, an indication of roughness characteristics (Klimczak et al., 2010). There are two main approaches to infer hydraulic apertures, one is based on experimental work, and the other is through back-calculation in field tests (see Tsang, 1992), conditional to known fracture geometry (size) and pressure gradient.

Until 1985, fractures were conceptualized as the space between pairs of parallel planes with constant separation, i.e., aperture. Later studies,

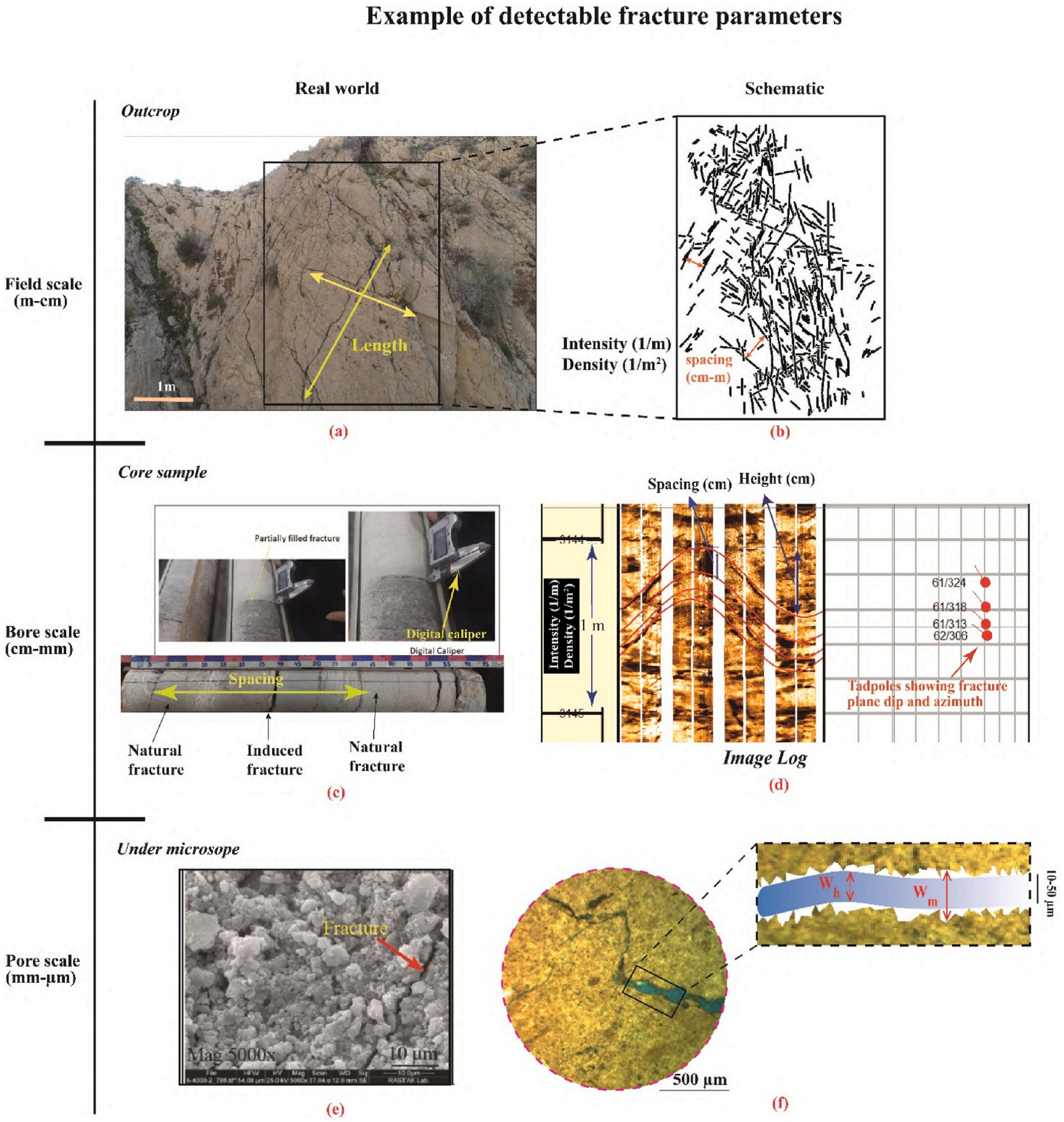


Fig. 1. A schematic representation of selected fracture parameters observed at different scales of observations: (a) length of fracture identified parallel to the flow direction in carbonate rocks in outcrop, south Iran; (b) line-drawing of the outcrop fracture network illustrating *fracture spacing, density and intensity*; (c) fractured carbonate core sample and a view of aperture measurement using digital caliper on partially filled facture; (d) image log at borehole scale showing fracture spacing and height; (e) fracture identified under Scanning Electron Microscope (SEM); (f) identification of fracture under optical microscope at the scale of the grain assemblage, showing how fracture mechanical (W_m) and hydraulic (W_h) apertures are defined.

and notably a seminal field experiment in the Stripa mine in Sweden (Abelin et al., 1985), showed that this assumption is inadequate for describing fluid flow and transport through a fracture. Indeed, the spatial heterogeneity of apertures can strongly affect fluid flow. For example, a narrow neck in a single fracture may suffice to retard flow through many wider fractures around it.

In-situ conditions describe the naturally occurring conditions (e.g., stress, temperature and pressure) under which some subsurface features, including fractures, were formed. Laubach and Ward (2006) suggested that aperture is influenced by surface roughness, cementation, and dissolution, while fluid pressure was also reported as an important factor by Zhang and Sanderson (1996). It is therefore desirable to analyze fracture parameters in-situ; however, there exist persistent technical and practical challenges making it an almost impossible task in most cases.

A key consideration is that fracture aperture varies from one fracture to another within a naturally fractured formation. These spatial variations in fracture apertures have an impact on fluid flow and transport processes. Thus, it is especially problematic to assign a constant value, such as an average value of aperture, to all fractures (cf. Min et al., 2004; Hardebol et al., 2015; Chen, 2020). In fact, any assumption of constant fracture aperture is an oversimplification.

In the Discrete Fracture Network (DFN) approach, a widely used modelling technique, the aperture size is taken either as constant or stochastically distributed over the fracture network (Moreno et al., 1988; Nordqvist et al., 1996; Jing and Stephansson, 2007). This is well illustrated by Huang and Jiang (2018), as shown in Fig. 2, who investigated the effects of heterogeneity in aperture distribution on hydraulic properties of 3D models created through DFN modelling. They revealed

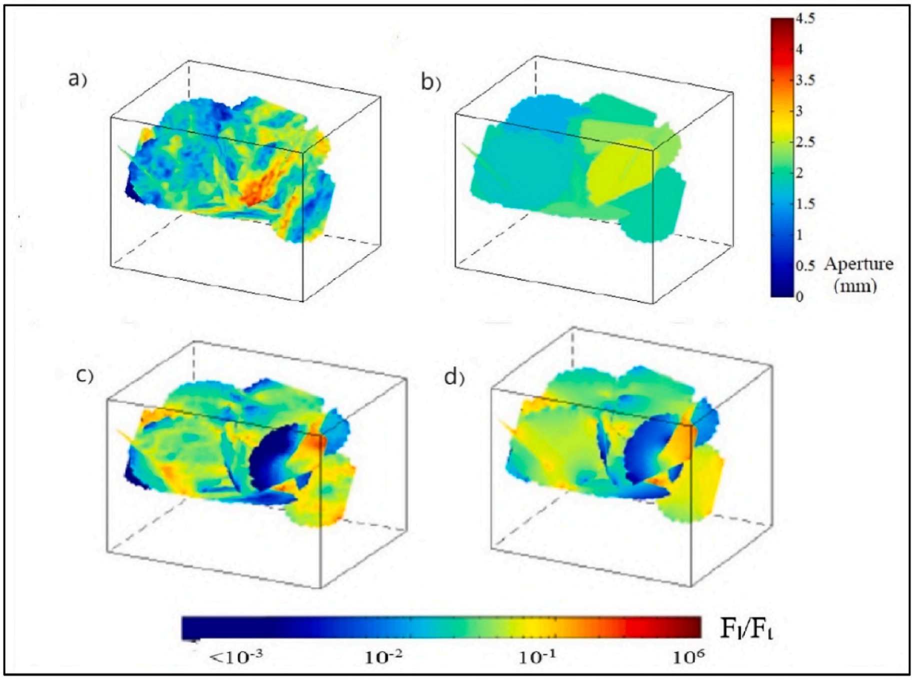


Fig. 2. Comparison of models with heterogeneous (a & c) and uniform (b & d) aperture distribution. a and b presents the developed fracture network; c and d are the observed preferential flow paths with the ratios of local flow rate (Fl) to the total flow rate (Ft) (modified from Huang and Jiang (2018).

the role of large apertures as the main channels for fluid flow, higher permeability in models with uniform apertures relative to those with heterogeneous apertures, and a general decrease in the difference of flow patterns between parallel fracture models and heterogeneous fracture models under conditions of increasing mean aperture and fracture density.

In another study, Sun and Schechter (2015) compared the production performance of a gas reservoir over a 10 years' simulation period and reported a change in cumulative production by a factor two upon increase of the aperture range from 0.003 to 3 mm.

2. Summary of previous work

Previous studies demonstrate the need for a detailed characterization of aperture distribution in fracture networks. However, each of the existing methods has its own limitations with respect to cost, time, quality, and computational power, while the measured data come from different scales making it difficult to produce a realistic fracture-network model that integrates all observations. For example, borehole imaging tools are among the most costly and time-consuming methods but can determine fracture aperture on the order of microns in conductive mud successions (Tiab and Donaldson, 2015). In contrast, outcrop studies usually report mm-scale apertures, but the measured apertures do not directly represent hydraulic fracture properties at depth, mainly due to unrepresentative stress conditions at the surface. Therefore, the presence of a quick, cost-effective, stress-and-scale-independent method to estimate the aperture size of detected fractures can be useful for the purpose of developing a more realistic fracture-network model.

A selection of previous studies, techniques, and key outcomes is presented in Table 1.

3. Aperture measurement methods

Fracture aperture can be measured through a range of available multi-scale approaches. For instance, in the laboratory it is possible to estimate the amount of fracture aperture through application of stress to the core during fluid injection and subsequent microscopic analysis (Hakami and Larsson, 1996). Microscopic aperture measurement can be undertaken through several methods, for example by measuring the topography and separation of the fracture planes or by injection of resin and measurement of resin thickness after sample slicing (Gentier et al., 1989). Furthermore, fracture aperture can be estimated through imaging techniques, such as X-ray Computed Tomography (CT) (Cappuccio et al., 2020), 3D laser scanning (Shao et al., 2022), cathodoluminescence observations (Reed et al., 2004), and outcrop studies (Miranda et al., 2018). Fig. 3 shows examples of microscopic scale images of fractures identified in carbonate core samples.

The identification and delineation of fractures at microscopic scale are hindered by the size of the fracture aperture being thinner than the imaging resolution, and by lack of contrast between the fracture trace and surrounding rock matrix. These issues can be addressed though image processing. For example, Cappuccio et al. (2020) introduced a new algorithm that performs separation and recombination of fractures in 3D computed tomography (CT) datasets based on reduction in the gray value within the open fractures. This approach enables measurement of parameters, such as fullwidth-half-maximum (FWHM) at halfway between air and rock matrix gray values (see Fig. 4), and is applicable for measurement of fracture aperture (e.g., Ketcham, 2006; Ketcham et al., 2010).

Xu et al. (2021) studied fractured outcrops of granite and proposed the Measuring Ruler Dispersion-Tangent Middle Axis (MRD-TMA) technique as a cost- and time-efficient method for acquiring morphological characteristics of apertures during field fracture logging. This method includes imaging, image processing and extraction of fracture medial axis including a series of continuous points along the middle of a fracture opening. This technique ensures the efficient and convenient acquisition of geometric features related to fracture apertures. In the initial step of this approach, high-precision photographs are taken to calculate the fracture opening. Following the methodology outlined by Xu et al. (2021), photos of fractures are taken with a steel ruler placed parallel to the fracture strike so that the ruler can be used as a datum to convert the obtained aperture in pixels into real-world units regardless of the conditions of the camera. Subsequently, an orthophoto correction

Table 1
An overview of previous research on fracture aperture.

Authors	Rock type/ Measurement condition	Aim and objectives	Methods	Key outcomes
Vermilye and Scholz (1995)	Various sedimentary and metamorphic rocks/In-situ	- To determine a general scaling relationship between fracture length and aperture	Thin-section analysis	- Maximum displacement-length plots indicate a linear relationship between length and aperture for single segment fractures.
Zhang and Sanderson (1996)	Sandstone/In-situ	- To study the effect of stress on 2D permeability tensor of natural fracture networks	Numerical modelling	- Increases in compressive stress cause the closure of fracture aperture and consequent permeability reduction.
Bai et al. (2000)	Not specified	- To investigate the mechanical controls on apertures in confined and unconfined systems using the theory of elasticity	Analytical and numerical modelling (FEM)	- It has been shown that within a homogeneous, isotropic medium, the ratio of aperture to height[b] (aspect ratio) of an unconfined fracture[c] is linearly related to the average strain, overburden stress and internal fluid pressure in the fracture.
Olsson and Barton (2001)	Granite/Laboratory	- To use experimental results from hydromechanical shear tests to propose an improved version of the original model by Barton (1982) for predicting hydraulic aperture (e) from mechanical aperture (E) and joint roughness coefficient (JRC): $e = E^2/JRC^{2.5}$	Hydromechanical shear tests	- Results are applicable for relating the hydraulic and mechanical apertures with joint roughness coefficient. - Coupled shear-flow test results show that hydraulic aperture increases during increased shear displacement
Olson (2003)	Veins with different fillings in calcite-cemented siltstone/ Variable	- To explore aperture-to-length relationship and their mechanistic significance	Analysis of published data and correlations	- Development of a nonlinear aperture-to-length relationship - Aperture effectively stops increasing where fracture height is constrained by bed thickness, and where fracture length is four times greater than the fracture height.
Matthäi and Belayneh (2004)	Not specified/ Subsurface	- To investigate the characteristics of slightly compressible, laminar, steady flow through a fractured porous medium	Finite-element simulations	- Based on flow-velocity spectra, Darcy velocity is only poorly correlated with permeability; flow velocities have characteristic values even if fracture-length aperture relations follow a power law, and fracture and matrix velocities overlap - The work suggests Gaussian velocity spectra for both isolated fractures with a mechanically controlled aperture and well interconnected fractures with fixed orientation-dependent aperture.
Olson Jon et al. (2007)	Sandstone/Variable	- To investigate the effect of diagenesis on rock properties - To study the effect of strain anisotropy on fracture patterns and apertures.	Finite difference modelling	- Diagenesis causes smaller-aperture fractures to fill. - Older fractures have larger aperture. - A non-uniform aperture distribution leads to preferential flow paths - As the anisotropy increases, aperture development is more likely in fractures parallel to the shortening direction
Baghbanan and Jing (2008)	Crystalline rocks/ Variable	- To investigate the significance of fracture aperture and fracture length correlation on hydraulic behaviors of fractured rocks, considering the effects of stress.	Discrete element method	- These results show significant differences between correlated and non-correlated aperture and fracture length distributions and highlight more significant scale and stress dependency of hydro-mechanical parameters.
Hooker et al. (2009)	Sandstone/ Laboratory	- To analyze micro-fracturing in sandstone	Scanning Electron Microscope Cathodoluminescence (SEM-CL)	- A log-normal distribution was observed for aperture-size data below 0.012 mm and above 1 mm. - A power-law aperture-size distribution is suggested for the case of relatively sparse data between 0.012 mm and 1 mm.
Elsworth and Yasuhara (2010)	Micro-crystalline sedimentary rocks/ Ideal	- Development of a model to investigate the effect of dissolution/precipitation on fracture flow/sealing behaviors.	Modelling and experiment	- Reduction in aperture with increasing applied stress and temperatures was observed; this reduction increases with precipitation on the fracture walls when the system is hydraulically closed and initially in equilibrium.

(continued on next page)

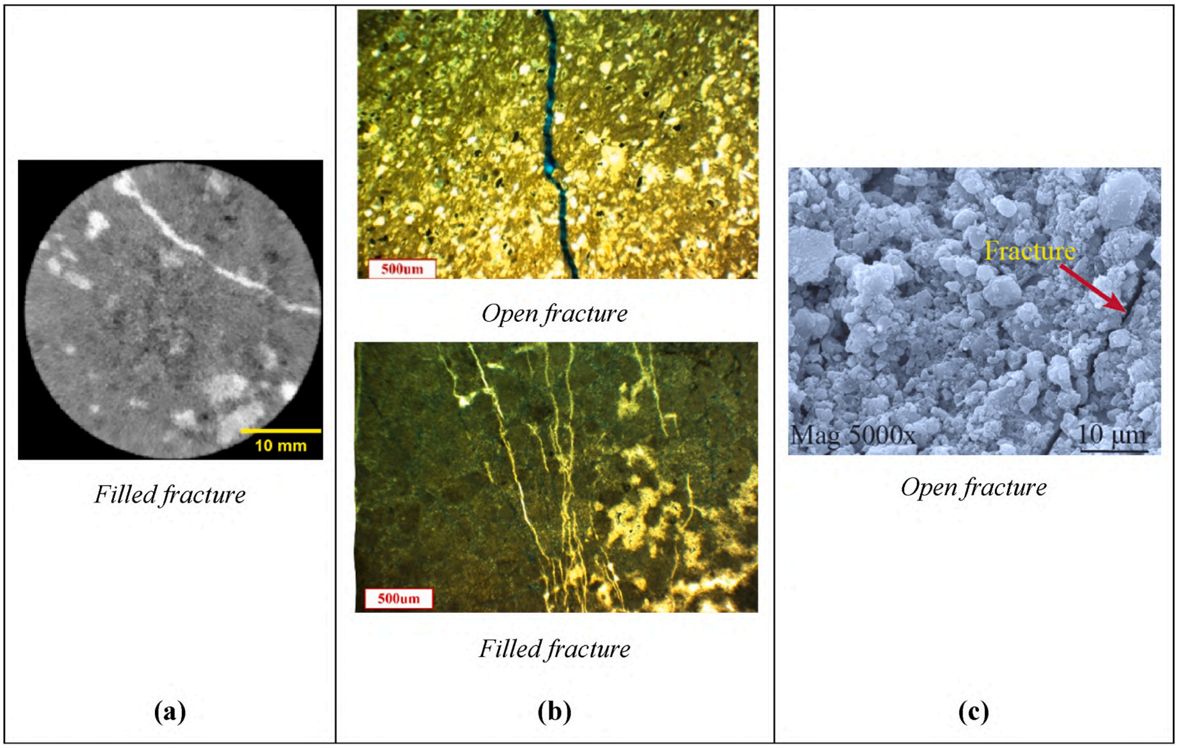
Table 1 (*continued*)

Authors	Rock type/ Measurement condition	Aim and objectives	Methods	Key outcomes
Hooker et al. (2014)	Sandstone/Surface	- To investigate fracture populations	- Scanning Electron Microscope Cathodoluminescence (SEM-CL) Hand lens on macroscopic specimens	- Typical crack-seal texture was observed for power law–distributed fractures with a narrow range of aperture sizes.
Lei et al. (2015)	Limestone/In-situ	- Large-scale hydromechanical characterization of natural fractures based on small-scale features.	Approach based on discrete-time random walkers in recursive growth lattices and the finite-discrete element method.	- Deviated fractures are associated with greater permeability due to their larger aperture.
Ponziani et al. (2015)	Limestone/Variable	- To investigate electric response of fractures	- Laboratory experiments Numerical simulations of electric response of the full-bore formation micro-imaging (FMI) tool	- Development of a relationship between the measured integrated current and the fracture aperture assuming the other parameters are known.
Bisdom et al. (2016a)	Sandstone & carbonate/Surface	- Comparison of three different aperture models and their impact on equivalent permeability in naturally fractured reservoirs, using equivalent permeability models (e.g., Matthäi and Belayneh, 2004).	Models for identification of aperture based on outcrop observations (power-law scaling), fundamental mechanics (sublinear length-aperture scaling), and experiments (Barton-Bandis conductive shearing).	- Linear length-aperture scaling predicts the largest kinematic apertures, relative to other scaling approaches. - The smallest apertures result from power-law frequency scaling and decrease for increasing power-law exponents. - Aperture in Barton-Bandis model is a function of roughness, which changes nonlinearly as a function of stress. - Outcrop data indicate that a variable aperture is likely more representative than an averaged constant aperture.
Gong and Rossen (2017)	Not specified	- To report the effect of aperture distribution on the dominant sub-network that retains 90% of the effective permeability of the original fracture network. - To model a two-dimensional fractured volume in which the matrix is impermeable and fractures are well-connected.	Fracture network and flow modelling in a quasi-two-dimensional fractured reservoir using MaficTM, a companion program of FracManTM	- If the aperture distribution is broad enough, the fracture control on effective permeability is negligible.
Agheshlui et al. (2018)	Limestone/In-situ	- Estimation of fracture aperture from deviatoric stresses due to block rotations and rock-matrix deformation as opposed to far-field stresses - Estimation of equivalent permeability considering complex stress states and aperture variations in individual fracture segments	Finite Element Analysis (FEA)	- Mechanical properties of neighboring layers were found to be important for aperture prediction in fragmented rock layers, due to their significance in determining the block deformation. For instance, surrounding rocks with lower strain rates may undergo larger displacements and rotations that can result in larger apertures for the fragmented rock layer.
Ghoochaninejad et al. (2018)	Anhydrite, bedded dolomite, limestone, and shale/In-situ	- To estimate hydraulic aperture of detected fractures using well-log responses	Using teaching–learning-based optimization algorithm into a fuzzy inference system	- Resistivity, Neutron porosity, density and sonic logs showed the highest correlations with aperture size.
Milliotte et al. (2018)	Carbonate/In-situ	- Accumulating features of single-layer models to find features of multi-layer models with sensitivity on equivalent permeability relation to fracture aperture.	Discrete fracture and matrix (DFM) simulation	- The results suggest that maximum aperture is nearly double for a case where a single set of fracture is critically stressed in tension, compared to a case where all fractures are critically stressed in shear.
Liu et al. (2021)	Tight sandstone/In-situ[a]	- To investigate the relationship between average fracture aperture (AFA) and other fracture parameters	Finite element geomechanical modelling	- The rate of decrease in average fracture aperture was observed to be reduced in horizontal stress differences greater than 10 MPa. - For fracture spacing less than 2 m, fracture aperture increases with increasing fracture spacing mainly due to changes in stress distribution around the fractures.
Zhou et al. (2021)	Tight clastic rock reservoir/In-situ	Introducing a fracture aperture prediction using well-log data	Committee Machine (CM) model improved using analytic hierarchy process and joint neural network model.	- Caliper, resistivity, SP and gamma-ray logs are sensitive to fracture aperture.

[a] **In-situ conditions:** Subsurface conditions at the study site.

[b] **Height of fracture:** fracture extension measured perpendicular to the bedding surface, commonly reported in centimeters or meters.

[c] **Unconfined fracture:** A situation in which the fracture height is negligible compared with the layer thickness.



Filled fracture

Open fracture

Filled fracture

Open fracture

(a)   (b)   (c)

Fig. 3. Example of microscopic images taken from fractured carbonate rock samples using (a) X-ray Computed Tomography (CT) (b) Optical microscopy (c) Scanning Electron Microscope (SEM).

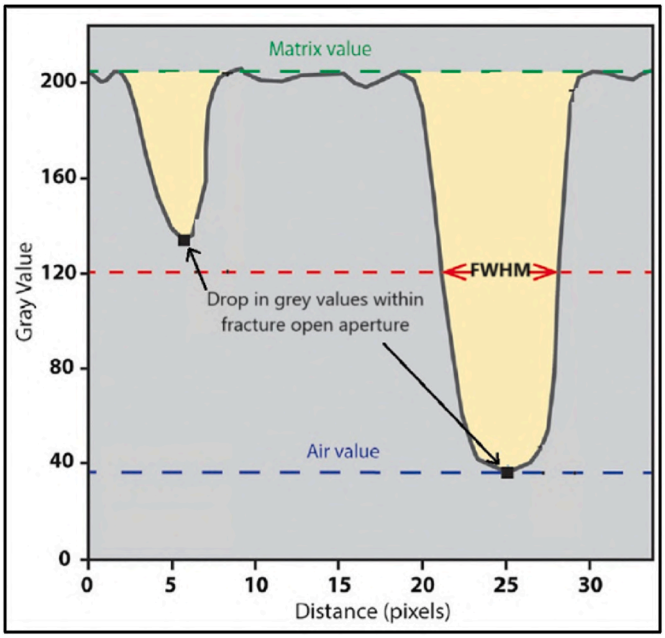


Fig. 4. Chart of drops in gra- value profiles across two open fractures of different widths where parameters such as fullwidth-half-maximum (FWHM) is derived (modified after Cappuccio et al., 2020).

method is employed to process the images, generating an unbiased and undistorted standard image. The digital image processing technique is then applied to derive the effective fracture area. Finally, the tangent middle axis measurement algorithm, based on an enhanced polygon centroid, is utilized to evaluate the aperture.

The in-situ measurement of fracture aperture is a challenging task. Advanced downhole petrophysical imaging methods, such as using the Formation Micro-Imager (FMI) (Kulatilake et al., 2006; Dardashti and Ajalloeian, 2015), Azimuthal Resistivity Imager (ARI) logs (Sausse and Genter, 2005), and the borehole televiewer (Deng et al., 2015) can provide direct observations on in-situ fracture aperture. These types of imaging tools are based on measurement of properties such as the electrical conductivity of the borehole wall and the travel time of sonic waves. However, application of these methods may be hampered by their limited availability and high cost.

Additionally, only four- and six-arm micro-image logs have the capability to detect the fracture aperture, because of the strong resistivity contrast between different features (Aghli and Aminshahidy, 2022). Aghli et al. (2017) claim that electrical image logs are reliable for evaluating fracture and reservoir parameters, when there is no core available for a well. The application of fullbore formation microimaging (FMI) and electrical microimaging (EMI) for fracture evaluation is more reliable than observations on core data, due to low recovery factor for core in the fractured reservoirs. Khoshbakht et al. (2012) argue that aperture values computed using a formation microscanner (FMS) are reliable for inferring effective permeability of fractures by taking into account the stress sensitivity of fracture, and assuming that the aperture measured in core is in agreement with aperture values determined from the FMS.

4. Correlating aperture with other parameters

Statistical methods and correlations have been presented by researchers to approximate fracture aperture versus various fracture parameters such as length (Liu et al., 2018; Lei et al., 2015) and stress (Willis-Richards et al., 1996; Jing et al., 1998; Bisdom et al., 2016b).

In-situ fracture aperture can be constrained based on correlation with other fracture parameters. With this regard, cross-plots of aperture versus other fracture parameters can be developed during field studies and laboratory studies. This type of empirical characterization has been carried out in several past studies, examples of which are mentioned in the following sections. These studies attempted to correlate fracture aperture with length and stress; however, further research is needed to develop integrated empirical relationships that can be used to constrain fracture aperture based on a combination of available multiscale 1D, 2D or 3D data (e.g., wellbore, outcrop, rock sample and seismic).

And example of such a multiscale work is that by Liu et al. (2021), who used a combination of 3D laser scanning, numerical simulations, and rock-mechanics experiments to determine in-situ fracture aperture values through correlation with other selected fracture parameters (Fig. 5).

4.1. Fracture length and aperture

The correlation between fracture length and aperture is controversial. According to Gong and Rossen (2017), any relationship between fracture aperture and fracture length is conditional to both parameters following power-law distributions. In addition, field measurements and theoretical studies raise the possibility of a nonlinear and linear relationships relationship between fracture aperture and fracture length based on elastic theory and field data (Stone, 1984; Hatton et al., 1994; Vermilye and Scholz, 1995; Johnston and McCaffrey, 1996; Renshaw and Park, 1997).

Moreover, Bisdom et al. (2016a) discussed previously published correlations and models (e.g. by Olson, 2003; Barton, 1982, Table 1), and offered the relationship illustrated in Fig. 6 between fracture length and maximum fracture aperture.

4.2. Reservoir heterogeneity and mechanical stratigraphy

Reservoir heterogeneity refers to the spatial variation of reservoir properties, such as porosity, permeability, saturation, pressure, and temperature. These can be caused by different geological and tectonic processes, such as sedimentation, diagenesis and deformation. Reservoir heterogeneity can be characterized and quantified through various surface and subsurface approaches, including well-log and core analyses.

Reservoir heterogeneity and fracturing style are mutually dependent and influence each other. According to the published literatures, studies in mechanical stratigraphy tend to focus on length, width, spacing and orientation, and only a few of them looked at aperture. Notably, there is a stratigraphic control on the occurrence and geometrical parameters of fractures, such as height, length, spacing and aperture, in relation to stratigraphic variations in the mechanical properties of rock units (e.g., Price, 1966; Cook and Erdogan, 1972; Helgeson and Aydin, 1991; Narr, 1991; Narr and Suppe, 1991; Gross et al., 1995, 1997; Cooke, 1997; Laubach et al., 1998; Lorenz et al., 2002; Di Naccio et al., 2005; Shackleton et al., 2005; Cooke et al., 2006; Laubach and Ward, 2006; Ortega et al., 2006; Wennberg et al., 2006; Hayes and Hanks, 2008; Lezin et al., 2009). While these stratigraphic variations may largely reflect variations in primary products of sedimentation, the mechanical properties of the units are also influenced by their diagenetic characteristics, which themselves are controlled by primary lithological heterogeneity (Marin et al., 1993; Dvorkin et al., 1994; Rijken et al., 2002; Shackleton et al., 2005). Reservoir heterogeneity affects fracture propagation during hydraulic fracturing operation (Wu et al., 2021). According to Aghli et al. (2020a, b), fracture aperture greatly affects reservoir properties, as underscored by cases where a clear relationship between core porosity and permeability is lacking. Chen (2022) reported on the importance of fracture geometric properties in the accuracy of highly heterogeneous upscaled equivalent fracture models (EFMs), employed for numerical reservoir simulation for media with widely distributed multiple-scale fractures. The significance of fracture properties in reservoir characterization has also been highlighted by Aghli et al. (2017): fracture aperture was reported to have the greatest effect on pore volume, pore connectivity, and by reflection, permeability.

Olson Jon et al. (2007) discussed the effect of diagenesis on loss of connectivity through the preferential filling of fracture apertures. By accounting for mechanical behaviors in finite difference, steady-state flow simulations, variability in fracture aperture distributions was linked to permeability loss caused by systematic diagenetic fracture sealing. In a case study on the Aquitanian sequence of the Asmari Formation in SW Iran, Wennberg et al. (2006) reported that fracture intensity has a relationship with the Dunham texture class, but is not affected by the degree of dolomitization. Olson et al. (2009) conducted research on tight gas sandstones to determine the effect of mechanical behaviors and diagenesis on aperture and the development of permeable networks of opening-mode fractures. It was found that, in quartz-rich sandstones, the presence of syn-kinematic cement in the fractures and in the rock mass helps maintain the magnitude of fracture aperture during unloading.

There have been several studies on outcropping carbonate units reporting on relationships between fracture parameters, diagenesis and mechanical stratigraphy. For instance, Di Naccio et al. (2005) and Barbier et al. (2012) reported a strong dependency of fracture density and intensity on facies heterogeneities determined dominantly by the combination of sedimentary and diagenetic facies. Also, Lamarche et al. (2012) suggested that the mechanical and petrographic properties of carbonates are significant factors in determining fracture pattern.

In summary, fracture is one of the aspects of reservoir heterogeneity along with spatial variations in other geological, geomechanical and petrophysical features. However, while on one hand the genesis of fracture networks is affected by pre-existing heterogeneities, fracture networks contribute to forms of mechanical and petrophysical heterogeneity that themselves affect subsequent fracturing events.

The relationships between reservoir rock heterogeneity, mechanical stratigraphy and fracture aperture still need to be elucidated and should be investigated in future work.

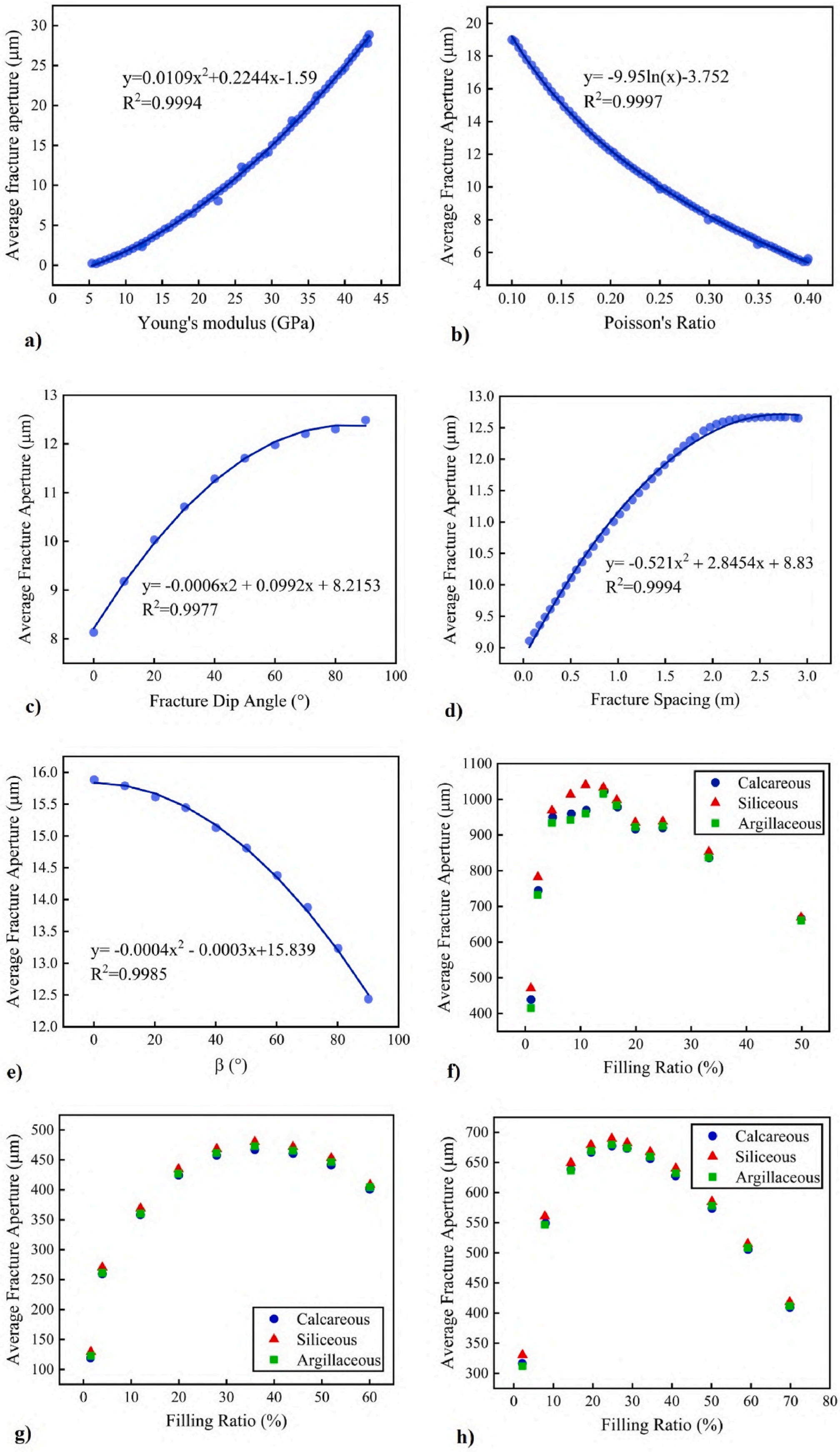
4.3. Wave velocity and fracture aperture

According to Aghli and Aminshahidy (2022), fluctuations of acoustic wave velocity are directly controlled by fracture density and fracture aperture: the larger the density and aperture the lower the wave velocity. Both compressional and shear wave velocities (Vp and Vs) are expected to decrease as the fracture aperture increases, and the Vp/Vs ratio is mainly controlled by fracture aperture. In addition, Aghli and Aminshahidy (2022) reported that dolomitic zones show greater deviations in wave velocity in relation to wider fracture apertures and lower fracture density compared to surrounding geological volumes. A similar observation was reported by Aghli et al. (2020a, b), who documented a rapid increase in transit time of acoustic wave where fractures density or aperture increase. According to Aghli et al. (2016), the presence of open fractures results in markedly reduced formation density thereby increasing the sonic transit time; this is especially evident in rock units with high aperture values. Previous studies confirmed the notion that Vp is more sensitive to open fractures than Vs, and that fractured zones correspond to a lower Vp/Vs ratio (Lavenu et al., 2014).

Bouchaala et al. (2019) conducted a study at seismic scale and reported a strong interference phenomenon, manifested as strong scattering in the Vertical Seismic Profile (VSP), in highly fractured reservoir units. The observed variation of the attenuation profiles is deemed to be due to the heterogeneity of the carbonate reservoir, while the frequency dependence of high scattering anomalies is due to the variation in fracture size. As the frequency range in which the anomalies are displayed increases, the size range of fracture increases, and vice versa.

4.4. Fracture aperture equations

Barton (1982) investigated drillcore and water bore data and proposed the following exponential function, relating the hydraulic aperture (e) to the mechanical aperture (E) and the joint roughness (JRC), valid for $E \geq e$ only:



(caption on next page)

Fig. 5. Average fracture aperture against (a) the Young's modulus of host rock; (b) the Poisson's ratio of host rock; (c) fracture dip angle; (d) fracture spacing; (e) the angle (β) between the fracture strike and the horizontal maximum principal stress direction; (f) filling ratio (the fraction of fracture that is infilled by cements), for three different filling materials showing uniform filling pattern that is evenly distributed on the fracture surface; (g) filling ratio, for three different filling materials with a striped pattern; (h) filling ratio, for three different filling materials distributed in clusters on the fracture surface (modified from Liu et al., 2021). Data were collected through a combination of 3D laser scanning, triaxial compressive strength test, standard shear test and finite element modelling.

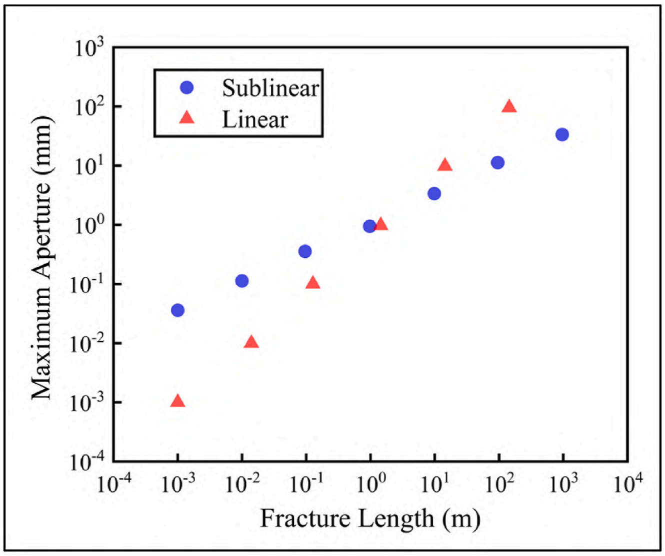


Fig. 6. Relationship between fracture length and maximum fracture aperture (modified from Bisdom et al., 2016a).

$$e = \frac{E^2}{JRC^{2.5}} \tag{1}$$

Luthi and Souhaite (1990) undertook three-dimensional finite-element modelling of FMI data and suggested the following relationship between the response of an FMI tool to an open (conductive) fracture:

$$W = cA\, R_m^b R_{xo}^{1-b} \tag{2}$$

where W (mm) is the fracture aperture or width, A (μA.mm/V) is the integrated additional current,[1] R_{xo} (Ω.m) is the resistivity of the formation, R_m (Ω.m) is the resistivity of the mud; b and c are tool-dependent coefficients in which: b indicates the sensitivity of A to the resistivity contrast between formation and borehole mud, which is mainly influenced by the borehole diameter along with the amount of current (Aghli et al., 2020a, b); c is related to a geometric factor that integrates the measured resistance to the actual formation resistivity.

According to Bona et al. (2003), and based on a range of lab-based analyses on core samples, fracture permeability (mD) can also be estimated based on the following correlation to the fracture aperture, w_f (μm):

$$k_f = 33 w \varphi_t w_f^2 \tag{3}$$

where ω is the storability ratio and φ_t is the total porosity.

Ray et al. (2012) studied fracture conductivity calibrated using well testing and Poiseuille's Law. They reported the following relationship between fracture permeability, k_f (mD), and fracture aperture, a (mm):

$$k_f = \frac{a^3}{12 \times 0.98 \times 10^{-6}} \tag{4}$$

In general, these empirical equations are affected by significant issues, mainly due to the limited size of the data underpinning them, the different scales of observation at which these data are collected, and the approaches with which these data are obtained. In view of all this, a thorough evaluation of a fracture network needs to be founded on a range of multi-scale data on both the properties of a single fracture (e.g. mechanical and hydraulic aperture, fracture plane orientation, length, height and surface roughness) and the spatial distribution and topology of multiple fractures (spacing, density, intensity, and fracture patterns). However, fracture apertures cannot be reliably derived from outcrop studies, as outcrop observations reflect the changes experienced by fractures during exhumation and weathering.

4.5. *Graphical correlations*

Further examples of the reported relationships between fracture aperture against time, stress, strain, and other geometrical factors are presented in this section.

To describe the evolution of permeability in relation to a series of chemical processes, such as, pressure solution, precipitation, and dissolution, Elsworth and Yasuhara (2010) developed models that are mechanistically sound but idealized; examples of these are shown in Fig. 7. Such results are applicable to a range of applications, such as the characterization of geothermal or hydrocarbon reservoirs or of waste repositories, where knowledge of the trade-off between stresses, temperatures, and chemical equilibrium is crucial.

As explained in Table 1, Lei et al. (2015) investigated hydromechanical characteristics of natural fractures based on finite-discrete element method and reported a relationship between fracture length and aperture, as shown in Fig. 8. This type of knowledge can assist in-situ characterization of fracture aperture wherever subsurface geology is mapped, such as through seismic survey, at a resolution that is enough to enable extraction of fracture length data.

Olsson and Barton (2001) conducted hydromechanical shear tests (also see Table 1) and suggested an empirical relationship between mechanical and hydraulic apertures incorporating the Joint Roughness Coefficient (JRC), as presented in Fig. 9. The results are applicable where deformation of both the joints and intact rock occur as a result of the stress changes, such as in repositories for radioactive waste, dam foundations, excavation of tunnels and caverns, geothermal energy plants, oil and gas production.

As shown in Fig. 10, Vermilye and Scholz (1995) studied veins in different rock types and suggested a relationship between length and variations in aperture for non-connected to partially connected and well-connected fractures. The suggested relationship can be used to predict variations in fracture aperture based on available data from fracture length to be used in a range of modelling work, such as, in hydrology, mining and mineral deposition.

Baghbanan and Jing (2008) studied the effect of stress on permeability based on the Discrete Element Method (DEM), and reported a relationship between aperture and normal stress as shown in Fig. 11. The outcome of this study is specifically important for numerical modelling of coupled hydro-mechanical process of fractured rocks, in applications such as dam foundations, underground excavations, oil recovery, and geothermal reservoirs (e.g., Rutqvist and Stephansson (2003).

Ponziani et al. (2015) conducted experiments and numerical simulations to study the electric response of fractures to FMI. As a result, they introduced a relationship between integrated additional current, resistivity contrasts and fracture aperture, as shown in Fig. 12. This relationship significantly improves the accuracy of subsurface aperture

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[1] The additional current which can be injected into the formation divided by the voltage, integrated along a line perpendicular across the fracture trace.

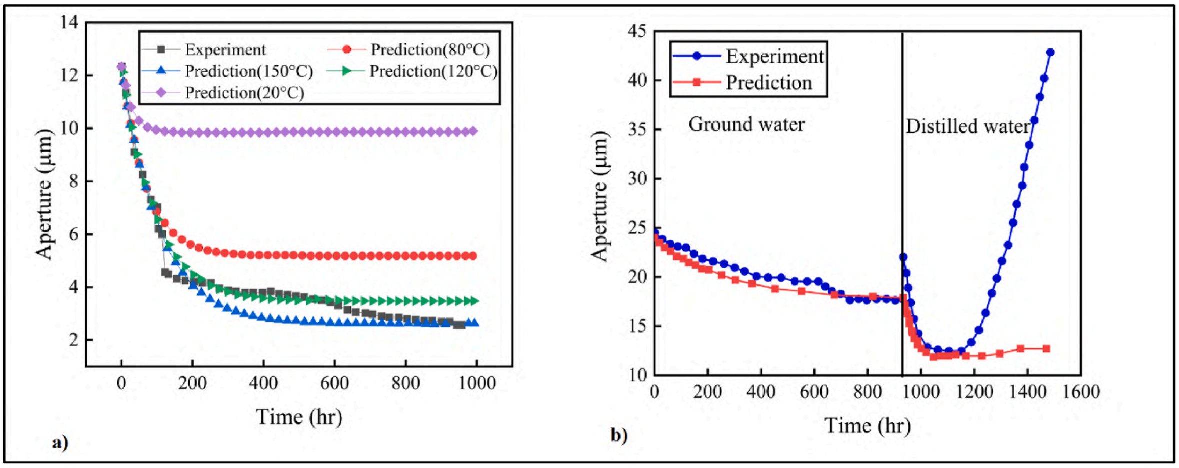

Fig. 7. (a) Variation of aperture with time showing a sudden drop in aperture due to excursion in pressure with pump failure. (b) Lab and model-based variations in aperture with fluid flow and precipitation on fracture wall. Modified from Elsworth and Yasuhara (2010).

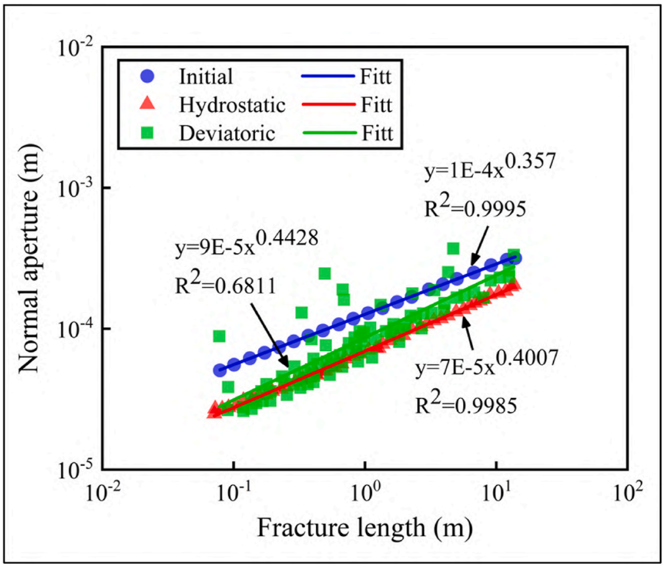

Fig. 8. Relationship between length-weighted average apertures and fracture lengths in 3 different stress conditions. Modified from Lei et al. (2015).

estimations from FMI images.

Bai et al. (2000) performed analytical and numerical investigations on the mechanical controls on fractures that terminate at layer boundaries (called confined, or stratabound, fractures) and those that are negligible in size compared with the layer thickness (called unconfined fractures). On this basis, a number of relationships were developed between aspect ratio (fracture aperture to height ratio) of confined fractures, fracture spacing/layer thickness ratio, average axial strain and overburden stress, as shown in Fig. 13. The results are applicable for prediction of in-situ fracture aperture wherever data is available from other fracture or tectonic parameters.

Matthäi and Belayneh (2004) performed field-based finite-element flow simulations in fractured rock volumes and reported the variation of aperture against spacing and matrix permeability, as shown in Fig. 14. The results are important for an accurate prediction of the flow in cases where both fracture and rock matrix contribute to the definition of flow paths.

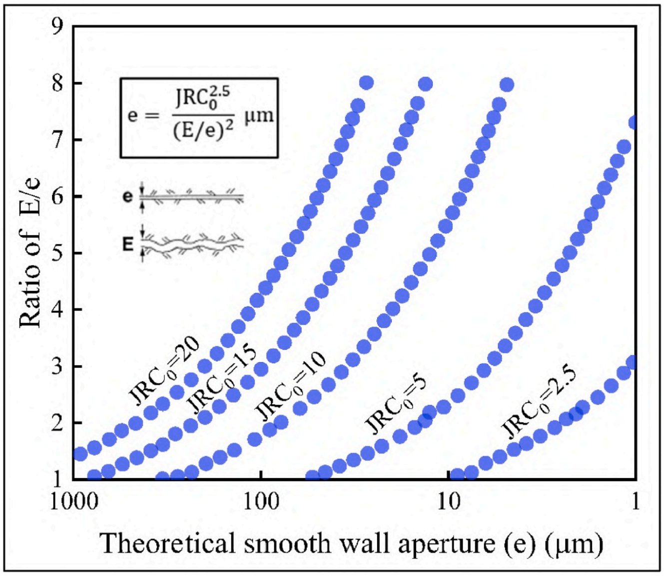

Fig. 9. Relationship between mechanical aperture (E) and hydraulic aperture ® incorporating joint roughness (JRC). Modified from Olsson and Barton (2001).

4.6. Machine learning algorithms and outcomes

Until recent times, only limited research has been undertaken on the prediction of fracture aperture by machine learning applied to in-situ conditions. Recent studies reported estimations of fracture aperture obtained with the help of machine learning algorithms using in-situ data taken from conventional borehole logs (Ghoochaninejad et al., 2018; Zhou et al., 2021).

Zhou et al. (2021) studied tight clastic fractured reservoirs to predict the aperture of natural fractures based on selected conventional log data (caliper, total resistivity, gamma ray and spontaneous potential logs) and using a version of the Committee Machine (CM) model named Hierarchical Expert Committee Machine (HECM), improved through the addition of a joint neural network model and an analytical hierarchy process.

Model training was based on well-log data set including sonic, density, caliper, SP, gamma-ray, and resistivity logs. Quantitative evaluation of the prediction accuracy of fracture aperture was based on a hierarchical structure model composed of target layer, criterion layer and scheme layer. Here, input to the committee machine and formation

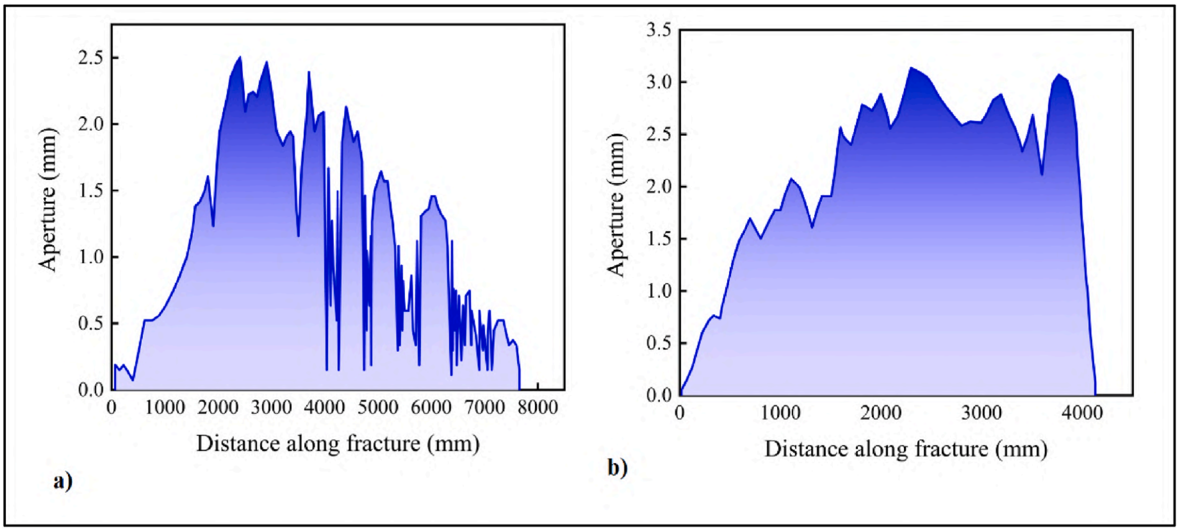

Fig. 10. Variation of fracture aperture along the length of a fracture composed of (a) non-connected to partially connected segments (b) well-connected segments. Modified from Vermilye and Scholz (1995).

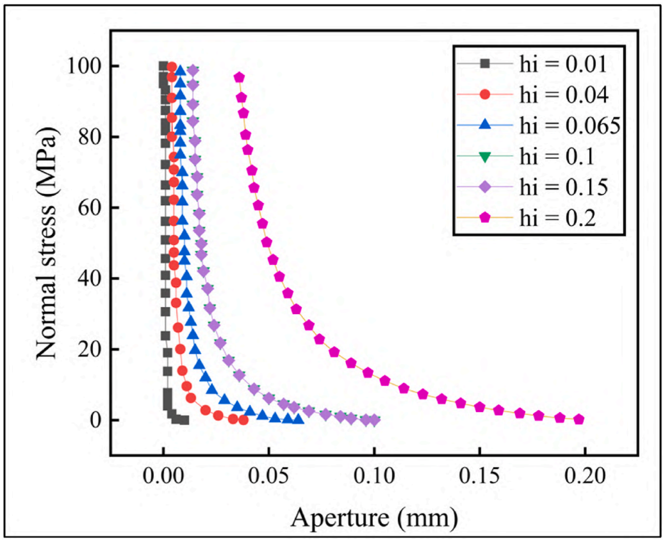

Fig. 11. Variation of fracture aperture with normal stress for assumed initial fractures. Modified from Baghbanan and Jing (2008).

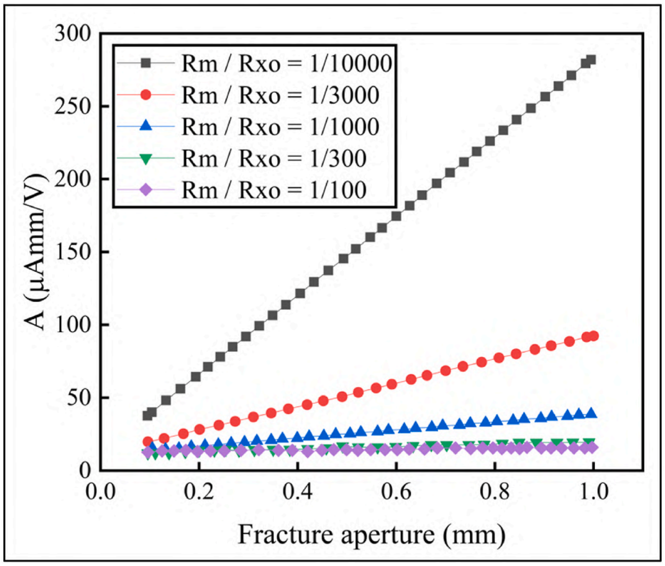

Fig. 12. Variation of fracture aperture against computed values of integrated additional current (A). Modified from Ponziani et al. (2015). Rm: drilling mud resistivity; Rxo: Flushed zone resistivity.

of a hierarchical model was based on the output of three selected basic neural networks including Kernel Ridge Regression (KRR), Support Vector Regression (SVR) and BP Network (BPN). The performance of the models was compared based on Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Total Absolute Error (TAE) and coefficient of determination (R^2). At the end, the results were validated based on aperture data derived from image logs and core samples: this demonstrates that the HECM model performs better compared with CM and SVR (Fig. 15).

Ghoochaninejad et al. (2018) applied a teaching–learning-based optimization algorithm (TLBO) to train an initial fuzzy inference system to estimate hydraulic aperture. Data for both training and testing of the algorithms were collected from Electromagnetic Induction (EMI) borehole logging, and selected conventional logs including acoustic travel time (DT), bulk density (RHOB), deep laterolog (LLD) and neutron porosity (NPHI). Ghoochaninejad et al. (2018) combined fuzzy inference system with a teaching–learning-based optimization algorithm (TLBO) to increase the model accuracy and to estimate the hydraulic aperture from well logs in a carbonate reservoir. For the Teaching–Learning-Based Optimization Fuzzy Inference System (TLBOFIS) model, fuzzy optimization was performed by TLBO, during which clustering with a radius of 0.6 showed the highest accuracy, associated with the highest correlation coefficient (R) and the lowest Root Mean Square Error (RMSE). Fig. 16 shows a comparison of predicted aperture values against the measured ones.

Moreover, several other optimization algorithms including Adaptive Neuro-Fuzzy Inference System (ANFIS), Genetic Algorithm (GA), Artificial Bee Colony (ABC), and Ant Colony Optimization (ACO) were proposed to train the fuzzy structure, but they were shown to be less efficient compared to the TLBOFIS model under the same conditions.

In summary, in the independent studies by Ghoochaninejad et al. (2018) and Zhou et al. (2021), fracture aperture prediction was undertaken through the application of machine learning techniques leveraging on conventional well logs. In these studies, fracture apertures were determined using image logs, and correlations were established between individual conventional well logs and fracture aperture values,

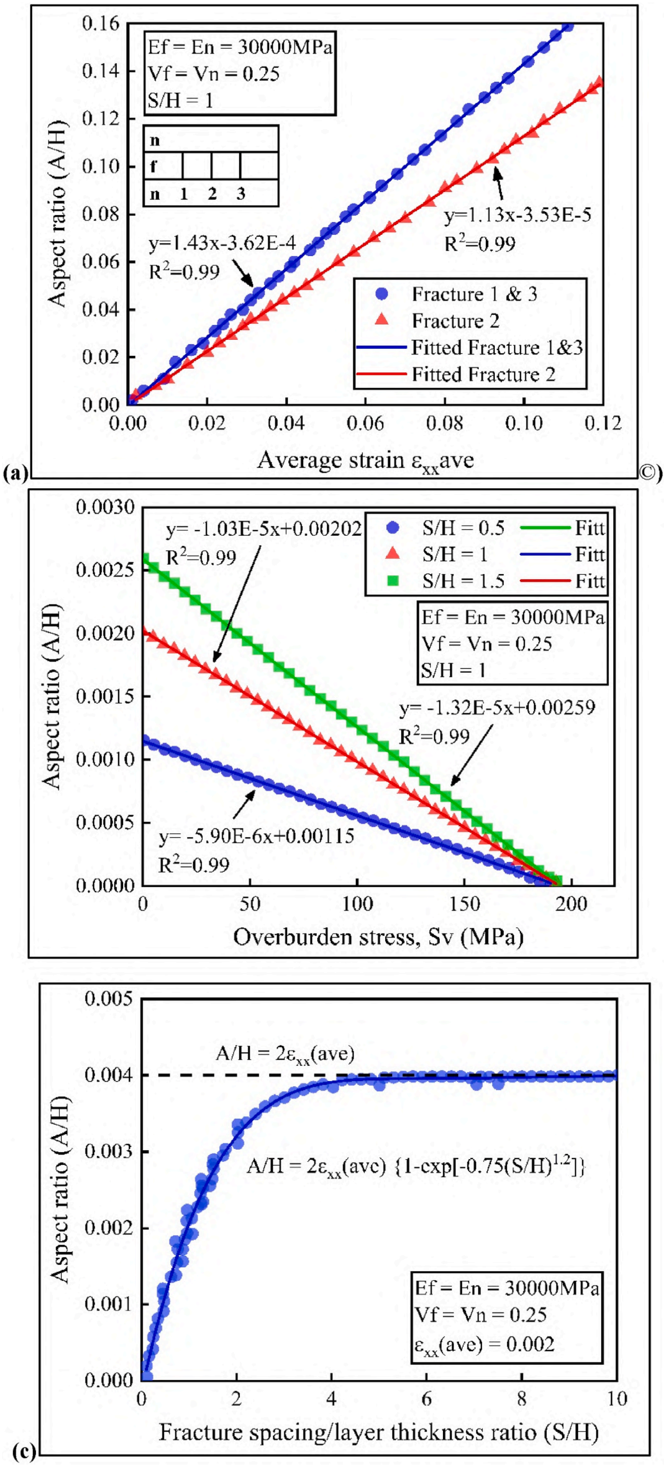

Fig. 13. Variations of aspect ratio (aperture to height ratio) for three equally spaced confined fractures against (a) normal strain (b) overburden stress (c) fracture spacing/layer thickness ratio (modified from Bai et al. (2000).

where selected conventional logs exhibiting stronger correlations with fracture aperture were chosen as inputs for machine learning models. At the end, the results were achieved through comparison of AI-based predicted aperture values with those obtained from image logs.

As indicated by Aghli et al. (2020a, b), sonic and resistivity along with neutron porosity and gamma ray logs are recommended as the most reliable proxies for fracture parameters. In particular, neutron porosity was revealed to have the highest relevance for fracture aperture, due to its dependency on the concentration of hydrogen content in the filling fluid. According to Aghli and Aminshahidy (2022), a combination of neutron porosity and sonic log data is recommended for the detection of open fractures in the absence image logs. Lyu et al. (2016) also support the use of conventional logs, such as sonic, porosity, gamma ray and resistivity, as the most effective logs for evaluation of fractured intervals.

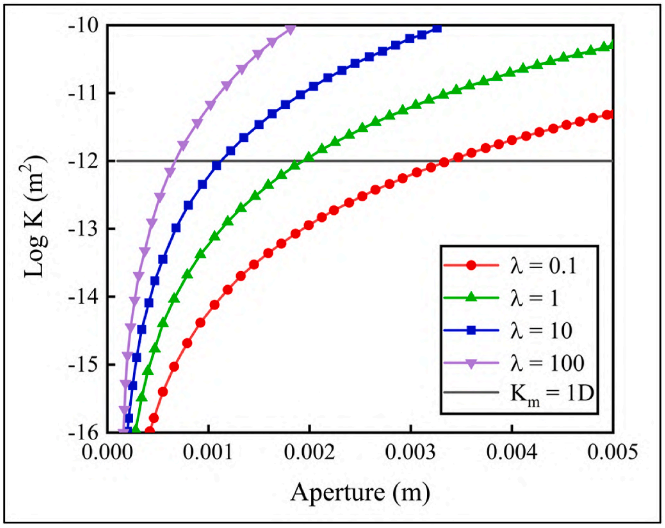

Fig. 14. Variation of aperture against spacing) λ (and matrix permeability (Km). After Matthäi and Belayneh (2004).

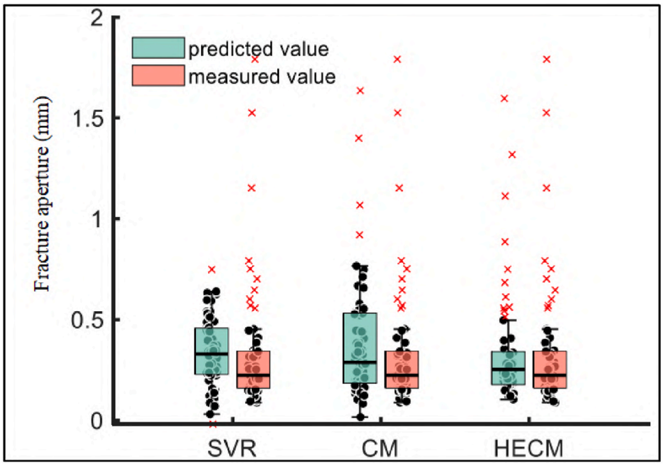

Fig. 15. Example of predicted and measured values for fracture aperture using different AI models as reported by Zhou et al. (2021); SVR: Support Vector Regression; CM: Committee Machine; HECM: Hierarchical Expert Committee Machine.

To conclude, while there has been some effort on training of AI tools based on conventional logs to predict fracture aperture, it must be recognized that there are many factors that control log responses, including lithology, matrix porosity, density, formation water, etc. Thus, correlations between aperture and conventional logs are yet to be fully understood.

5. Conclusion and future recommendations

Detailed characterization of aperture distributions in fracture networks is challenging, due to limitations in the existing measurement methods; such limitations concern cost, time, quality, computational power, and a need for multi-scale datasets. The difficulty in gathering

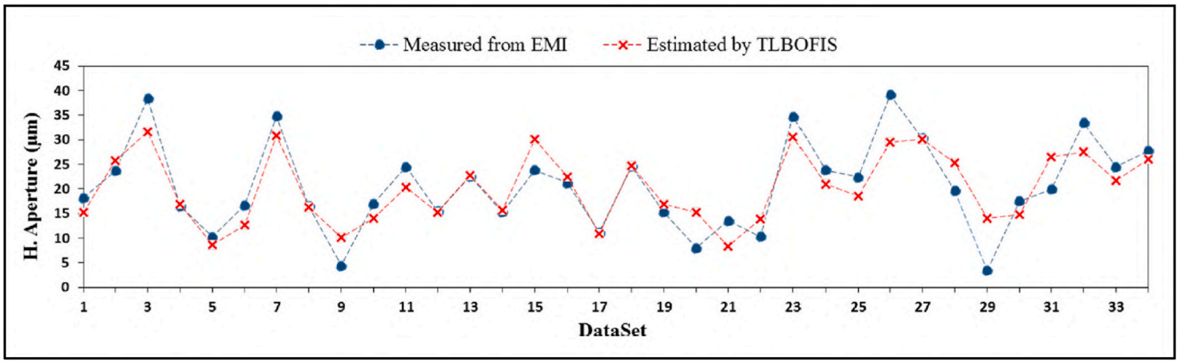

Fig. 16. A comparison of Teaching–Learning-Based Optimization Fuzzy Inference System (TLBOFIS) model-based estimations of fracture aperture against log-based measured fracture apertures, as reported by Ghoochaninejad et al. (2018); EMI: Electromagnetic Induction.

comprehensive data is currently an obstacle to the creation of realistic fracture-network models, with fracture apertures obtained or inferred from direct in-situ measurements. Several specific obstacles have been highlighted and discussed in this review, in particular: (i) the scarcity of data due to, among other factors, the limited availability of downhole facilities for collection of in-situ fracture information; (ii) lack of information about other single or network fracture parameters; (iii) missing data on regional stress regimes. An alternative approach to circumvent these obstacles could be to collect a wider range of subsurface data types, even if not directly addressing the aperture and properties of fractures, and to use them to infer fracture aperture data. This review indeed showed that effective correlations exist between a wider range of data types and fracture aperture data. Exploiting such correlations to indirectly estimate fracture apertures might significantly reduce the reliance on impractical direct measurements, thus reducing operational hassle and costs. However, there are some challenges with such correlations, mainly due to their reliance on heterogeneous data sets which might be compiled from various sources and/or collected at different times, by different people, under different measurement conditions, and at different scales; availability of partial datasets only may be another issue too. Additionally, relationships between the reservoir heterogeneity and fracture apertures still need to be clarified. Within this picture, machine learning methods may become a key tool for teasing out correlations and estimating fracture aperture, while also managing uncertainties from heterogeneous and incomplete datasets. The adoption of machine learning techniques in this area of research is still in its infancy, and there are various aspects that can be improved. Nevertheless, machine learning is a promising avenue for developing accurate fracture network models in the near future.

CRediT authorship contribution statement

Zahra Pouraskarparast: Conceptualization, Data curation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing, Investigation. **Hamed Aghaei:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Luca Colombera:** Methodology, Resources, Supervision, Validation, Writing – review & editing. **Enrico Masoero:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing, Investigation, Validation. **Mojtaba Ghaedi:** Conceptualization, Supervision, Validation, Writing – review & editing, Investigation, Methodology.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Hamed Aghaei reports was provided by University of Pavia. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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