

Electrical Identification of Fractures in Oil and Gas Reservoirs: Rock-Physics Foundations, Resistivity Logging, Borehole Imaging, and Intelligent Interpretation

Lan Yang

Xi'an Petroleum University, Xi'an, Shaanxi, 710065, China

Abstract

Natural fractures may dominate fluid transport in tight sandstones, carbonates, shales, volcanic rocks, and basement reservoirs despite contributing little bulk porosity. Their electrical signatures are nevertheless non-unique because lithology, fluid salinity, saturation, mud invasion, borehole geometry, and tool sensitivity can reproduce or obscure fracture-related anomalies. This narrative critical review, informed by structured literature searches, links fracture-scale conduction to the responses of conventional resistivity, dual laterolog, multicomponent induction, and electrical borehole imaging tools. The synthesis distinguishes four levels of inference: fracture detection, geometric characterization, potential conductivity, and dynamically confirmed effectiveness. Conductive image traces and deep-shallow resistivity separation can support fracture detection under favorable contrast, whereas position, orientation, and apparent electrical aperture remain tool- and model-dependent estimates. None of these electrical measurements alone establishes reservoir-scale connectivity or permeability. We therefore organize interpretation as a four-stage architecture that conditions the measurements, detects and classifies candidate features, inverts electrical attributes with uncertainty, and tests the resulting hypotheses against core, pressure, mud-loss, sonic, nuclear magnetic resonance, production, or well-test evidence. Automated interpretation may improve consistency, but its field value depends on well-level or field-level external validation and explicit uncertainty calibration. The framework defines which conclusions are directly observed, which are conditional inversions, and which require independent dynamic evidence.

Keywords

Naturally Fractured Reservoir; Electrical Resistivity; Dual Laterolog; Formation Microimager; Borehole Image Log; Multicomponent Induction; Fracture Aperture; Resistivity Anisotropy; Machine Learning; Formation Evaluation.

1. Introduction

Naturally fractured reservoirs occupy an unusual place in formation evaluation. Fractures commonly contribute little to total porosity, yet they can dominate permeability, pressure communication, water breakthrough, stimulation efficiency, and production decline. Their economic importance is therefore controlled less by their volumetric abundance than by their aperture, connectivity, orientation relative to the present stress field, and interaction with the matrix pore system. This mismatch between small storage volume and large transport impact explains why fractures can be difficult to identify from conventional porosity logs but conspicuous in flow tests or production data.

Electrical methods are attractive because brine is usually much more conductive than the mineral framework, oil, or gas. A fluid-filled fracture may therefore create a narrow conductive pathway, alter the effective formation factor, and introduce directional conductivity. The same

sensitivity is also the source of ambiguity. Clay-rich laminations, stylolites, conductive minerals, mud invasion, borehole enlargement, and thin beds can mimic a fracture response. Conversely, a mineralized, hydrocarbon-filled, or poorly invaded fracture may be electrically inconspicuous. Electrical fracture identification is consequently an inverse problem: the objective is not merely to recognize an anomaly, but to infer the fracture properties and uncertainty that are consistent with the measured response and the geological context.

The historical development of electrical fracture evaluation has followed three partly overlapping paths. First, conventional resistivity and dual laterolog measurements have been used to detect fracture-related conductivity and invasion effects. The finite-element work of Sibbit and Faivre [1] established that the separation of deep and shallow laterolog curves can contain information about fracture orientation, invasion, and opening. Second, pad-based electrical imaging tools transformed azimuthally resolved microresistivity measurements into high-resolution images of the borehole wall. Luthi and Souhaité [2] further related the integrated excess current across a conductive fracture trace to an apparent aperture. Third, multicomponent induction tools and modern numerical solvers have enabled tensor-resistivity estimation and fracture characterization in environments where galvanic contact is difficult or where directional information is required.

Table 1. Positioning of the present review relative to representative recent reviews

Review	Primary emphasis	Limited coverage relative to the present scope	Distinct role of the present review
Lai et al. [3]	Image-log applications in structural and sedimentary analysis	Electrical rock physics, inversion uncertainty, and dynamic effectiveness	Links fracture-scale conduction to image and non-image electrical observables
Kharrat and Ott [4]	Multidisciplinary fracture characterization and production impact	Tool-specific electrical response and evidence boundaries	Separates detection, geometric characterization, conductivity, and effectiveness
Wood [5]	Borehole-image applications in reservoir heterogeneity and fracture analysis	Conventional resistivity, multicomponent induction, and uncertainty propagation	Integrates electrical logging families within one causal framework
Pouraskarparast et al. [6]	Fracture-aperture concepts, measurements, and research gaps	Downhole electrical-tool response and claim-specific validation	Places electrical aperture within a hierarchy of observable and inferred quantities
Viswanathan et al. [7]	Coupled flow and transport processes in fractured rock	Petroleum logging workflow and borehole-scale electrical interpretation	Connects logging evidence to scale transfer while retaining reservoir-specific limits

Existing reviews have established the value of borehole images for structural and sedimentological interpretation, summarized fracture characterization across reservoir disciplines, or emphasized the expanding role of image logs [3, 4, 5]. Their broad coverage leaves a more specific interpretive problem unresolved: how a fracture-scale electrical property becomes a tool-dependent measurement and how far that measurement can support

a geological or reservoir claim. The present review addresses this gap by organizing the literature along a causal and evidential chain rather than by instrument alone. It distinguishes direct observations from model-derived attributes, separates electrical detectability from hydraulic effectiveness, and proposes explicit evidence levels for increasing claim strength.

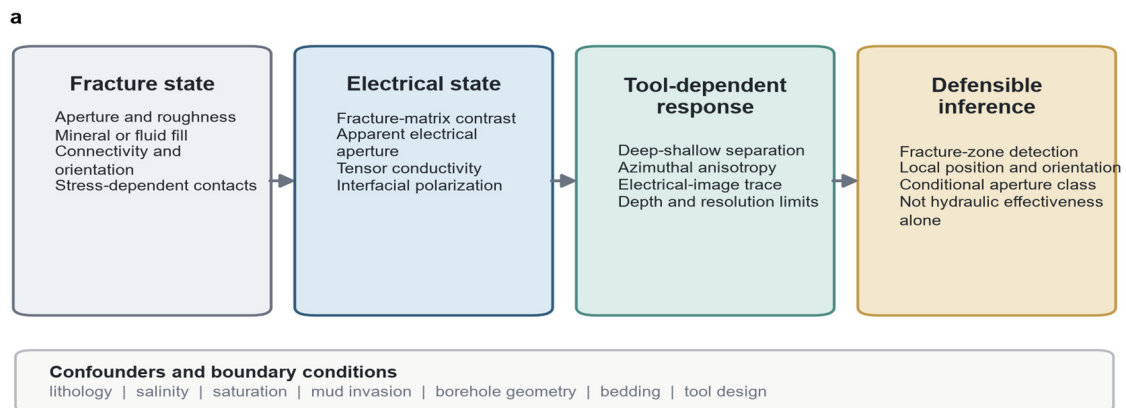


Figure 1. Causal chain from fracture state to defensible electrical interpretation. Fracture geometry, fill, connectivity, orientation, and stress determine the electrical state, which is filtered by tool sensitivity before interpretation. Lithology, saturation, invasion, borehole geometry, bedding, and tool design remain confounding or boundary conditions.

2. Scope, Literature Search, and Evidence Appraisal

2.1. Search and Selection

This article is a narrative critical review informed by structured searches rather than a systematic review or formal meta-analysis. Searches were conducted up to 9 October 2026 using Crossref- and OpenAlex-indexed metadata, supplemented by publisher pages and backward and forward reference chaining. A representative Boolean structure was `(fracture AND (resistiv OR conductiv OR anisotrop OR polarization) AND (laterolog OR induction OR multicomponent OR image log OR borehole image OR logging while drilling OR machine learning))`; equivalent field-specific variants were used because database syntax and indexing differ. The principal publication window was 2000-2026, with earlier studies retained when they established physical relations, tool concepts, or aperture models that remain in use.

Peer-reviewed articles were prioritized when they contained a physical model, laboratory measurement, numerical forward model, core-log comparison, field validation, or reproducible automated method. Groundwater and geothermal studies were included only when the fracture-electrical mechanism was transferable to petroleum reservoirs. Surface electrical-resistivity tomography, purely seismic characterization, and cased-hole production logging were outside the main scope. Conference papers were retained selectively when they introduced a foundational logging concept not adequately documented in a journal article. Records were selected iteratively for mechanistic coverage rather than screened as an exhaustive corpus; consequently, no PRISMA flow diagram, pooled effect estimate, study-count claim, or formal risk-of-bias score is reported.

2.2. Evidence Appraisal and Synthesis

Evidence was interpreted according to the strongest validation represented in each study. Analytical and numerical studies establish sensitivity and identifiability under stated assumptions; laboratory studies test mechanisms under controlled fluids, stress, and geometry; core-log or single-field comparisons evaluate geological plausibility at the borehole scale; and

multiwell, blind-well, or cross-field tests are required to support claims of operational transferability.

Table 2. Evidence appraisal of representative studies used in the synthesis

Study	Evidence setting	Independent comparison	Most defensible contribution and boundary
Sibbit and Faivre [1]	Finite-element laterolog modeling	Tool-response consistency under prescribed geometry	Establishes sensitivity to fracture dip, invasion, and opening under idealized assumptions; does not establish field uniqueness
Luthi and Souhaité [2]	Electrical borehole-scan model and field application	Comparison with borehole-image response	Supports apparent electrical-aperture estimation after calibration; the output is not a direct mechanical aperture
Piggott and Elsworth [8]	Laboratory test on a natural granite fracture	Hydraulic and electrical aperture measurements	Shows conditional agreement for a low-contact fracture; transfer across roughness, stress, and mineral filling is limited
Kirkby et al. [9]	Random-resistor network modeling	Permeability and resistivity across simulated connectivity states	Identifies a percolation-controlled relation; coefficients remain contrast- and model-dependent
Genter et al. [10]	Core and borehole-image comparison in fractured crystalline rock	Direct versus indirect fracture sampling	Demonstrates systematic sampling differences; neither source is interchangeable ground truth
Khoshbakht et al. [11]	Carbonate-reservoir electrical images	Core comparison	Supports detection of open fractures more strongly than filled fractures and faults; hydraulic effectiveness was not independently established
Lai et al. [12]	Oil-based-mud field workflow	Electrical image, sonic log, and geological interpretation	Shows the value of complementary acoustic evidence when electrical contrast is weak; conclusions remain tool- and field-specific
Aghli et al. [13] and Shalaby and Islam [14]	Conventional-log fracture-zone interpretation	Correlation with image logs or geological evidence	Supports interval screening where image data are absent; individual fractures and permeability remain non-unique
Hu et al. [15]	Synthetic dual-laterolog inversion with a learning surrogate	Numerical forward-model tests	Demonstrates computationally efficient inversion within the simulated domain; field transfer requires independent wells and environmental mismatch tests
Du et al. [16] and Dong et al. [17]	Automated fracture detection from image or conventional logs	Core comparison or blind-well tests reported by the studies	Supports automated detection under the tested data distributions; cross-basin and cross-tool calibration remain unresolved

These categories are not treated as interchangeable. In particular, agreement with synthetic data does not establish field accuracy, and a local image-log/core match does not demonstrate reservoir-scale hydraulic connectivity.

The synthesis therefore asks three questions for every method: what is measured directly, what is inferred through a model, and what independent evidence is needed before the inference can guide a reservoir decision. This evidence-centered approach also limits comparisons among commercial tools whose processing, electrode geometry, depth of investigation, and environmental corrections are partly proprietary.

Table 2 is intentionally representative rather than exhaustive. Its purpose is to expose the strongest claim supported by each evidence setting and the point at which an additional inference would require independent data.

3. Electrical Rock Physics of Fractured Reservoir Rocks

3.1. From Archie-Type Conduction to Dual-Porosity Media

For a clean, fully water-saturated porous rock, the formation factor is conventionally written as

$$F = \frac{\rho_0}{\rho_w} = a\phi^{-m} \quad (1)$$

where ρ_0 is the bulk resistivity of the fully water-saturated rock, ρ_w is the pore-water resistivity, ϕ is porosity, m is the cementation exponent, and a is an empirical coefficient. Under partial water saturation, the resistivity index is commonly represented as

$$I = \frac{\rho_t}{\rho_0} = S_w^{-n} \quad (2)$$

where S_w is water saturation and n is the saturation exponent [18]. These relations remain fundamental, but their parameters are not universal material constants. They incorporate pore topology, tortuosity, connectivity, wettability, saturation history, and, in shaly formations, surface conduction.

A fractured reservoir contains at least two interacting pore systems: matrix pores and fractures. The fracture may be represented as a highly oblate pore, a conducting sheet, or an explicit lower-dimensional feature embedded in the matrix. In a clean formation saturated with conductive brine, current preferentially follows connected fractures, especially when the matrix is tight. The effective conductivity can then increase substantially even though fracture porosity is small. If fractures are isolated, mineralized, oil filled, or closed by stress, they may contribute little to bulk current. The electrical response is therefore more sensitive to connected electrical aperture than to geometric fracture abundance alone.

Simple Archie behavior can fail in fractured-vuggy carbonates because current partitions among matrix pores, fractures, and vugs. Digital-rock and analytical studies show that formation-factor and resistivity-index trends may become nonlinear on log-log coordinates, and that apparent Archie exponents vary with fracture geometry and saturation [19]. Digital models also indicate that preferentially oriented fractures generate different formation factors parallel and normal to the fracture plane [20, 21]. These results caution against transferring matrix-derived saturation parameters unchanged into intervals dominated by secondary porosity.

3.2. Aperture, Roughness, Contacts, and Connectivity

The electrical aperture of a fracture is the aperture of an idealized parallel plate that would have the same conductance as the real fracture. It is not necessarily equal to mechanical, hydraulic, or tracer aperture. For a smooth fracture containing an electrolyte, electrical

conductance scales approximately with fluid conductivity and aperture, whereas laminar hydraulic transmissivity scales with the cube of hydraulic aperture. Rough walls, mineral coatings, and contacting asperities affect the two transport processes differently. A small change in contact topology can therefore produce a modest electrical change but a large permeability change.

Laboratory and numerical studies nevertheless demonstrate useful conditional relationships. Piggott and Elsworth [8] found comparable hydraulic and electrical apertures for a natural granite fracture with little surface contact. Kirkby et al. [9] used random-resistor networks to show that fracture permeability and resistivity evolve together above a percolation threshold, although the relation depends on matrix-to-fluid resistivity contrast. Experiments on artificial single fractures also show an inverse relation between normalized resistivity and aperture, modified by roughness and wavelength [24]. Sawayama et al. [22, 23] further related formation factor to permeability across rough mated fractures and demonstrated the roles of tortuosity and flow-path percolation. More recent coupled simulations indicate that permeability may be dominated by aperture while resistivity becomes particularly sensitive to contact area under stress [25].

These findings support two practical conclusions. First, electrical measurements can rank changes in fracture openness or connectivity when fluid chemistry and stress conditions are controlled. Second, a universal resistivity-to-permeability transform is not defensible across lithologies, stress states, and scales. Calibration against core, pressure-transient, formation-tester, mud-loss, or production data is required before electrical aperture is treated as a hydraulic property.

3.3. Fluid, Salinity, Mineral Filling, and Surface Conduction

The sign and magnitude of a fracture anomaly depend on conductivity contrast. In water-based mud, invasion commonly introduces conductive filtrate into an open fracture intersecting the borehole. The fracture then appears conductive relative to a resistive carbonate or tight sandstone. A calcite-, quartz-, anhydrite-, or bitumen-filled fracture may instead resemble the matrix or appear resistive. Oil-based mud reverses or weakens the simple conductive-fracture contrast and also limits galvanic current injection, motivating specialized oil-mud imagers and greater reliance on acoustic images [12].

Salinity and temperature control electrolyte conductivity. Clay minerals and charged mineral surfaces add surface conduction, especially at low salinity or in small pores. In such formations, the measured current cannot be assigned solely to the connected brine volume. Complex-conductivity measurements add a phase-sensitive polarization component and may help separate matrix and fracture effects. Qi et al. [26] showed, for single-fracture systems, that nonlinear fracture-matrix coupling becomes important at low salinity or for a highly polarizable matrix and that aperture can be estimated only after accounting for this coupling. This direction is promising, but it remains less mature for routine oilfield logging than direct-current or induction methods.

3.4. Fracture-induced Electrical Anisotropy

For a fractured medium, Ohm's law is more appropriately written in tensor form:

$$\mathbf{J} = \boldsymbol{\sigma} \mathbf{E} \quad (3)$$

where $\mathbf{J}$ is current density, $\mathbf{E}$ is electric field, and $\boldsymbol{\sigma}$ is the conductivity tensor. A connected set of brine-filled fractures makes conduction easier along the fracture planes than across them. Laboratory measurements on synthetic fractured samples show that anisotropy increases with the ratio of fracture porosity to background porosity, although the magnitude depends strongly on the experimental geometry [27]. Effective-medium and interconnected-crack models

similarly predict that crack orientation, aspect ratio, connectivity, and matrix anisotropy jointly determine the tensor response.

Fracture-induced anisotropy is not unique. Thin conductive beds, shale laminations, aligned pores, stress-sensitive microcracks, and dipping beds can all produce directional resistivity. An inversion that assumes transverse isotropy may therefore map a biaxial fracture response into erroneous horizontal and vertical resistivities. Directional logs become geologically useful only when bedding orientation, borehole trajectory, and image-log observations are incorporated.

4. Electrical Logging Methods and Their Fracture Sensitivity

4.1. Conventional Resistivity Logs and Dual Laterolog

Conventional resistivity logs provide continuous, widely available measurements and can identify intervals in which fractures alter bulk conductivity or invasion. In water-based mud and resistive formations, conductive mud filtrate entering open fractures commonly decreases apparent resistivity. Deep and shallow laterolog measurements sample different radial volumes, so their separation may reflect the combination of fracture dip, conductivity, aperture, and invasion extent. The classical finite-element analysis of Sibbit and Faivre [1] showed distinct responses for low- and high-angle fractures and established the basis for estimating fracture opening from dual laterolog data under restrictive assumptions.

Subsequent three-dimensional modeling has refined these relationships. Dual laterolog responses depend on matrix resistivity, fracture-fluid resistivity, dip, aperture or fracture porosity, borehole geometry, and invasion [28, 29]. In general, curve separation can be useful for classifying fracture-dominated intervals, but its sign is not a universal dip indicator because tool design, contrast, invasion, shoulder beds, and borehole deviation modify the response. High-resolution azimuthal laterolog measurements improve directional sensitivity and can constrain fracture dip direction and aperture more effectively than non-azimuthal curves [30]. Inverse models now combine three-dimensional forward simulation with optimization or neural-network surrogates to estimate fracture porosity from dual laterolog data [31, 15]. These methods are computationally efficient but inherit the assumptions of their synthetic training domain. Errors can remain small in numerical tests while field uncertainty is dominated by unmodeled heterogeneity, irregular boreholes, incorrect mud resistivity, or multiple fracture sets. Dual laterolog interpretation should therefore report posterior ranges or scenario envelopes rather than a single fracture-porosity curve.

4.2. Induction and Multicomponent Electromagnetic Logging

Induction tools sense the electromagnetic response without requiring galvanic contact and are consequently useful in nonconductive muds. A conventional coaxial induction log mainly measures an averaged formation conductivity and has limited ability to isolate thin fractures. Numerical experiments show that fracture conductivity, length, and aperture can affect the response, but the relation is non-monotonic at extreme contrasts and individual effects are difficult to separate [32].

Multicomponent induction tools use orthogonal transmitters and receivers to recover axial and cross-component responses. Under an appropriate model, these measurements can estimate triaxial resistivities, formation dip, and azimuth. Hou et al. [33] demonstrated that biaxial processing can improve the characterization of formations in which fractures introduce azimuthal anisotropy that a transversely isotropic model cannot represent. Three-dimensional modeling further shows that combinations of coplanar and cross components are sensitive to fracture azimuth and dip [34].

The same physics has been extended to hydraulic-fracture diagnostics, particularly when conductive proppant or a strong fluid contrast is present. Laboratory prototypes and

simulations demonstrate sensitivity to fracture area, dip, and aspect ratio [35], while multi-spacing, multicomponent configurations can in principle estimate fracture length, aperture, and height [36]. These results illustrate the information content of tensor electromagnetic measurements but should not be transferred uncritically to natural fractures. Natural networks are rough, branching, partially mineralized, and electrically heterogeneous; induced fractures used in validation studies are often simplified conductive sheets.

4.3. Electrical Borehole Images

Electrical borehole imaging extends the azimuthal borehole-wall mapping introduced by early televiewer concepts into dense arrays of pad-electrode measurements [37]. Planar features intersecting a cylindrical borehole plot as sinusoids, from which dip and azimuth can be obtained after tool orientation and borehole-deviation correction. Because the measurement is shallow and finely sampled, electrical images resolve features far below the vertical resolution of conventional resistivity logs.

In conductive water-based mud, open fractures invaded by mud commonly appear as dark conductive sinusoids, whereas resistive mineralized fractures appear bright. Partial sinusoids may indicate discontinuous traces, incomplete pad coverage, or limited contrast. En echelon structures, stylolites, bedding, drilling-induced tensile fractures, breakouts, and tool artifacts must be distinguished using geometry, symmetry, geological context, and complementary logs. Natural fractures usually cross-cut bedding and are not constrained to occur as a borehole-symmetric pair. Drilling-induced tensile fractures tend to appear as narrow, approximately vertical features separated by about 180°, whereas breakouts form wider opposed zones and are better characterized by acoustic caliper information.

Core-image comparisons provide the most direct validation. Genter et al. [10] found systematic sampling differences between core and borehole images in fractured crystalline rock. In a fractured carbonate reservoir, Khoshbakht et al. [11] reported that electrical images were effective for open fractures but less reliable for filled fractures, faults, and some compactional features. These differences are not simply tool failures. Core can lose or mechanically open fractures during recovery, image logs sample the borehole circumference rather than the full volume, and depth matching is imperfect. The two data types should therefore be reconciled statistically rather than treated as interchangeable ground truth.

Electrical images support fracture counts, orientation sets, linear intensity, spacing, circumferential continuity, and an apparent aperture. They can also guide secondary-porosity and permeability indices when calibrated against core and dynamic data [38, 39]. Their principal limitation is locality: only fractures intersecting the borehole are directly observed, and orientation bias depends on borehole trajectory. Terzaghi-type corrections or forward sampling of a discrete fracture network are required when image-derived orientation and intensity are extrapolated to the reservoir.

4.4. Water-based Mud, Oil-based Mud, and Logging While Drilling

The mud system is a first-order design variable. Water-based mud facilitates galvanic contact and commonly enhances the visibility of open conductive fractures. Oil-based mud provides a highly resistive borehole environment that degrades conventional pad-contact imaging; specialized tools use capacitive coupling, alternative electrode configurations, or high-frequency measurements. Under oil-based mud, fracture contrast can be weak or polarity can differ from the familiar water-mud case. Lai et al. [12] showed that combining oil-mud electrical images with ultrasonic and conventional sonic logs improves fracture detection because acoustic reflectivity and Stoneley-wave responses do not require the same electrical contrast.

Logging-while-drilling electrical images reduce the delay between drilling and measurement and may capture the borehole before substantial deterioration. They also provide azimuthal

information in high-angle and horizontal wells, where fracture-borehole intersection geometry can be favorable. However, standoff, rotation speed, irregular motion, invasion dynamics, and lower or tool-dependent resolution complicate quantitative comparison with wireline images. Numerical studies demonstrate that LWD image amplitude can be inverted for aperture, but an image trace wider than the nominal fracture does not directly measure mechanical opening [40].

Table 3. Comparative value of electrical logging methods for fracture evaluation

Method	Primary observable	Most defensible fracture output	Main strengths	Main limitations
Conventional deep/shallow resistivity	Radially averaged apparent resistivity	Fracture-zone screening; invasion-related anomalies	Widely available; continuous; useful for legacy wells	Low spatial resolution; strong lithology, saturation, invasion, and borehole ambiguity
Dual laterolog	Deep-shallow focused resistivity response	Scenario-based fracture porosity/opening and dip class	Sensitive to conductive invaded fractures in resistive formations	Non-unique; requires conductive mud; sensitive to invasion, dip, and borehole geometry
Azimuthal laterolog	Sector resistivity and azimuthal contrast	Fracture direction, dip tendency, and anisotropy	Adds directional information	Environmental correction and 3-D modeling required
Conventional induction	Electromagnetic conductivity	Bulk conductive fracture-zone response	Operates in resistive mud; deeper investigation than microimages	Limited resolution and weak uniqueness for individual natural fractures
Multicomponent induction	Axial and cross-component EM responses	Triaxial resistivity, azimuthal anisotropy, fracture orientation	Sensitive to direction and applicable in oil-based mud	Bedding and fractures can be confounded; inversion is model dependent
Electrical borehole image	High-resolution azimuthal microresistivity	Position, trace, orientation, sets, intensity; conditional aperture	Direct geometric visualization at the borehole wall	Shallow investigation; incomplete coverage; mud and contact dependence; orientation bias
LWD resistivity image	Rotational/azimuthal resistivity while drilling	Near-real-time trace and orientation	Early acquisition; useful in deviated and horizontal wells	Motion, standoff, resolution, and invasion dynamics
Complex conductivity/IP	Frequency-dependent magnitude and phase	Experimental separation of matrix and fracture polarization; possible aperture	Adds physicochemical information beyond DC resistivity	Limited routine oilfield deployment and network-scale validation

5. From Electrical Anomalies to Fracture Attributes

5.1. Detection and Classification

Reliable interpretation begins by separating three questions: Is a fracture present? What are its geometric and electrical properties? Is it hydraulically effective? Each question uses different evidence. An image sinusoid can establish the presence and orientation of a borehole-intersecting planar feature, but not its reservoir-scale connectivity. A dual laterolog anomaly can indicate a conductive disturbed zone, but not uniquely prove a fracture. A production-log inflow point can demonstrate hydraulic contribution, but may integrate several unresolved fractures.

Fracture classification should combine image geometry with electrical polarity and geological context. Recommended classes include open conductive fracture, partially open fracture, resistive or mineralized fracture, possible fracture, drilling-induced tensile fracture, breakout-related feature, stylolite, and bedding or lamination. A binary fracture/non-fracture label discards information needed for reservoir modeling and makes machine-learning validation artificially simple.

5.2. Aperture Estimation

Luthi and Souhaité [2] related apparent fracture aperture W to the additional conductance integrated normal to the fracture trace:

$$W = cA R_m^\beta R_{xo}^{1-\beta} \quad (4)$$

where A is integrated excess conductance, R_m is mud resistivity, R_{xo} is flushed-zone resistivity, and c and β are tool- and geometry-dependent coefficients. This relation is physically motivated and remains widely used, but its output is an electrically equivalent aperture. The result depends on image normalization, background selection, pad contact, fracture dip, tool geometry, mud properties, and the assumed flushed-zone resistivity. It should not be presented as a direct mechanical measurement.

The most defensible reporting practice is to provide an aperture class or uncertainty interval, show the sensitivity to R_m and R_{xo} , and calibrate the relation against core or other independent data. A recent review of aperture estimation emphasizes that in-situ aperture remains a major source of uncertainty in fracture-network models [6]. For LWD images, tool-specific forward modeling is essential because electrode geometry and acquisition differ from wireline scanners [40].

5.3. Fracture Density, Porosity, and Network Sampling

Image logs provide one-dimensional samples of a three-dimensional network. Common measures include fracture count per unit borehole length, cumulative aperture, linear intensity P_{10} , and orientation-resolved intensity. These quantities are trajectory dependent. A well parallel to a dominant fracture set will under-sample that set; a perpendicular well will intersect it frequently. Correcting this bias requires the borehole trajectory, fracture orientation distribution, and an explicit sampling model.

Fracture porosity can be approximated from aperture and spacing or inverted from resistivity responses, but both routes are uncertain. Image-based porosity depends on aperture calibration and assumes that observed traces represent the surrounding volume. Laterolog-based porosity depends on matrix resistivity, fracture-fluid conductivity, invasion, and dip. Agreement between the two estimates is informative but does not constitute independent validation if both are conditioned by the same mud-invasion process.

5.4. Hydraulic Effectiveness

Electrical openness and hydraulic effectiveness are related but not equivalent. A fracture may accept conductive mud filtrate near the borehole yet terminate within centimetres. Another fracture may be electrically subtle because of mineral coating or hydrocarbon fill but connect to a productive network. Effectiveness should therefore be assessed by integrating at least one dynamic measurement, such as mud loss, formation-tester mobility, pressure interference, production logging, tracer response, Stoneley-wave attenuation, temperature anomaly, or test-derived permeability.

Table 4. Common electrical signatures, alternative causes, and discriminating evidence

Observed signature	Fracture interpretation	Important alternatives	Discriminating evidence
Narrow conductive sinusoid in water-based mud	Open, mud-invaded natural fracture	Conductive bedding, stylolite, pyrite/clay seam	Cross-cutting geometry, core, acoustic image, dip-set consistency
Bright resistive sinusoid	Mineralized or hydrocarbon-filled fracture	Resistive bed boundary, anhydrite, poor pad contact	Mineralogy, core, multi-pad continuity, acoustic reflectivity
Opposed near-vertical conductive traces	Drilling-induced tensile fractures	High-angle natural fracture set	Approximately 180° symmetry, borehole stress context, breakout orientation
Deep-shallow laterolog separation	Invaded fractured interval	Permeable matrix invasion, thin beds, shoulder effects	Image log, invasion model, caliper, porosity/permeability logs
Azimuthal resistivity anisotropy	Preferred fracture orientation	Dipping laminations, intrinsic matrix anisotropy	Bedding dip, multicomponent inversion, image orientation sets
Low-resistivity interval	Brine-filled connected fractures	Shale, conductive minerals, high water saturation	Spectroscopy/mineralogy, gamma ray, saturation model, image geometry
High apparent aperture on image	Wide open fracture	Excess contrast, normalization artifact, tool standoff	Raw-button QC, sensitivity analysis, core calibration
Dense image traces without flow response	Abundant but ineffective fractures	Drilling damage or sealed network	Production log, pressure transient, mud-loss and Stoneley evidence

The proposed evidence hierarchy assigns four distinct claim levels. Detection establishes that a credible trace or interval anomaly is present. Geometric characterization adds position, orientation, continuity, intensity, or an apparent aperture class. Potential conductivity requires electrical contrast and openness that are consistent with a connected fluid path but does not establish flow at reservoir scale. Dynamic effectiveness is reserved for fractures supported by independent pressure or flow evidence. The hierarchy is cumulative: a higher-level claim should retain the uncertainty established at the preceding levels rather than replacing it with a binary effective/ineffective label.

This distinction changes how results should be reported. Image-log fracture counts belong to the detection and geometric levels; electrically derived aperture belongs to the conditional inversion level; and permeability or productivity requires dynamic calibration. A conductive image trace should therefore not be converted directly into productive fracture permeability.

6. Automated and Intelligent Interpretation

6.1. From Image Morphology to Deep Learning

Manual image interpretation is time consuming and interpreter dependent. Early automated workflows enhanced sinusoidal or curvilinear features, applied thresholding and morphological operators, and fitted fracture traces. Path-morphology methods can separate matrix, fractures, and vugs over multiple scales and derive geometric parameters from the extracted objects [41]. These approaches are transparent and can work with modest data volumes, but their thresholds and structuring elements often require field-specific tuning.

Deep learning reduces manual feature engineering. Du et al. [16] applied Mask R-CNN to electrical images and reported high precision and recall after image repair, augmentation, and testing, with additional comparison against core. Object-detection models have also been applied directly to conventional log panels, treating fracture identification as an imbalanced detection problem [17]. Generative augmentation may help address data scarcity, but its value remains conditional on geological realism and on separation of wells and fields between training and testing.

6.2. Why Reported Accuracy May not Transfer

Randomly splitting adjacent image tiles from the same wells can produce optimistic results because training and test samples share tool response, lithology, processing style, and local fracture morphology. Class imbalance may also make accuracy misleading; precision, recall, intersection-over-union, fracture-level detection rate, and orientation error are more informative. A model evaluated within one field has not by that test alone demonstrated transfer to a different basin, tool generation, mud system, or preprocessing workflow. The blind-well and cross-lithology tests reported by Dong et al. [17] provide a stronger design than random record-level splitting, but broader cross-tool calibration remains an open requirement. A rigorous validation design should therefore use well-level separation at minimum and field- or basin-level external validation where possible. Labels should include interpreter confidence and fracture class. The reference standard should combine image interpretation with core or dynamic evidence rather than assuming that one interpreter's picks are error free. Calibration curves and uncertainty maps are needed if predictions are to support reservoir decisions [16, 17].

6.3. Physics-guided and Multimodal Learning

Image architecture alone does not resolve acquisition bias or non-unique electrical contrast. A physically constrained model could use raw or lightly processed button data together with mud resistivity, caliper, borehole deviation, formation resistivity, gamma ray, sonic, density-neutron separation, and core labels. Constraints may enforce sinusoidal geometry, orientation continuity, plausible resistivity contrast, or consistency with forward-modeled tool response. Whether these additions improve transferability remains a testable hypothesis rather than an established advantage.

Multimodal learning is especially important in oil-based mud, poor-borehole conditions, or incomplete pad coverage. Electrical and acoustic images provide complementary contrast mechanisms, while conventional logs extend predictions into intervals or wells without images.

The aim should be a probabilistic fracture description with traceable evidence, not an opaque binary curve.

7. Uncertainty, Failure Modes, and Reporting Standards

Electrical fracture evaluation contains uncertainty at four levels. Acquisition uncertainty includes pad contact, standoff, missing buttons, tool eccentricity, motion, mud properties, and borehole rugosity. Petrophysical uncertainty includes matrix resistivity, salinity, saturation, clay and conductive minerals, wettability, and invasion. Geometric uncertainty includes fracture orientation relative to the well, multiple sets, roughness, partial filling, and sampling bias. Interpretational uncertainty includes image normalization, thresholds, background selection, model parameterization, and training-label subjectivity [2, 3, 40].

Several recurrent failure modes deserve explicit reporting:

These include equating every conductive feature with an open natural fracture; using the sign of dual laterolog separation as a universal dip rule; treating image-derived aperture as a direct physical measurement; estimating permeability from aperture without stress and connectivity calibration; applying Archie parameters obtained from matrix-dominated plugs to fracture-dominated intervals; ignoring oil-based versus water-based mud when interpreting image polarity; training and testing machine-learning models on overlapping wells or image tiles; reporting a single deterministic fracture-porosity curve without sensitivity analysis; extrapolating borehole-intersection statistics directly to a three-dimensional network.

For reproducibility, publications should report the tool family and generation, mud system and resistivity at downhole temperature, borehole size and deviation, vertical sampling and azimuthal coverage, static or dynamic image normalization, fracture-picking rules, aperture equation and coefficients, correction for orientation bias, validation data, and uncertainty metric. Machine-learning studies should additionally report the number of wells and fields, split strategy, class distribution, label protocol, external-validation results, and performance at the fracture-object level [16, 17].

8. An Integrated Interpretation Architecture

A defensible workflow proceeds from measurement conditioning to reservoir decision while preserving the distinction between observation and inference. The architecture comprises four stages, each with a defined output and a boundary on the claims that it can support.

8.1. Decision Definition and Measurement Conditioning

The interpretation target should be specified before processing because fracture detection, well-placement orientation, aperture ranking, effective permeability, and completion selection require different evidence. Environmental conditioning then establishes whether the measurements can address that target. Required checks include mud type and resistivity at downhole temperature, caliper, pad coverage, standoff, tool motion, borehole deviation, electrode quality, and invasion state. Raw and dynamically normalized images should be retained because they preserve different information [12, 3].

Background electrofacies should be defined from mineralogy, gamma ray, density, neutron, sonic, and conventional resistivity. This step identifies bedding, shale, conductive minerals, saturation changes, and borehole effects that could otherwise be classified as fractures. Its output is an interval-specific background model and a record of acquisition limitations.

8.2. Detection and Feature Classification

Candidate intervals are screened using deep-shallow resistivity behavior, azimuthal or multicomponent anisotropy, conventional-log derivatives, mud losses, and image texture. High

sensitivity is useful at this stage, but candidate selection should not be reported as confirmed fracture permeability. Electrical and, where available, acoustic images are then used to distinguish natural conductive or resistive fractures from bedding, stylolites, drilling-induced tensile fractures, breakouts, and tool artifacts [13, 14, 12].

The output should include feature class, location, confidence, and the evidence supporting each pick. Ambiguous features should remain explicitly uncertain rather than being forced into a binary class. Machine-learning models should be evaluated at the fracture-object and well levels because random image-tile splits do not test transfer to unseen wells.

8.3. Geometric and Electrical Inversion

Fracture dip, azimuth, set membership, spacing, and linear intensity are calculated after correcting for borehole trajectory and intersection bias. Trace-fitting uncertainty and incomplete pad coverage should accompany these estimates. Apparent electrical aperture or fracture porosity may then be inverted with a tool-specific forward model, but the reported result should retain sensitivity to mud resistivity, flushed-zone resistivity, invasion, background selection, fracture dip, and model coefficients.

Ranges, posterior intervals, or scenario envelopes are more defensible than a single deterministic curve. Agreement between two electrical outputs is not independent validation when both depend on the same invasion process or background model [31, 15].

8.4. Dynamic Validation and Reservoir Upscaling

Electrical hypotheses are tested against core and dynamic observations, including mud loss, formation-tester mobility, Stoneley-wave attenuation, pressure-transient behavior, temperature, production logs, and well tests. Separate models should be maintained for fracture detection and hydraulic effectiveness. A fracture may be confidently detected yet remain unproven as a reservoir flow path [10, 11, 7].

Upscaling combines orientation sets and effectiveness probabilities with geomechanics, seismic attributes, outcrop analogues, and discrete-fracture-network models. Borehole sampling bias and uncertainty should be propagated rather than discarded. Prospective validation on blind wells or later production data is required before thresholds or model priors are treated as transferable.

8.5. Worked Evidence Mapping from Published Validation Studies

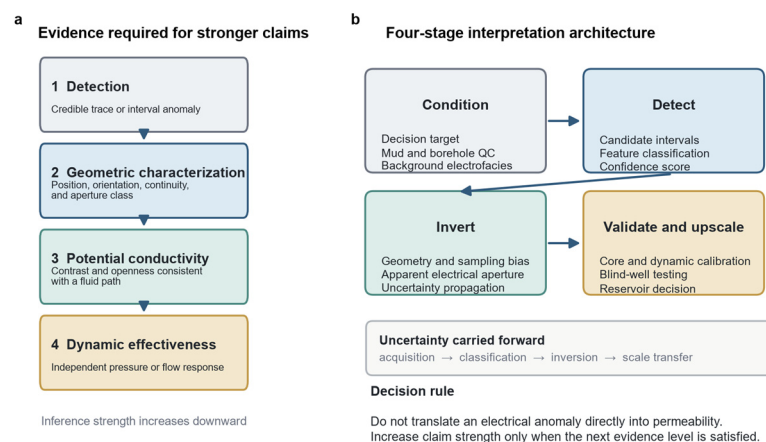


Figure 2. Evidence hierarchy and four-stage interpretation architecture. Stronger fracture claims require progressively stronger evidence, from detection and geometric characterization to potential conductivity and independent dynamic confirmation. The workflow carries acquisition, classification, inversion, and scale-transfer uncertainty into the final reservoir decision.

Published comparisons show how the evidence hierarchy prevents an electrical observation from being promoted directly to a reservoir-flow claim. Genter et al. [10] documented systematic differences between core and borehole-image fracture sampling, whereas Khoshbakht et al. [11] found stronger image reliability for open fractures than for filled fractures and faults. These comparisons support detection and geometric characterization when traces and core features agree, but they do not by themselves establish connected transmissivity. In oil-based mud, the combined electrical-image and sonic workflow of Lai et al. [12] adds an independent contrast mechanism and can strengthen classification, yet dynamic effectiveness still requires pressure or flow evidence. The example therefore ends at the highest evidence level actually supported rather than assigning permeability from image appearance alone.

9. Research Priorities

9.1. Coupled Fracture-Matrix Electrical Models

Many operational interpretations represent fractures as ideal conductive sheets or effective anisotropy, which limits their ability to distinguish rough contacts, partial filling, and dynamic invasion. A useful next step would couple aperture fields, matrix surface conduction, multiphase saturation, stress-dependent contact, and invasion within models calibrated against laboratory and downhole measurements. Complex conductivity could provide an additional constraint, but its added value should be tested against direct-current and induction baselines before routine deployment is claimed [9, 26, 25].

9.2. Quantitative Uncertainty and Experimental Benchmarks

The literature reviewed here did not reveal a widely adopted open benchmark that permits quantitative comparison among processing and machine-learning methods. A useful benchmark would link raw electrical-image measurements, environmental logs, processing parameters, oriented core, laboratory resistivity, and dynamic flow evidence while preserving well-level separation. Controlled blind tests across tool types and basins would reveal whether an algorithm learns transferable fracture physics or field-specific visual style. Synthetic data remain valuable for testing identifiability within a known forward model, but they cannot substitute for blind field validation [16, 17].

9.3. From Apparent Aperture to Effective Connectivity

The main unresolved scale transition is from local apparent electrical aperture to connected transmissivity. Hierarchical models should combine electrical aperture, fracture-set orientation, geomechanical slip tendency, and dynamic flow observations to estimate a probability of effectiveness rather than a deterministic permeability. Such models should be challenged with pressure communication and production data from wells not used for calibration. Success would be demonstrated by calibrated probabilities and improved reservoir decisions, not only by agreement with image-log interpretations.

9.4. Physics-guided Artificial Intelligence

Current automated methods are vulnerable to label subjectivity, class imbalance, spatial leakage, and changes in tool or field characteristics. Physics-guided models should therefore incorporate acquisition constraints, geological context, and calibrated uncertainty while exposing the observations supporting each pick. Domain adaptation, self-supervised learning, and generative augmentation remain hypotheses until they improve fracture-object detection and orientation estimates on blind wells. Ablation studies should separate gains due to architecture, augmentation, preprocessing, and additional log channels.

9.5. Real-time Interpretation While Drilling

LWD resistivity images and deep directional measurements can update fracture predictions during drilling, but real-time use imposes explicit limits on latency, quality control, and decision thresholds. The appropriate test is whether a continuously updated probability of intersecting a target fracture set improves a predefined steering or completion decision under blind operational conditions. A definitive fracture map is not a defensible real-time output when image coverage, invasion, or trajectory uncertainty remains unresolved.

10. Limitations of the Present Review

This review is narrative and evidence-centered but not systematic. It does not provide exhaustive database coverage, a PRISMA screening count, formal study-quality scores, or pooled quantitative effect estimates. The literature also combines laboratory fractures, numerical models, individual field cases, and proprietary tool workflows that cannot be normalized to a single performance metric. Consequently, method comparisons are qualitative and conditional on mud system, lithology, borehole geometry, processing, and validation design. The review does not independently reprocess raw logs or test commercial algorithms. Publication bias may favor successful fracture interpretations, and field studies with negative or ambiguous results are less visible. Rapidly evolving tool designs and machine-learning workflows further limit the transfer of reported performance values. These constraints reinforce the need for open benchmark data, blind-well validation, and explicit reporting of uncertainty and failure cases.

11. Conclusion

Electrical logs provide valuable evidence for fractures because they respond to conductivity contrast and directional pore structure, but no resistivity anomaly has a unique geological interpretation. Aperture, connectivity, roughness, filling, saturation, salinity, stress, invasion, orientation, background lithology, borehole conditions, and tool physics jointly control the response.

Conventional resistivity and dual laterolog measurements are most defensible for interval screening and scenario-based inversion when the borehole environment and invasion are characterized. Multicomponent induction adds directional information, although bedding and matrix anisotropy remain competing explanations. Electrical borehole images provide local evidence for trace position and orientation, whereas apparent electrical aperture is a model-dependent inversion. None of these outputs alone establishes hydraulic effectiveness.

The principal contribution of this review is an evidence hierarchy that separates detection, geometric characterization, potential conductivity, and dynamically confirmed effectiveness. Its four-stage interpretation architecture conditions measurements, classifies candidate features, inverts electrical attributes with uncertainty, and tests those hypotheses against independent core and dynamic data. This framework supports probabilistic, decision-specific fracture characterization while making clear where the available evidence ends. Automated and multimodal methods may strengthen the workflow, but claims of transferability require blind-well or cross-field validation.

References

- [1] Sibbit, A. M., & Faivre, O. (1985). The dual laterolog response in fractured rocks. In SPWLA 26th Annual Logging Symposium (Paper T, pp. T1–T34). Dallas, United States.
- [2] Luthi, S. M., & Souhaité, P. (1990). Fracture apertures from electrical borehole scans. *Geophysics*, 55(7), 821–833.

- [3] Lai, J., Wang, G., Wang, S., et al. (2018). A review on the applications of image logs in structural analysis and sedimentary characterization. *Marine and Petroleum Geology*, 95, 139–166.
- [4] Kharrat, R., & Ott, H. (2023). A comprehensive review of fracture characterization and its impact on oil production in naturally fractured reservoirs. *Energies*, 16(8), 3437.
- [5] Wood, D. A. (2024). Expanding role of borehole image logs in reservoir fracture and heterogeneity characterization: A review. *Advances in Geo-Energy Research*, 12(3), 194–204.
- [6] Pouraskarparast, Z., Aghaei, H., Colombero, L., et al. (2024). Fracture aperture: A review on fundamental concepts, estimation methods, applications, and research gaps. *Marine and Petroleum Geology*, 164, 106818.
- [7] Viswanathan, H. S., Ajo-Franklin, J., Birkholzer, J. T., et al. (2022). From fluid flow to coupled processes in fractured rock: Recent advances and new frontiers. *Reviews of Geophysics*, 60(1), e2021RG000744.
- [8] Piggott, A. R., & Elsworth, D. (1993). Laboratory assessment of the equivalent apertures of a rock fracture. *Geophysical Research Letters*, 20(13), 1387–1390.
- [9] Kirkby, A., Heinson, G., & Krieger, L. (2016). Relating permeability and electrical resistivity in fractures using random resistor network models. *Journal of Geophysical Research: Solid Earth*, 121(3), 1546–1564.
- [10] Genter, A., Castaing, C., Dezayes, C., et al. (1997). Comparative analysis of direct (core) and indirect (borehole imaging tools) collection of fracture data in the Hot Dry Rock Soultz reservoir. *Journal of Geophysical Research: Solid Earth*, 102(B7), 15419–15431.
- [11] Khoshbakht, F., Azizzadeh, M., Memarian, H., et al. (2012). Comparison of electrical image log with core in a fractured carbonate reservoir. *Journal of Petroleum Science and Engineering*, 86–87, 289–296.
- [12] Lai, J., Wang, G., Fan, Z., et al. (2017). Fracture detection in oil-based drilling mud using a combination of borehole image and sonic logs. *Marine and Petroleum Geology*, 84, 195–214.
- [13] Aghli, G., Soleimani, B., Moussavi-Harami, R., et al. (2016). Fractured zones detection using conventional petrophysical logs by differentiation method and its correlation with image logs. *Journal of Petroleum Science and Engineering*, 142, 152–162.
- [14] Shalaby, M. R., & Islam, M. A. (2017). Fracture detection using conventional well logging in carbonate Matulla Formation, Geisum oil field, southern Gulf of Suez, Egypt. *Journal of Petroleum Exploration and Production Technology*, 7(4), 977–989.
- [15] Hu, S., Wang, X., Wang, J., et al. (2023). Quantitative evaluation of fracture porosity from dual laterlog based on deep learning method. *Energy Geoscience*, 4(2), 100064.
- [16] Du, L., Lu, X., & Li, H. A. (2023). Automatic fracture detection from the images of electrical image logs using Mask R-CNN. *Fuel*, 351, 128992.
- [17] Dong, S., Hao, J., Zeng, L., et al. (2024). A deep-learning object-detection method for fracture identification using conventional well logs. *IEEE Transactions on Geoscience and Remote Sensing*, 62, 5920716.
- [18] Archie, G. E. (1942). The electrical resistivity log as an aid in determining some reservoir characteristics. *Transactions of the AIME*, 146(1), 54–62.
- [19] Tang, T., Lu, T., Zhang, H., et al. (2017). Electrical characteristics of rocks in fractured and caved reservoirs. *Journal of Geophysics and Engineering*, 14, 1437–1444.
- [20] Zhao, J., Sun, J., Liu, X., et al. (2013). Numerical simulation of the electrical properties of fractured rock based on digital rock technology. *Journal of Geophysics and Engineering*, 10(5), 055009.
- [21] Yue, W. (2019). Pore-scale explanation of the Archie's cementation exponent: Microstructure, electrical anisotropy, and numerical experiments. *Geophysical Research Letters*, 46(10), 5799–5807.
- [22] Lee, H., Lee, J.-W., & Oh, T.-M. (2021). Permeability evaluation for artificial single rock fracture according to geometric aperture variation using electrical resistivity. *Journal of Rock Mechanics and Geotechnical Engineering*, 13(4), 787–797.

- [23] Sawayama, K., Ishibashi, T., Jiang, F., et al. (2021). Scale-independent relationship between permeability and resistivity in mated fractures with natural rough surfaces. *Geothermics*, 94, 102065.
- [24] Sawayama, K., Ishibashi, T., Jiang, F., et al. (2023). Relationship between permeability and resistivity of sheared rock fractures: The role of tortuosity and flow-path percolation. *Geophysical Research Letters*, 50(20), e2023GL104418.
- [25] Sawayama, K., Ishibashi, T., Jiang, F., et al. (2026). Microstructural control of permeability, electrical resistivity, and seismic velocity and their relationships in sheared rock fractures under normal stress. *International Journal of Rock Mechanics and Mining Sciences*, 202, 106505.
- [26] Qi, Y., Nakagawa, S., Manga, M., et al. (2026). Complex electrical conductivity of a single-fractured rock: Fracture-and-matrix coupling mechanism and aperture-size predictions. *Geophysical Research Letters*, 53(12), e2026GL122204.
- [27] Mohammed, T. E., & Schmitt, D. R. (2020). Preliminary experiments towards understanding the influence of fractures on the anisotropy of electrical conductivity. *Journal of Applied Geophysics*, 182, 104197.
- [28] Shi, G., He, T., Wu, Y., et al. (2004). A study on the response of dual-lateral well logs to fractures using forward numerical modelling. *Chinese Journal of Geophysics*, 47, 405–410. (in Chinese)
- [29] Deng, S., Wang, X., Zou, D., et al. (2006). Interpreting dual laterolog fracture data in fractured carbonate formation. *Journal of China University of Geosciences*, 17(2), 168–172. (in Chinese)
- [30] Deng, S., Li, L., Li, Z., et al. (2015). Numerical simulation of high-resolution azimuthal resistivity laterolog response in fractured reservoirs. *Petroleum Science*, 12(2), 252–263.
- [31] Saboorian-Jooybari, H., Dejam, M., Chen, Z., et al. (2016). Comprehensive evaluation of fracture parameters by dual laterolog data. *Journal of Applied Geophysics*, 131, 214–221.
- [32] Khoshbakht, F., Rasaie, M. R., & Shekarifard, A. (2016). Investigating induction log response in the presence of natural fractures. *Journal of Petroleum Science and Engineering*, 145, 357–369.
- [33] Hou, J., Donderici, B., Torres, D., et al. (2015). Fast determination and characterization of formation resistivity anisotropy, dip, and fracture using multicomponent induction data. *Interpretation*, 3(3), ST55–ST71.
- [34] Nan, Z., Tan, M., Wang, J., et al. (2023). Multi-component induction logging detection characteristics of the fracture azimuth and dip angles and the fast extraction methods of fracture distribution parameters. *Geoenergy Science and Engineering*, 226, 211711.
- [35] Shiriyev, J., Brick, Y., Zhang, P., et al. (2018). Experiments and simulations of a prototype triaxial electromagnetic induction logging tool for open-hole hydraulic-fracture diagnostics. *Geophysics*, 83(3), D73–D81.
- [36] Kang, Z., Zhang, Y., Hou, B., et al. (2022). Using the multi-component induction logging data to evaluate the geometric parameters of the hydraulic fracture. *Journal of Geophysics and Engineering*, 19(5), 1163–1179.
- [37] Zemanek, J., Caldwell, R. L., Glenn, E. E., Jr., et al. (1969). The borehole televiewer-A new logging concept for fracture location and other types of borehole inspection. *Journal of Petroleum Technology*, 21(6), 762–774.
- [38] Aghli, G., Moussavi-Harami, R., & Mohammadian, R. (2020). Reservoir heterogeneity and fracture parameter determination using electrical image logs and petrophysical data: A case study of the carbonate Asmari Formation, Zagros Basin, SW Iran. *Petroleum Science*, 17(1), 51–69.
- [39] Stadtmüller, M. (2019). Well logging interpretation methodology for carbonate-formation fracture-system properties determination. *Acta Geophysica*, 67, 1933–1943.
- [40] Kang, Z., Li, X., Ni, W., et al. (2021). Using logging while drilling resistivity imaging data to quantitatively evaluate fracture aperture based on numerical simulation. *Journal of Geophysics and Engineering*, 18(3), 317–327.
- [41] Li, X., Shen, J., Yang, W., et al. (2019). Automatic fracture-vug identification and extraction from electric imaging logging data based on path morphology. *Petroleum Science*, 16(1), 58–76.