A Review on Pore Geometry and Connectivity as Controls on Seismic Response in Hydrocarbon Reservoirs

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Abstract
Pore architecture is a fundamental control on the seismic response of hydrocarbon reservoir rocks, yet conventional rock-physics interpretation often relies primarily on total porosity. This review examines how pore geometry and connectivity influence elastic and dynamic seismic properties across sandstone, carbonate, and fractured reservoirs. Particular attention is given to pore shape and aspect ratio, pore-size distribution, pore-throat geometry, grain contacts, cementation, fractures, and three-dimensional pore connectivity. Available experimental and theoretical evidence demonstrates that rocks with similar porosity can exhibit substantially different seismic responses because pore architecture controls both the mechanical compliance of the solid framework and hydraulic communication within the pore network. Low-aspect-ratio pores and fractures generally increase compliance and pressure sensitivity, whereas stronger grain contacts and cementation increase frame stiffness and seismic velocity. Pore-throat geometry, tortuosity, and connectivity regulate pressure communication and fluid redistribution, thereby linking pore architecture with attenuation and velocity dispersion in addition to P- and S-wave velocities. These effects are particularly important in heterogeneous carbonate and fractured reservoirs, where multiple pore systems coexist and conventional velocity–porosity relationships frequently become non-unique. This review further evaluates pore-characterization techniques, rock-physics models, three-dimensional imaging, and digital rock approaches for translating pore-scale architecture into effective seismic properties. Major remaining challenges include quantitative characterization of connectivity, representation of multiscale pore systems, separation of mechanical and hydraulic controls, and upscaling from pore and core measurements to well-log and field-seismic scales. Future advances are expected from integrated multiscale and 4D imaging, digital rock physics, broadband measurements, coupled mechanical-hydraulic modeling, and physics-informed data-driven methods. Overall, incorporating pore geometry and connectivity as independent rock-physics variables provides a more physically constrained framework for seismic characterization of reservoir quality, fractures, permeability architecture, and subsurface heterogeneity.

Keywords: Pore geometry; pore connectivity; seismic response; rock physics; seismic velocity; attenuation; dispersion; digital rock physics; hydrocarbon reservoirs.

1. Introduction and Rock-Physics Basis

1.1 Background and Significance

Seismic properties of hydrocarbon reservoir rocks are commonly related to porosity, mineral composition, fluid saturation, and effective pressure. However, total porosity alone cannot fully explain the elastic behavior of many reservoir rocks. Samples with similar porosity and mineralogy may exhibit substantially different P- and S-wave velocities because their pore spaces differ in shape, size, connectivity, grain-contact geometry, and degree of cementation. This variability is particularly pronounced in carbonate reservoirs, where inter-particle pores, micro-pores, molds, vugs, and fractures may coexist within the same rock. Pore architecture influences seismic response primarily by controlling the mechanical compliance of the rock frame. Rounded or nearly spherical pores generally produce a smaller reduction in elastic stiffness than thin cracks and other low-aspect-ratio pores. Consequently, pore shape and aspect ratio can strongly influence elastic moduli and seismic velocity even when total porosity remains unchanged [1-6,11,14,16]. Grain contacts and cement distribution further determine how stresses are transmitted through the solid framework, making compaction and diagenesis important controls on seismic properties [7,9]. Pore connectivity introduces an additional control because it determines communication among individual pores and governs possible fluid-pressure redistribution through the pore network. Pore-throat dimensions, coordination, tortuosity, fractures, and connected pore pathways can therefore influence not only permeability but also frequency-dependent seismic behavior. Understanding these relationships is important for improving the interpretation of seismic and sonic data in heterogeneous hydrocarbon reservoirs.

Pore geometry describes the physical form of the void space within a rock and includes **pore size, shape, aspect ratio, pore-throat dimensions, surface morphology, and spatial distribution**. These characteristics determine how strongly pores deform when subjected to an applied stress.

A useful geometric parameter is the pore aspect ratio, which can be expressed conceptually as

$$\boldsymbol{\alpha} = \frac{\boldsymbol{b}}{\boldsymbol{a}}$$

Where *b* represents the short dimension and *a* is the long dimension of an idealized pore. Values approaching unity represent approximately equant pores, whereas very small values represent crack-like pores. Low-aspect-ratio pores are highly compliant and can therefore produce disproportionately large reductions in elastic stiffness and seismic velocity [1]. Connectivity describes the degree to which individual pores and pore throats form continuous networks. It can be represented through parameters such as coordination number, connected porosity, tortuosity, and pore-throat topology. Two rocks may therefore contain the same total pore volume but have fundamentally different pore systems: one may consist primarily of isolated pores, whereas another contains a highly interconnected network. This distinction is important because **porosity quantifies how much pore space exists, whereas pore geometry and connectivity describe how that pore space is organized**. The latter determines both mechanical deformation and hydraulic communication within the reservoir.

1.3 Why Porosity Alone Is Insufficient

The conventional velocity–porosity relationship generally predicts decreasing seismic velocity with increasing porosity because replacing solid mineral material with pore space reduces effective rock stiffness. However, considerable scatter is commonly observed around this general relationship [2,4,6,14]. The reason is that equal amounts of porosity can have different mechanical effects depending on pore architecture. For example, a rock containing rounded, relatively stiff pores may maintain higher elastic moduli than a rock with the same porosity dominated by thin cracks. Similarly, cement concentrated at grain contacts can substantially increase frame stiffness without requiring a major change in total porosity [7,9]. Carbonate rocks provide an especially important example. Anselmetti and Eberli [6,11] demonstrated that pore type strongly influences

1.2 Pore Geometry and Connectivity

sonic velocity, while Weger et al. [16] showed that quantitative measures of pore structure improve the interpretation of velocity and permeability. Consequently, the relationship:

Porosity → Seismic velocity

is often inadequate for heterogeneous reservoirs. A more physically meaningful framework is

Porosity + pore geometry + connectivity + grain contacts → effective elastic properties → seismic response.

This framework explains why pore architecture should be treated as an independent rock-physics control rather than simply as a secondary consequence of porosity.

1.4 Pore Architecture and Elastic Properties

For an isotropic rock, P- and S-wave velocities can be expressed as

$$\boldsymbol{V_P} = \sqrt{\left[\frac{\boldsymbol{K} + \frac{4\boldsymbol{G}}{3}}{\boldsymbol{\rho}}\right]}$$

and

$$\boldsymbol{V_S} = \sqrt{\frac{\boldsymbol{G}}{\boldsymbol{\rho}}}$$

Where *K* is the effective bulk modulus, *G* is the effective shear modulus, and *ρ* is bulk density.

Pore architecture affects seismic velocity primarily through its influence on *K* and *G*. Compliant cracks and elongated pores reduce effective moduli more strongly than stiff, equant pores. Grain contacts and cementation can have the opposite effect by strengthening the load-bearing framework and increasing elastic stiffness [7,9]. The concept of critical porosity provides another useful framework. As porosity increases toward a critical value, the load-bearing mineral framework progressively loses mechanical continuity, producing substantial changes in elastic behavior [8,10]. However, the critical-porosity concept does not eliminate the importance of pore geometry because rocks with similar porosity may possess different grain contacts, cement distributions, and pore networks. Connectivity becomes particularly important for dynamic seismic properties. Connected pores provide pathways for pore-pressure communication, whereas isolated pores restrict fluid movement. Consequently, pore connectivity, permeability, and characteristic pore dimensions can influence attenuation and velocity dispersion when seismic deformation induces fluid-pressure gradients. The seismic response of a reservoir can therefore be viewed as the combined result of two related aspects of pore architecture:

Mechanical architecture:
Pore shape + aspect ratio + grain contacts + cementation → frame compliance → elastic moduli and velocity
Hydraulic architecture:
Pore throats + connectivity + tortuosity + fractures → pressure communication → attenuation and dispersion
This distinction provides a useful basis for interpreting the different roles of pore geometry and connectivity throughout this review.

1.5 Scope and Objectives of the Review

This review examines how **pore geometry and connectivity control seismic response in hydrocarbon reservoir rocks**, with emphasis on P- and S-wave velocity, elastic moduli, attenuation, and dispersion. Particular attention is given to pore shape and aspect ratio, pore-size distribution, pore throats, grain contacts, cementation, fractures, vugs, and connected pore networks. This review combines experimental data, theoretical rock-physics models, pore-scale imaging and digital rock simulations to assess the influence of pore architecture on seismic properties in sandstone, carbonate and fractured reservoirs. It also considers the limitations of conventional porosity-based interpretation and the challenges involved in transferring pore-scale observations to sonic-log and field-seismic scales. The central premise of the review is:
Pore geometry and connectivity → mechanical and hydraulic architecture → elastic and dynamic rock properties → seismic response → reservoir characterization.
Understanding this relationship is essential for moving from empirical velocity–porosity correlations toward more physically constrained seismic characterization of complex hydrocarbon reservoirs.

2. Effects of Pore Geometry and Connectivity on Seismic Response

2.1 Pore Shape and Aspect Ratio

Pore shape is one of the most important controls on the elastic behavior of reservoir rocks because pores with different geometries respond differently to applied stress. Equant or approximately spherical pores are relatively stiff, whereas elongated pores and thin cracks are highly compliant. Consequently, rocks containing low-aspect-ratio pores may exhibit substantially lower elastic moduli and seismic velocities than rocks having similar porosity but more rounded pores [1,6]. Cheng and Toksöz [1] demonstrated that seismic velocities can be related to a spectrum of pore aspect ratios rather than to a single average pore shape. This is important because natural reservoir rocks commonly contain several pore populations simultaneously. Low-aspect-ratio pores also exhibit strong pressure sensitivity. Increasing effective pressure preferentially closes compliant cracks, increasing the effective elastic moduli and seismic velocity. Therefore, pore geometry influences not only the magnitude of velocity but also its pressure dependence.
A useful relationship is:

Lower pore aspect ratio → greater compliance → lower elastic stiffness → lower seismic velocity and stronger pressure sensitivity.
Reservoir rocks commonly contain pores spanning several orders of magnitude in size. Their seismic response therefore depends not simply on average pore size but on the distribution and mechanical role of different pore populations. In sandstones, intergranular pores generally dominate the pore system, although microporosity associated with clay minerals and cement may also be significant. Carbonates are considerably more complex and may simultaneously contain interparticle pores, intraparticle pores, micropores, molds, vugs, and fractures [6,11,14,16]. Large pores do not necessarily produce the greatest reduction in velocity. Their effect depends strongly on shape and location within the load-bearing framework. A large rounded vug may have less influence on frame compliance than a much smaller crack-like pore. Therefore,
pore size ≠ pore compliance.
Instead, pore size must be considered together with pore shape, grain contacts, and spatial distribution. Multiscale porosity also creates difficulties for simple velocity–porosity models. Micropores may contribute substantially to total porosity while producing a different elastic response from large connected pores or fractures. Models incorporating multiple pore populations are therefore more appropriate for rocks with complex pore systems [22].

2.2 Pore-Throat Geometry and Connectivity

Pores in reservoir rocks are connected through pore throats that determine communication across the pore network. Important parameters include throat size, coordination number, connected porosity, tortuosity, and network topology. **Coordination number** describes the number of pore throats connected to a pore. Higher coordination generally indicates a more interconnected pore network, whereas low coordination can produce isolated or poorly connected pore regions. Connectivity has two important consequences. First, it strongly influences permeability because fluids must move through connected pore-throat networks. Second, connectivity determines the extent over which pore pressures can communicate during seismic deformation. Consequently, two rocks with identical porosity may behave differently:

Rock A: high porosity + poor connectivity → substantial pore volume but restricted fluid communication.

Rock B: similar porosity + high connectivity → continuous pressure-communication pathways.

Silin and Patzek [15] demonstrated how pore-space morphology can be represented through geometrical network analysis, while later pore-scale studies have increasingly emphasized the importance of three-dimensional connectivity. Pore throats may therefore provide a physical link between static pore architecture and dynamic seismic behavior:

Pore-throat geometry → connectivity → pressure communication → dynamic elastic response.

2.3 Grain Contacts, Compaction, and Cementation

Although pores represent void space, the seismic stiffness of a rock is ultimately determined by how the solid grains transmit stress. Grain-contact geometry is therefore closely linked to pore architecture. In poorly consolidated sediments, grain contacts are relatively compliant and seismic velocities are low. Compaction increases contact area and coordination among grains, strengthening the load-bearing framework and increasing elastic moduli. Cementation can produce an even stronger effect. Cement deposited at grain contacts significantly increases contact stiffness and may cause a large velocity increase with only a relatively small reduction in porosity. This explains why rocks with similar porosity can exhibit markedly different seismic velocities depending on their diagenetic history. Dvorkin et al. [7] and Dvorkin and Nur [9] demonstrated the importance of grain contacts and cementation in controlling sandstone elasticity. These relationships are particularly relevant when comparing unconsolidated reservoir sands with strongly cemented sandstones. The fundamental relationship can be summarized as:

Compaction/cementation → stronger grain contacts → increased frame stiffness → higher V_p and V_s.

Therefore, interpretation of seismic velocity purely in terms of porosity can be misleading when cementation and grain-contact structure vary spatially within a reservoir.

2.4 Fractures and Vuggy Pore Systems

Fractures represent an important form of low-aspect-ratio porosity and can strongly modify seismic properties even when they contribute only a small fraction of total porosity. Their high compliance makes seismic velocities particularly sensitive to fracture density and effective pressure.

Fracture orientation introduces an additional effect. Preferentially aligned fractures cause elastic properties to become direction dependent, generating **seismic anisotropy**. Wave velocity measured parallel to a fracture system may therefore differ from velocity measured perpendicular to it. Fracture connectivity is equally important for reservoir behavior. Connected fractures may form preferential fluid-flow pathways, whereas isolated fractures primarily affect mechanical compliance. Consequently, fracture networks influence both elastic and hydraulic properties. Vugs introduce additional complexity, particularly in carbonate reservoirs. Large rounded vugs may have relatively limited effects on elastic stiffness, whereas interconnected or fracture-associated vugs can substantially modify both fluid transport and seismic behavior. This helps explain the large scatter commonly observed in carbonate velocity–porosity relationships [6,14,16,23].

The seismic effect therefore depends on the combination of:

fracture/vug abundance + shape + orientation + connectivity + effective pressure.

2.5 Controls on P- and S-Wave Velocity

P- and S-wave velocities respond to pore architecture through its influence on effective bulk and shear moduli. In general, increasing compliant porosity reduces both moduli and therefore decreases seismic velocity. However, the magnitude of this decrease depends

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strongly on pore geometry. P-wave velocity is particularly sensitive to changes in bulk stiffness, whereas S-wave velocity reflects changes in shear rigidity. Crack-like pores can strongly affect both properties because they reduce the mechanical integrity of the rock framework. This explains why a universal velocity–porosity relationship cannot adequately describe all reservoir rocks. Han et al. [2] showed systematic effects of porosity and clay content in sandstones, while carbonate studies demonstrate considerably greater scatter because pore type and geometry vary strongly [6,13,14,16]. A more appropriate conceptual relationship is:

V_p , V_s = f (porosity, pore shape, connectivity, grain contacts, mineralogy, pressure, fluids).

Pore architecture therefore provides an important explanation for deviations from conventional velocity–porosity trends and should be incorporated into quantitative rock-physics interpretation.

2.6 Pore Architecture, Attenuation, and Dispersion

Pore geometry and connectivity also influence seismic attenuation and velocity dispersion, particularly when the pore space contains mobile fluids. Seismic deformation can generate different pore pressures within pores having different shapes, compliances, or fluid environments. If these regions are hydraulically connected, fluid moves in response to the pressure gradient. Viscous resistance to this movement dissipates seismic energy and contributes to attenuation. Because the ability of fluid pressure to equilibrate depends on wave period, the effective elastic modulus may also vary with frequency, producing velocity dispersion. Pore architecture controls this process through several parameters. Small pore throats can restrict fluid exchange, while highly connected networks facilitate pressure communication. Crack-pore systems may create strong compliance contrasts, and fractures can increase characteristic fluid-flow distances. Permeability and fluid viscosity further determine the rate of pressure diffusion. The mechanism can be summarized as:

Pore heterogeneity + connectivity → pore-pressure gradients → fluid redistribution → viscous energy loss → attenuation and dispersion.

Therefore, pore connectivity has a dual role: it controls reservoir fluid transport at geological timescales while also influencing dynamic pressure equilibration during seismic wave propagation.

2.7 Integrated Influence of Pore Architecture

The seismic response of a reservoir results from the combined effects of multiple pore characteristics rather than from any single parameter. Pore shape determines mechanical compliance, grain contacts determine frame stiffness, and pore throats and connectivity determine hydraulic communication. Fractures and vugs may modify several of these properties simultaneously.

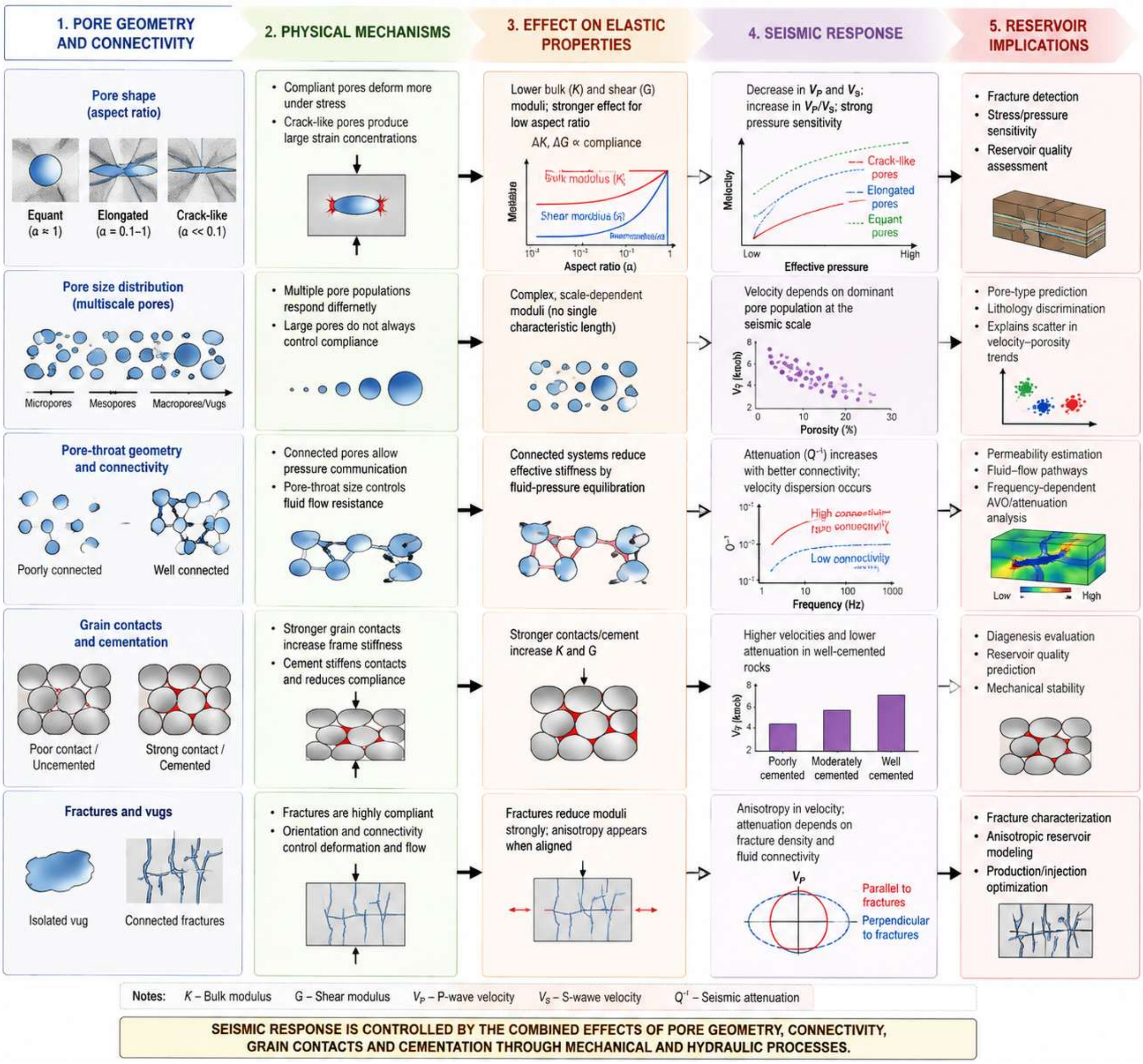

Figure 2. 1. Conceptual framework linking pore geometry and connectivity to seismic response in hydrocarbon reservoir rocks.

Pore shape, size distribution, pore-throat connectivity, grain contacts, cementation, fractures, and vugs control the mechanical compliance and hydraulic communication of the pore system. These properties alter effective elastic moduli and pore pressure redistribution and thus P- and S-wave velocities, seismic attenuation, velocity dispersion and anisotropy.. The resulting seismic signatures provide information for pore-type discrimination, fracture characterization, reservoir-quality assessment, and seismic reservoir interpretation.

Table 1. Principal pore-architecture controls on seismic response

Pore characteristic	Primary physical effect	Expected seismic influence
Total porosity	Reduces solid load-bearing volume	Generally decreases V_P and V_S
Pore aspect ratio	Controls pore compliance	Low aspect ratio strongly reduces stiffness and velocity
Pore size distribution	Produces multiscale elastic behavior	Contributes to velocity variability and frequency dependence
Pore-throat size	Controls hydraulic communication	Influences attenuation and dispersion
Connectivity	Determines pressure-communication pathways	Controls dynamic fluid response
Grain contacts	Determine load-bearing stiffness	Stronger contacts increase V_P and V_S
Cementation	Stiffens grain contacts	Can strongly increase velocity
Fracture density	Increases compliant porosity	Reduces stiffness and velocity
Fracture orientation	Produces directional stiffness	Generates seismic anisotropy
Vugs	Create large heterogeneous pores	Effect depends strongly on shape and connectivity
Tortuosity	Controls complexity of fluid pathways	Influences pressure diffusion and dynamic response

Overall, pore architecture influences seismic behavior through two interconnected pathways:
Pore geometry → mechanical compliance → elastic moduli → seismic velocity
and
Pore connectivity → pressure communication and fluid mobility → attenuation and dispersion.

These pathways explain why reservoir rocks with similar mineralogy and total porosity can exhibit markedly different seismic responses. Quantitative reservoir characterization therefore requires information about **how pore space is shaped, connected, and incorporated into the load-bearing rock framework**, rather than relying on porosity alone.

3. Pore-Scale Characterization, Modeling, and Reservoir Applications

3.1 Characterization of Pore Geometry and Connectivity

Reliable interpretation of seismic properties requires quantitative characterization of the pore system. No single experimental method can completely describe pore architecture because reservoir rocks contain features ranging from nanometer-scale micropores to millimeter-scale vugs and fractures. Consequently, complementary techniques are commonly required. **Thin-section petrography and scanning electron microscopy (SEM)** provide direct observations of pore shape, grain contacts, cement distribution, microfractures, and diagenetic alteration. These methods are particularly useful for identifying the origin and morphology of pores, although they mainly provide two-dimensional information. **Mercury intrusion capillary pressure (MICP)** provides information about pore-throat size distribution and connectivity. Because mercury enters progressively smaller pore throats as pressure increases, the resulting intrusion curve can characterize the hydraulic accessibility of the pore network. However, MICP primarily reflects pore-throat dimensions rather than the dimensions of pore bodies themselves. **Nuclear magnetic resonance (NMR)** provides complementary information on pore-size distribution and fluid-containing pore volumes through relaxation behavior. It is particularly valuable for distinguishing pore populations and evaluating movable and bound fluids. **X-ray computed tomography (CT) and micro-CT** have become increasingly important because they allow three-dimensional visualization of pores, fractures, vugs, and connected pathways. Unlike conventional two-dimensional imaging, CT-based methods permit direct evaluation of pore-network topology and provide geometries suitable for digital rock simulations [18,19]. The most reliable pore characterization therefore results from combining methods that capture different spatial scales and structural attributes.

Table 3.1. Principal Methods for Characterizing Reservoir Pore Architecture

Method	Main information obtained	Major strength	Main limitation
Thin section	Pore type, shape, mineral texture, cement	Direct petrographic interpretation	Mainly 2D
SEM	Micropores, grain contacts, clay and cement	High spatial resolution	Small observation area
MICP	Pore-throat distribution and accessibility	Strong sensitivity to pore throats	Indirect representation of pore bodies
NMR	Pore populations and fluid-associated pore volume	Non-destructive and fluid sensitive	Conversion to pore size requires calibration
X-ray CT	Vugs, fractures and internal heterogeneity	3D visualization	Limited resolution for very small pores
Micro-CT	3D pore geometry and connectivity	Suitable for digital rock analysis	Small sample volume and resolution trade-off

These techniques are most informative when used together because **pore geometry and connectivity are inherently three-dimensional and multiscale properties**.

3.2 Rock-Physics Modeling of Pore Architecture

Rock-physics models provide the connection between observed pore architecture and seismic properties. Different models emphasize different aspects of the pore system, and their applicability depends strongly on reservoir type. Effective-medium approaches represent pores as inclusions embedded within a solid matrix. Pore shape can be introduced through idealized geometries such as spheres, ellipsoids, or cracks. These approaches demonstrate that low-aspect-ratio pores produce substantially greater elastic compliance than rounded pores [1]. Critical-porosity models describe the transition between a load-bearing mineral framework and a poorly consolidated granular system [8,10]. They provide a useful first-order relationship between porosity and elastic moduli but do not explicitly represent the full complexity of pore connectivity. Contact-based models are particularly useful for granular sandstones. They relate elastic stiffness to grain contacts, effective pressure, and cementation. The cemented-sand framework developed by Dvorkin and colleagues demonstrates that small quantities of cement located at grain contacts can significantly increase seismic velocity [7,9]. Reservoir rocks containing several distinct pore populations require more complex approaches. Multiple-pore-type models allow different pore geometries to contribute separately to effective elastic properties and are therefore particularly relevant to heterogeneous carbonates [22]. No single rock-physics model is universally applicable. Model selection should therefore be based on the dominant pore architecture rather than solely on porosity.

3.3 Digital Rock Physics

Digital rock physics provides a direct approach for connecting three-dimensional pore architecture with effective physical properties. The workflow typically begins with high-resolution CT or micro-CT imaging, followed by image segmentation into solid and pore phases. The reconstructed pore geometry is then used for numerical calculations of elastic, hydraulic, or transport properties [18,19]. A major advantage of this approach is that complex pore geometries do not have to be represented entirely by idealized spherical or crack-like inclusions. Real pore shapes, pore throats, fractures, and connectivity can be incorporated explicitly into numerical models. Digital simulations can be used to calculate effective elastic moduli and investigate wave propagation through realistic pore structures. Wang et al. [20], for example, demonstrated pore-scale modeling of elastic-wave propagation in carbonate rocks. Digital rock physics also enables controlled numerical experiments. Pore geometry, connectivity, mineral composition, or fluid distribution can be modified independently to determine their individual effects on seismic response. This is difficult to achieve experimentally in natural rock samples. However, digital rock methods remain sensitive to image resolution, segmentation quality, representative volume size, and numerical assumptions. Microporosity below the imaging resolution may be omitted, while very high-resolution imaging usually reduces the physical size of the analyzed sample. Thus, the central challenge is not only imaging the pore system but also ensuring that the digital volume adequately represents the reservoir rock.

3.4 Sandstone Reservoirs

Sandstones generally have simpler pore systems than carbonates, making relationships between porosity and seismic velocity comparatively systematic. Intergranular porosity, grain contacts, clay content, compaction, and cementation are the dominant controls. Han et al. [2] demonstrated systematic relationships among porosity, clay content, and seismic velocity in sandstones. However, variations in grain contacts and cementation can cause significant departures from simple porosity trends. Cement located at grain contacts increases frame stiffness and velocity, whereas poorly consolidated sands with weak contacts remain highly compliant [7,9]. Pore connectivity in sandstones is also closely related to sorting and cementation. Well-connected intergranular pore networks generally support greater permeability, whereas pore-filling cement and clay can narrow or isolate pore throats. Therefore, seismic interpretation of sandstone reservoirs benefits from considering:

Porosity + clay content + grain contacts + cementation + pore connectivity.

These variables provide a more physically meaningful description of reservoir quality than porosity alone.

3.5 Carbonate Reservoirs

Carbonate reservoirs present a substantially greater rock-physics challenge because depositional and diagenetic processes generate highly heterogeneous pore systems. Microporosity, interparticle pores, intraparticle pores, molds, vugs, and fractures may coexist within the same reservoir interval. As a result, carbonates commonly exhibit considerable scatter in velocity at a given porosity. Anselmetti and Eberli [6,11] demonstrated that pore type is a major control on sonic velocity, while Eberli et al. [14] emphasized the importance of depositional texture and diagenetic modification. Weger et al. [16] further quantified the influence of pore structure on sonic velocity and permeability. Their results reinforce an important principle:

Equal carbonate porosity does not imply equal elastic stiffness or permeability.

Microporous carbonates may contain substantial pore volume but relatively small pores, whereas moldic and vuggy systems contain larger and potentially isolated voids. Fractured-vuggy systems introduce additional compliance, connectivity, and anisotropy. Consequently, carbonate seismic interpretation requires explicit consideration of **pore type, pore shape, connectivity, and diagenetic history**, rather than relying primarily on conventional velocity–porosity relationships.

3.6 Fractured Reservoirs

Fractures can dominate seismic behavior despite representing a relatively small proportion of total porosity. Their low aspect ratios produce high elastic compliance, while preferential fracture orientation generates directional differences in stiffness. Seismic anisotropy can therefore provide information about fracture orientation and intensity. However, fracture effects depend on whether fractures are open, mineralized, fluid filled, or hydraulically connected. Connectivity is particularly important because connected fractures may form reservoir-scale fluid pathways. In fractured carbonate systems, fractures can also connect otherwise isolated vugs, fundamentally changing both permeability and dynamic fluid communication. Thus, fracture characterization requires consideration of:

fracture density + aperture + orientation + connectivity + filling material + effective pressure.

These factors determine whether fractures primarily influence mechanical stiffness, hydraulic transport, or both.

3.7 From Pore Architecture to Seismic Reservoir Characterization

The practical objective of pore-scale rock physics is to improve interpretation of sonic logs and field seismic data. Conventional seismic interpretation frequently relates velocity or impedance to porosity. However, pore-architecture effects introduce substantial non-uniqueness into these relationships. The velocity-deviation approach proposed by Anselmetti and Eberli [11], for example, uses deviations from expected velocity–porosity trends to provide information about carbonate pore type and permeability tendencies. Such approaches demonstrate that seismic properties can contain information about pore architecture beyond total porosity. Integration with seismic inversion provides further potential. Inversion-derived acoustic or elastic properties may be interpreted using rock-physics templates that incorporate porosity, pore type, cementation, and pressure. Nevertheless, field seismic resolution is much lower than the scale of individual pores, meaning that pore architecture is generally inferred indirectly through its effect on effective elastic properties. The interpretation pathway can therefore be represented as:

Pore architecture → effective elastic properties → sonic/seismic observables → rock-physics interpretation → reservoir properties.

Table 3.2. Representative Studies Linking Pore Architecture with Seismic Properties

Study	Reservoir/rock focus	Main pore-architecture parameter	Main contribution
Cheng & Toksöz [1]	General porous rocks	Pore aspect ratio	Related seismic velocity to pore aspect-ratio spectrum
Han et al. [2]	Sandstones	Porosity and clay	Established sandstone velocity relationships
Anselmetti & Eberli [6]	Carbonates	Pore type	Demonstrated strong pore-type control on sonic velocity
Dvorkin et al. [7]	Granular rocks	Cement and grain contacts	Linked contact cementation with elastic stiffness
Dvorkin & Nur [9]	Sandstones	Grain-contact structure	Explained elasticity of high-porosity sandstone
Anselmetti & Eberli [11]	Carbonates	Pore type/permeability	Developed velocity-deviation interpretation
Weger et al. [16]	Carbonates	Quantitative pore structure	Connected pore geometry with velocity and permeability
Andrä et al. [18,19]	Digital rocks	3D pore architecture	Established digital-rock imaging and property benchmarks
Wang et al. [20]	Carbonates	Digital pore geometry	Modeled elastic-wave propagation at pore scale
Zhang et al. [22]	Multiple pore systems	Multiple pore types	Extended rock physics to complex pore populations
Zhang et al. [23]	Carbonates	Pore structure/connectivity	Linked carbonate pore systems with acoustic velocity and permeability

3.8 Integrated Multiscale Framework

The principal challenge is connecting microscopic pore architecture with seismic observations made at much larger spatial scales. Pore geometry may be measured at micrometer scale, laboratory acoustic properties at centimeter scale, well logs at decimeter-to-meter scale, and seismic data at meter-to-tens-of-meters scale. A comprehensive workflow therefore requires integration across scales rather than direct extrapolation from a single pore-scale measurement.

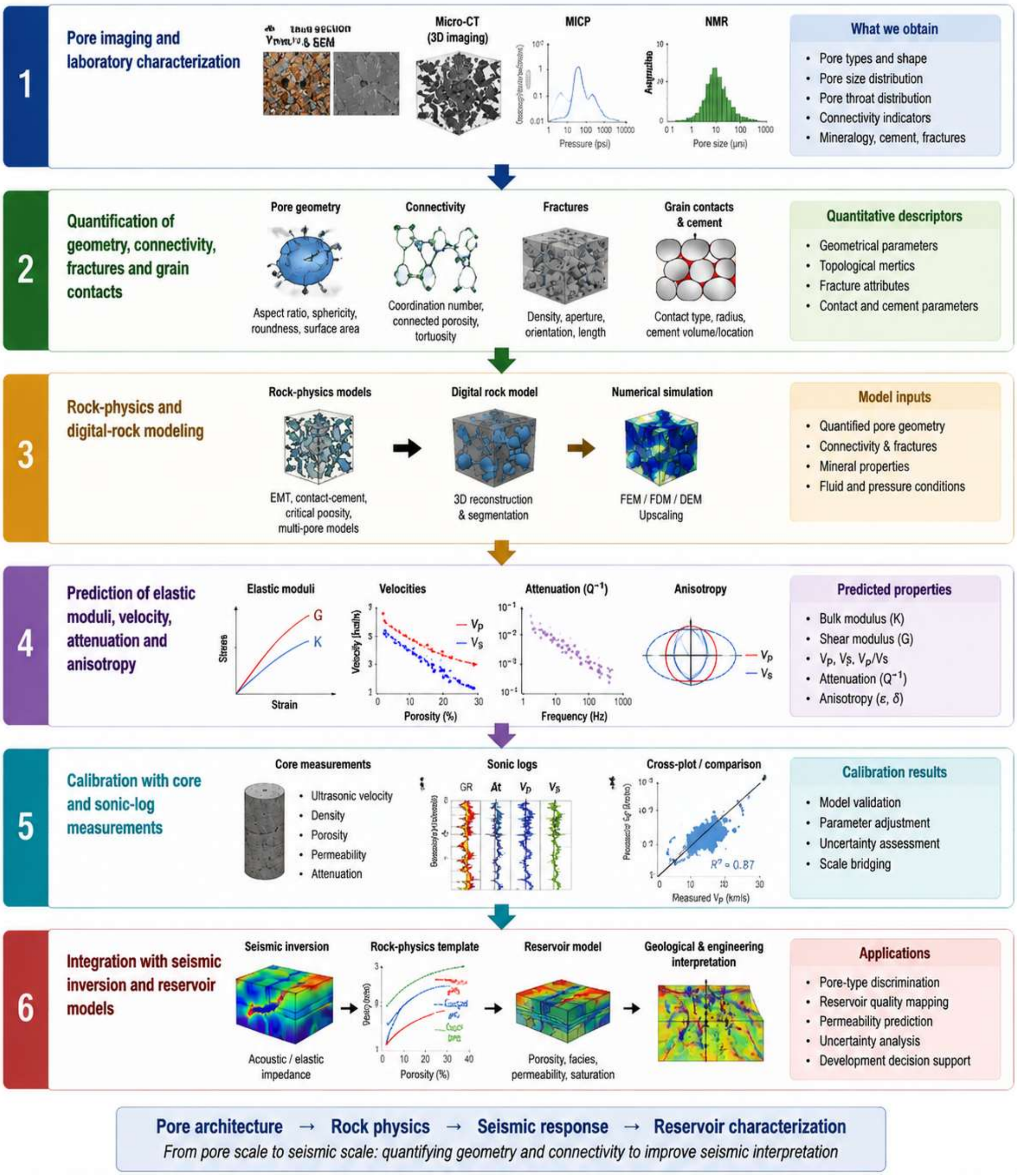

Figure 2. Multiscale workflow linking pore architecture to seismic reservoir characterization.

Pore-scale information obtained from petrography, SEM, MICP, NMR and three-dimensional CT imaging is converted into quantitative descriptors of pore geometry and connectivity. Rock-physics and digital-rock models translate these descriptors into effective elastic and dynamic properties, which are calibrated against laboratory and well-log measurements before application to field seismic interpretation. The central implication is that pore-scale information becomes useful for reservoir seismology only when it can be translated into **effective properties measurable at progressively larger scales**. Integration of imaging, laboratory measurements, rock physics, digital simulation, well logs, and seismic inversion therefore provides the most promising route for incorporating pore architecture into quantitative hydrocarbon reservoir characterization.

4. Critical Synthesis, Research Gaps, and Future Directions

4.1 Current Understanding of Pore-Architecture Controls

The available evidence demonstrates that pore architecture is a fundamental control on seismic properties and explains much of the variability that cannot be described by total porosity alone. Three relationships are particularly well established. First, **pore shape controls mechanical compliance**. Low-aspect-ratio cracks and elongated pores deform more readily than equant pores and therefore produce stronger reductions in elastic moduli and seismic velocity [1,6]. Their high compliance also makes them particularly sensitive to effective pressure. Second, **grain contacts and cementation control frame stiffness**. Cement concentrated around grain contacts can significantly increase P- and S-wave velocities even when the corresponding reduction in porosity is relatively small [7,9]. Consequently, diagenetic history can be as important as pore volume in determining seismic properties. Third, **pore connectivity controls hydraulic communication**. Pore-throat geometry, coordination, tortuosity, and fracture connectivity determine how effectively fluids and pore pressures communicate through the rock. Connectivity therefore links pore architecture with permeability and can also influence attenuation and dispersion when seismic deformation induces pressure gradients. These relationships indicate that reservoir seismic response is better represented as

Seismic response = f (porosity, pore geometry, connectivity, grain contacts, fluids, pressure, frequency)

rather than as a simple function of porosity.

4.2 Why Seismic Interpretation Remains Non-Unique

Despite these established relationships, pore architecture cannot generally be determined uniquely from seismic velocity. Different pore systems may produce similar effective elastic properties.

For example, a reduction in P-wave velocity could result from increased porosity, compliant cracks, weak grain contacts, changes in effective pressure, or fluid substitution. Conversely, two rocks with similar porosity may exhibit very different velocities because one contains stiff intergranular pores while the other contains compliant cracks or complex vugs [6,14,16]. The problem becomes greater in carbonates, where several pore types commonly coexist. Microporosity, moldic pores, interparticle pores, fractures, and vugs may contribute differently to elastic and hydraulic behavior. A single effective pore-shape parameter may therefore be insufficient to represent the complete rock. This non-uniqueness means that seismic properties should ideally be interpreted together with geological, petrophysical, and pore-structure information rather than independently.

Table 4. Established Relationships and Remaining Uncertainties

Question	Current understanding	Remaining uncertainty
Does total porosity control velocity?	Increasing porosity generally reduces stiffness and velocity	Porosity alone cannot explain velocity scatter
Does pore shape matter?	Low-aspect-ratio pores strongly increase compliance	Natural rocks contain distributions of pore shapes
Does connectivity matter?	Controls hydraulic communication and permeability	Difficult to derive directly from seismic data
Does cementation affect velocity?	Contact cement strongly increases frame stiffness	Cement geometry is difficult to determine at reservoir scale
Do fractures affect seismic response?	Strong effects on compliance and anisotropy	Density, aperture and connectivity are often uncertain

Question	Current understanding	Remaining uncertainty
Are carbonates more complex?	Multiple pore types produce large velocity variability	No single model represents all carbonate pore systems
Can attenuation constrain architecture?	Sensitive to dynamic fluid-pressure communication	Several attenuation mechanisms may overlap
Can digital rocks represent real reservoirs?	Preserve realistic 3D pore geometry	Resolution and representative-volume limitations remain

4.3 Multiscale and Upscaling Challenges

One of the largest unresolved problems is the difference between the scale at which pore architecture is measured and the scale at which seismic properties are interpreted. SEM and micro-CT observations may resolve features at micrometer or smaller scales, whereas core measurements represent centimeters, well logs represent larger volumes, and field seismic data average properties over meters to tens of meters. A pore network observed in a small digital volume may therefore not represent the heterogeneity encountered by a field seismic wave. A related problem is the **representative elementary volume (REV)**. Digital rock calculations require a volume sufficiently large to represent the statistical properties of the pore network. Increasing imaging resolution, however, commonly requires reducing sample size. This creates a trade-off between resolving microporosity and capturing larger-scale fractures, vugs, and heterogeneity. Future upscaling strategies should therefore integrate information across several scales rather than relying on a single imaging resolution.

Nano/micropore scale → pore-network scale → core scale → well-log scale → seismic scale

The effective properties predicted at each scale should be validated before being transferred to the next.

4.4 Limitations of Current Rock-Physics Models

Most conventional rock-physics models simplify the geometry of natural pore systems. Pores may be represented as spheres, ellipsoids, cracks, or idealized contacts even though real pore networks contain irregular shapes and complex connectivity. Effective-medium models are useful for identifying first-order effects of pore shape but may not adequately describe spatial connectivity. Contact and cement models perform well for many granular sandstones but are less applicable to strongly heterogeneous vuggy carbonates. Critical-porosity models provide useful bounds but simplify the evolution of pore architecture. Another limitation is that mechanical and hydraulic properties are often treated separately. In reality, the same pore network controls frame compliance, permeability, pressure diffusion, and fluid redistribution. Future models should therefore represent pore architecture as a coupled **mechanical-hydraulic system**.

4.5 Digital Rock Physics and Advanced 3D Imaging

Three-dimensional imaging and digital rock physics provide an important route for overcoming some limitations of analytical models [18–20]. CT and micro-CT can preserve realistic pore shapes, pore throats, fractures, and connectivity, allowing elastic properties to be calculated directly from reconstructed structures. Future developments should increasingly combine multiple imaging resolutions. High-resolution images can characterize microporosity and grain contacts, whereas larger-volume CT images can capture fractures, vugs, and macroscopic connectivity. Another important direction is **4D imaging**, in which pore structures are observed while stress, pressure, or fluid conditions change. Such measurements could reveal how cracks close, pore throats deform, and connectivity evolves under reservoir conditions. Digital rock physics should therefore move from static reconstruction toward dynamic representation of pore architecture under realistic pressure and fluid conditions.

4.6 Integrating Mechanical and Hydraulic Connectivity

An important conceptual distinction emerging from this review is between **mechanical connectivity** and **hydraulic connectivity**. Mechanical connectivity describes how the solid framework transmits stress through grain contacts and cement. Hydraulic connectivity describes how pore bodies, throats, and fractures communicate through the void network. A rock can therefore possess a mechanically strong framework while maintaining a connected pore network, or it may contain substantial porosity that is poorly connected hydraulically. Future seismic rock physics should explicitly consider both networks:

Solid-network connectivity → frame stiffness → V_P and V_S

Pore-network connectivity → fluid communication → permeability, attenuation and dispersion

Their interaction provides a more complete description of reservoir behavior than either porosity or permeability considered independently.

4.7 Physics-Informed Data-Driven Approaches

Machine learning offers opportunities for analyzing complex relationships among pore architecture and seismic properties, particularly when large CT and digital-rock datasets are available. Image-based models may potentially predict elastic moduli, permeability, or pore type directly from three-dimensional pore structures. However, purely data-driven predictions may perform poorly when applied to rocks outside the training dataset. Physics-informed approaches are therefore preferable. Parameters such as porosity, aspect ratio, coordination number, tortuosity, mineralogy, pressure, and fluid properties can be combined with physical constraints on elastic moduli and wave propagation. A useful future framework is:

3D pore images + quantitative pore descriptors + rock-physics constraints + machine learning → seismic-property prediction.

Such approaches should complement rather than replace physical rock-physics models.

4.8 Priority Directions for Future Research

Future studies should focus on pore architecture as a **multiscale, three-dimensional, and dynamically evolving system**.

Table 5. Priority Research Directions

Research priority	Current problem	Recommended direction	Expected benefit
Quantitative connectivity	Connectivity is difficult to represent with a single parameter	Develop standardized 3D topological metrics	Better link between pore networks and seismic properties
Multiscale imaging	Single resolution cannot capture all pore types	Integrate SEM, nano-CT, micro-CT and conventional CT	More complete pore architecture
Digital rock upscaling	Small digital volumes may not represent reservoirs	Multiscale REV and upscaling methods	Improved laboratory-to-field prediction
Dynamic pore evolution	Most models use static pore geometry	4D imaging under pressure and fluid changes	Better reservoir-condition modeling
Complex carbonates	Multiple pore types coexist	Multiple-pore and image-based models	Improved carbonate seismic interpretation
Fracture connectivity	Small fractures strongly affect elasticity and flow	Couple fracture-network and rock-physics models	Better fracture characterization
Attenuation and dispersion	Connectivity effects remain poorly constrained	Broadband dynamic measurements	Additional constraints beyond velocity
Physics-informed AI	Pure data models lack physical generalization	Combine pore images, descriptors and rock physics	More robust seismic prediction

4.9 Conclusion

Pore geometry and connectivity provide a critical link between reservoir microstructure and seismic response. Although porosity remains an important first-order property, it does not uniquely determine elastic behavior. Pore shape, aspect ratio, grain contacts, cementation, pore throats, fractures, vugs, and connectivity determine how the rock framework carries stress and how fluids communicate through the pore system. The reviewed studies show that low-aspect-ratio pores and fractures increase elastic compliance, whereas strong grain contacts and cementation increase frame stiffness. Connectivity controls hydraulic communication and therefore links pore architecture with permeability and dynamic seismic phenomena such as attenuation and dispersion. These effects are particularly important in carbonate and fractured reservoirs, where multiple pore systems commonly coexist. The central relationship emerging from this review can therefore be summarized as:

Pore geometry + mechanical connectivity + hydraulic connectivity → effective rock properties → velocity, attenuation, dispersion and anisotropy → seismic reservoir characterization.

Major challenges remain in quantifying three-dimensional connectivity, representing multiscale pore systems, separating overlapping controls on seismic properties, and transferring pore-scale observations to field seismic scales. Integration of high-resolution 3D/4D imaging, digital rock physics, broadband acoustic measurements, well-log calibration, and physically constrained data-driven methods offers the most promising route for addressing these limitations.

Ultimately, the principal implication is that **pore architecture should be treated as an independent rock-physics variable rather than as a secondary description of porosity**. Incorporating pore geometry and connectivity into seismic interpretation can provide a more physically realistic basis for characterizing reservoir quality, fractures, permeability architecture, and hydrocarbon reservoir heterogeneity.

References

[1] Cheng, C. H., & Toksöz, M. N. (1979). Inversion of seismic velocities for the pore aspect ratio spectrum of a rock. *Journal of Geophysical Research, 84*(B13), 7533–7543.
DOI: 10.1029/JB084iB13p07533

[2] Han, D., Nur, A., & Morgan, D. (1986). Effects of porosity and clay content on wave velocities in sandstones. *Geophysics, 51*(11), 2093–2107.
DOI: 10.1190/1.1442062

[3] Klimentos, T., & McCann, C. (1990). Relationships among compressional wave attenuation, porosity, clay content, and permeability in sandstones. *Geophysics, 55*(8), 998–1014.
DOI: 10.1190/1.1442928

[4] Klimentos, T. (1991). The effects of porosity-permeability-clay content on the velocity of compressional waves. *Geophysics, 56*(12), 1930–1939.
DOI: 10.1190/1.1443004

[5] Marion, D., Nur, A., Yin, H., & Han, D. (1992). Compressional velocity and porosity in sand-clay mixtures. *Geophysics, 57*(4), 554–563.
DOI: 10.1190/1.1443269

[6] Anselmetti, F. S., & Eberli, G. P. (1993). Controls on sonic velocity in carbonates. *Pure and Applied Geophysics, 141*, 287–323.
DOI: 10.1007/BF00998333

[7] Dvorkin, J., Nur, A., & Yin, H. (1994). Effective properties of cemented granular materials. *Mechanics of Materials, 18*(4), 351–366.
DOI: 10.1016/0167-6636(94)90044-2

[8] Mukerji, T., Berryman, J., Mavko, G., & Berge, P. (1995). Differential effective medium modeling of rock elastic moduli with critical porosity constraints. *Geophysical Research Letters, 22*(5), 555–558.
DOI: 10.1029/95GL00164

[9] Dvorkin, J., & Nur, A. (1996). Elasticity of high-porosity sandstones: Theory for two North Sea data sets. *Geophysics, 61*(5), 1363–1370.
DOI: 10.1190/1.1444059

[10] Nur, A., Mavko, G., Dvorkin, J., & Galmudi, D. (1998). Critical porosity: A key to relating physical properties to porosity in rocks. *The Leading Edge, 17*(3), 357–362.
DOI: 10.1190/1.1437977

[11] Anselmetti, F. S., & Eberli, G. P. (1999). The velocity-deviation log: A tool to predict pore type and permeability trends in carbonate drill holes from sonic and porosity or density logs. *AAPG Bulletin, 83*(3), 450–466.
DOI: 10.1306/00AA9BCE-1730-11D7-8645000102C1865D

[12] Avseth, P., Dvorkin, J., Mavko, G., & Rykkje, J. (2000). Rock physics diagnostic of North Sea sands: Link between microstructure and seismic properties.

 ISSN: **3107-6513**

Geophysical Research Letters, 27(17), 2761–2764. **DOI:** 10.1029/1999GL008468

[13] Assefa, S., McCann, C., & Sothcott, J. (2003). Velocities of compressional and shear waves in limestones. *Geophysical Prospecting, 51*(1), 1–13. **DOI:** 10.1046/j.1365-2478.2003.00349.x

[14] Eberli, G. P., Baechle, G. T., Anselmetti, F. S., & Incze, M. L. (2003). Factors controlling elastic properties in carbonate sediments and rocks. *The Leading Edge, 22*(7), 654–660. **DOI:** 10.1190/1.1599691

[15] Silin, D., & Patzek, T. (2006). Pore space morphology analysis using maximal inscribed spheres. *Physica A: Statistical Mechanics and its Applications, 371*(2), 336–360. **DOI:** 10.1016/j.physa.2006.04.048

[16] Weger, R. J., Eberli, G. P., Baechle, G. T., Massaferro, J. L., & Sun, Y.-F. (2009). Quantification of pore structure and its effect on sonic velocity and permeability in carbonates. *AAPG Bulletin, 93*(10), 1297–1317.
DOI: 10.1306/05270909001

[17] Fabricius, I. L., Bächle, G. T., & Eberli, G. P. (2010). Elastic moduli of dry and water-saturated carbonates: Effect of depositional texture, porosity, and permeability. *Geophysics, 75*(3), N65–N78. **DOI:** 10.1190/1.3374690

[18] Andrä, H., Combaret, N., Dvorkin, J., et al. (2013). Digital rock physics benchmarks—Part I: Imaging and segmentation. *Computers & Geosciences, 50*, 25–32. **DOI:** 10.1016/j.cageo.2012.09.005

[19] Andrä, H., Combaret, N., Dvorkin, J., et al. (2013). Digital rock physics benchmarks—Part II: Computing effective properties. *Computers & Geosciences, 50*, 33–43.
DOI: 10.1016/j.cageo.2012.09.008

[20] Wang, Z., Wang, R., Weger, R. J., Li, T., & Wang, F. (2015). Pore-scale modeling of elastic wave propagation in carbonate rocks. *Geophysics, 80*(1), D51–D63.
DOI: 10.1190/GEO2014-0050.1

[21] El-Husseiny, A., Vega, S., & Nizamuddin, S. (2019). The effect of pore structure complexity and saturation history on the variations of acoustic velocity as function of brine and oil saturation in carbonates. *Journal of Petroleum Science and Engineering, 179*, 180–191.
DOI: 10.1016/j.petrol.2019.04.019

[22] Zhang, J., Yin, Y., & Zhang, G. (2020). Rock physics modelling of porous rocks with multiple pore types: A multiple-porosity variable critical porosity model. *Geophysical Prospecting, 68*(3), 955–967. **DOI:** 10.1111/1365-2478.12898

[23] Zhang, S., Zou, C., Peng, C., Yan, L., & Wu, X. (2022). Pore structure and its effect on acoustic velocity and permeability of reef-shoal carbonates in the Tarim Basin, Northwest China. *Journal of Geophysics and Engineering, 19*(6), 1340–1354. **DOI:** 10.1093/jge/gxac087

[24] Sayers, C. M. (2023). The effect of clay and contacts between sand grains on the elastic properties of sandstones. *Geophysical Prospecting, 71*(3), 456–470. **DOI:** 10.1111/1365-2478.13318

[25] Vasconcelos, I., Mejia, C., Roehl, D., et al. (2026). Pore structure effects on elastic wave propagation in carbonate rocks. *Rock Mechanics and Rock Engineering*. **DOI:** 10.1007/s00603-026-05675-w