



Article

Discrimination of Tight Sandstone Reservoir Effectiveness Based on Pore-Throat Functional Fractal Characterization and Three-Dimensional Pore-Network Connectivity Constraints

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Abstract

Tight sandstone reservoir effectiveness is governed not by pore volume alone, but by the storage and flow contributions of different pore-throat scales, their structural complexity, and their three-dimensional connectivity. This study investigates tight sandstones of the Benxi Formation deposited in a marine–continental transitional mixed siliciclastic–carbonate setting in the Gaoqiao area, southern Ordos Basin. Petrophysical measurements, red-epoxy-impregnated thin-section petrography, mercury intrusion capillary pressure (MICP), segment-specific fractal analysis of functionally defined pore-throat regimes, X-ray micro-computed tomography (micro-CT), and pore-network modeling (PNM) were integrated. The MICP responses define three pore-throat structure types and two data-derived functional boundaries at 0.708 and 0.141 μm , which separate large-pore-throat-dominated, transitional pore-throat, and fine-throat-limited intervals. Using these nominal boundaries, Type I is strongly dominated by the large-pore-throat interval, which accounts for 88.7% of total mercury intrusion, whereas Type II exhibits a mixed large-to-transitional response, and Type III is characterized by negligible large-pore-throat intrusion and pronounced fine-throat restriction. Perturbing both functional boundaries by $\pm 5\%$ and $\pm 10\%$ does not alter these principal functional distinctions, although samples close to the second boundary exhibit the expected local transitional sensitivity. Among the three segment-specific fractal parameters, the fine-throat fractal dimension, D_B , shows the strongest association with median capillary pressure ($r = 0.834$, $p < 0.001$) and remains significantly related to displacement pressure, median pore-throat radius, and permeability, whereas D_T shows no significant linear correlation with the tested petrophysical and MICP parameters. The fractions of the largest connected pore cluster in representative Type I–III samples are 90.26%, 72.56%, and 64.65%, while their PNM permeabilities decrease successively from 64.32 mD to 0.850 and 0.121 mD. Together, these results indicate that, for the investigated samples, reservoir effectiveness reflects the combined influence of pore-throat size configuration, segment-specific structural complexity, and three-dimensional network connectivity.

Keywords: fractal dimension; functional pore-throat segmentation; mercury intrusion capillary pressure; pore-network model; reservoir effectiveness; tight sandstone



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1. Introduction

Tight sandstone gas reservoirs are major targets of unconventional natural-gas exploration and development worldwide. In these rocks, fluid storage and migration are governed less by bulk porosity than by the size, arrangement, and connectivity of pores and throats [1–3]. The Ordos Basin is one of China's most intensively explored tight-gas basins, and systematic reservoir models have been established for several Upper Paleozoic intervals, particularly the Shanxi and Shihezi formations [4–6]. In the Gaoqiao area of the southern basin, however, the Benxi Formation accumulated in a marine–continental transitional mixed siliciclastic–carbonate setting. Frequent interbedding of terrigenous clastics, carbonates, coal seams, and mud-rich deposits generated small, discontinuous sand bodies and rapid facies changes. Their pore-throat architecture reflects depositional composition, diagenetic modification, and heterogeneity inherent to mixed deposition, making effective-reservoir evaluation more challenging than in more uniform continental siliciclastic successions [7–9].

Studies of the Benxi Formation mixed depositional system have identified siliciclastic tidal flats, mixed tidal flats, and mixed lagoons and documented marked differences in lithologic assemblages and sequence architecture among these settings [10]. High-quality reservoir development in the Gaoqiao area is jointly controlled by paleogeomorphology, depositional model, sand-body type, and diagenetic modification. Paleogeomorphology governs sand-body distribution; depositional facies establish the primary reservoir fabric; compaction and cementation drive densification; and preservation of primary pores together with dissolution favors higher-quality intervals [7,11,12]. These studies explain the distribution and genesis of Benxi Formation sand bodies, but they do not fully resolve how pore-throat architecture controls reservoir effectiveness within a given sand-body type, particularly the distinct roles of different size ranges in storage, connectivity, and flow restriction.

Reservoir quality ultimately depends on the preservation of pore bodies, the development of throats, and the connectivity between them. Mercury intrusion capillary pressure (MICP) parameters, including displacement pressure, characteristic pore-throat radius, and pore-throat radius distribution, quantify the capillary resistance encountered as fluids enter and traverse the pore-throat system and are closely related to sandstone permeability [13,14]. Integrated applications of MICP, rate-controlled mercury intrusion (RMI), nuclear magnetic resonance (NMR), scanning electron microscopy (SEM), and X-ray micro-computed tomography (micro-CT) have characterized tight-sandstone pore systems in terms of pore-throat scale, pore morphology, fluid response, and three-dimensional structure [15]. These studies generally indicate that micro- and nanopores primarily contribute specific surface area and local storage volume, whereas medium and large pore throats and their connected networks exert more direct control on flow potential [16–18]. Evaluation of reservoir effectiveness must therefore account for throat restriction and three-dimensional connectivity in addition to pore abundance.

Fractal analysis quantifies the scale-dependent complexity of irregular pore structures and has been widely applied to pore-throat systems in tight sandstones and shales [19–21]. Compared with conventional descriptors such as pore-size distribution, pore volume, and specific surface area, fractal models derived from mercury intrusion, gas adsorption, NMR, and image analysis are well suited to characterizing multiscale pore-throat architecture and heterogeneity in unconventional reservoirs [22–24]. Zhang and Weller [25] demonstrated that fractal dimensions obtained by different methods may represent pore-surface roughness, pore-volume distribution, or pore-space complexity. Shao et al. [26] analyzed tight-sandstone pore-network fractals in the Ordos Basin using NMR data, whereas Wang et al. [27] combined MICP and RMI to predict pore-throat structure from multifractal di-

mensions. Zhou et al. [28] constructed a full-range pore-throat fractal model from MICP and RMI and cautioned that combining datasets at fixed pore-size thresholds may discard structurally important information. Fractal parameters have also been related to pore-throat scale, mineral composition, fluid occurrence, and reservoir quality [29–31]. Most published studies, however, emphasize overall heterogeneity or pore-size contrasts and do not explicitly link fractal dimensions to mercury-intrusion contribution, scale-transition behavior, and fine-throat flow restriction. Without resolving the contribution of individual pore-throat intervals during mercury intrusion, fractal parameters cannot adequately explain why samples with similar porosity differ greatly in permeability or why abundant local dissolution pores may remain poorly connected. Single or global fractal dimensions provide compact measures of overall pore-space heterogeneity, whereas multifractal or full-range approaches improve scale-dependent description but do not necessarily assign an explicit storage or flow role to each pore-throat interval [25–31]. Fixed pore-size partitions permit uniform comparison but may rely on prescribed or dataset-dependent thresholds [28]; in contrast, the present workflow identifies functional transition scales from changes in normalized mercury-intrusion increments and then relates sample-specific fractal responses to large-pore-throat-dominated intrusion, transitional behavior, and fine-throat restriction.

To address this gap, petrophysical measurements, MICP, three-dimensional micro-CT-based digital-rock reconstruction, and pore-network modeling (PNM) were applied to Benxi Formation tight sandstones from the Gaoqiao area. The samples were first classified as Types I–III on the basis of capillary-pressure curve morphology and the key parameters of displacement pressure, median capillary pressure, and median pore-throat radius. Incremental mercury intrusion per unit logarithmic pore-throat radius was then used to quantify the relative contribution of each size range. Changes in this contribution defined two functional transition boundaries and partitioned the pore-throat system into large-pore-throat-dominated, transitional pore-throat, and fine-throat-limited intervals. Sample-specific segmented fractal fitting was used to characterize the structural complexity associated with the three functional pore-throat regimes, while digital-rock and PNM analyses of representative samples constrained pore-body size, throat size, and three-dimensional connectivity. The resulting framework integrates mercury-intrusion contribution, structural complexity, and network connectivity to discriminate reservoir effectiveness in mixed tight sandstones. The working hypothesis is that reservoir-effectiveness differences can be resolved more clearly when pore-throat regimes are distinguished by their mercury-intrusion contribution and interpreted jointly with sample-specific fractal complexity and three-dimensional connectivity, rather than from bulk pore volume or a single global heterogeneity descriptor.

2. Geological Setting

The Ordos Basin lies in the western North China Craton and is one of China's major petroliferous basins. Its tectonic framework is stable, with limited internal faulting and folding, and comprises the Yimeng Uplift, Weibei Uplift, Jinxi flexural-fold belt, Yishan Slope, Tianhuan Depression, and western-margin thrust belt [1,32,33]. The Gaoqiao study area lies in the southern basin, tectonically within the southern Yishan Slope near the eastern flank of the central paleouplift. The strata are gently inclined and exhibit only minor structural relief (Figure 1a) [7,8].

Following uplift and denudation in the Late Ordovician, the basin underwent prolonged weathering and peneplanation before renewed subsidence began in the Late Carboniferous. During deposition of the Benxi Formation, the study area occupied a shallow, gently sloping zone east of the central paleouplift. Paleogeomorphology, sea-level fluctuations, terrigenous sediment supply, and tidal hydrodynamics jointly produced a marine–

continental transitional mixed succession in which terrigenous clastics, carbonate rocks, coal seams, and mud-rich deposits coexist (Figure 1b) [34,35]. Here, weathering refers to paleoweathering of the pre-Benxi Ordovician surface rather than variable post-depositional weathering of the deeply buried Benxi Formation sandstone samples analyzed in this study.

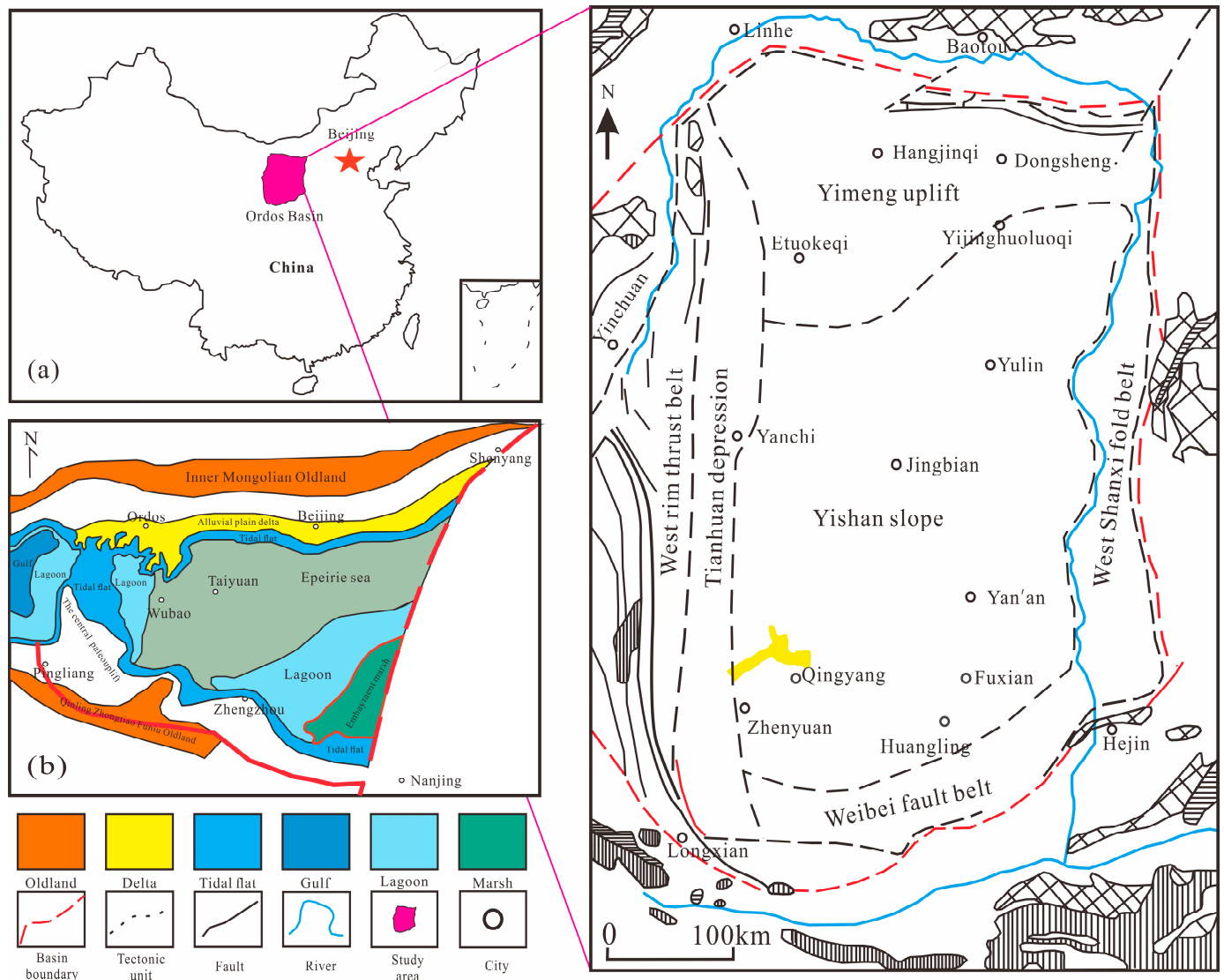


Figure 1. Tectonic location of the Gaoqiao area and depositional setting of the Benxi Formation. (a) Regional location of the study area; (b) tectono-depositional framework of the Benxi Formation (adapted from Ref. [7]).

The Benxi Formation unconformably overlies the Ordovician paleoweathering crust in the Gaoqiao area. It is approximately 10–75 m thick and is subdivided into the Ben 1 and Ben 2 depositional units. The succession consists mainly of dark-gray to black mudstone, siltstone, fine- to medium-grained quartz sandstone, coal seams, and locally thin limestone beds; ferruginous–aluminous mudstone or bauxitic deposits commonly occur at the base. Before deposition, the landscape was generally higher in the west and lower in the east and included local uplands, slopes, channels, and depressions that controlled sand-body distribution and depositional infill [7,36].

In plan view, the Benxi Formation grades eastward from siliciclastic tidal flats through mixed tidal flats to mixed lagoons. Sand-flat and tidal-channel bodies are comparatively well developed within the siliciclastic and mixed tidal-flat belts and represent the more

favorable reservoir settings. Mixed-lagoon deposits are dominated by mudstone, limestone, and thin sandstone beds with limited lateral continuity. Widespread compaction and cementation densified the sandstones, whereas local preservation of primary pores and dissolution improved storage space [9,37,38]. Because the sand bodies are small, facies changes are rapid, and pore-throat architecture is complex, effective-reservoir evaluation must explicitly consider pore-throat size distribution, fine-throat restriction, and three-dimensional connectivity.

3. Materials and Methods

Tight sandstone samples were collected from the Benxi Formation in the Gaoqiao area of the southern Ordos Basin and covered a range of lithologies, petrophysical properties, and pore-throat structures. Standard thin sections, red-epoxy-impregnated cast thin sections, MICP, micro-CT-based digital-rock reconstruction, and PNM analysis were used to characterize rock composition, reservoir space, pore-throat size distribution, and three-dimensional connectivity. Petrographic observations under polarized light documented sandstone type, detrital composition, pore type, and major diagenetic features, with particular attention to residual intergranular pores, intergranular and intragranular dissolution pores, intercrystalline pores within kaolinite aggregates, and sparse microfractures.

Petrographic characterization was based on 168 thin sections (standard and red-epoxy-impregnated cast thin sections) from the investigated Benxi Formation interval, providing the broader petrographic basis for identifying the principal sandstone types, reservoir-space types, and major diagenetic features used in this study.

The MICP dataset comprised 59 core samples spanning the observed petrophysical and capillary-pressure variability of the investigated Benxi Formation interval and formed the population used to derive the dataset-level functional transition scales. The ten samples M1–M10 listed in Table 1 were selected as representative examples of Types I–III to illustrate characteristic MICP responses and were not treated as the complete analytical population. The three digital-rock samples S1–S3 were subsequently chosen as type-contrast specimens to examine whether the MICP-defined differences were accompanied by corresponding three-dimensional network differences; they provide mechanistic cross-scale constraints rather than population-level statistics for the entire formation.

Table 1. Mercury-intrusion parameters and pore-throat structure classification of representative Benxi Formation tight sandstone samples. ϕ denotes porosity; K, permeability; P_d , displacement pressure; P_{50} , median capillary pressure; r_d , pore-throat radius corresponding to P_d ; r_{50} , median pore-throat radius; and $S_{Hg,max}$, maximum mercury-intrusion saturation.

Sample	Type	ϕ (%)	K (mD)	P_d (MPa)	P_{50} (MPa)	r_d (μ m)	r_{50} (μ m)	$S_{Hg,max}$ (%)
M1	Type I	11.65	19.73	0.02	0.2588	36.75	2.84	88.66
M2	Type I	10.42	17.54	0.02	0.2101	36.75	3.498	88.83
M3	Type II	5.89	1.325	0.029	0.4184	25.34	1.757	91.46
M4	Type II	7.88	1.283	0.15	1.01	4.9	0.7275	85.31
M5	Type II	11.58	0.9372	0.804	3.087	0.9142	0.2381	84.89
M6	Type II	6.97	0.2895	0.9491	3.207	0.7744	0.2292	76.05
M7	Type III	5.13	0.0998	2.044	10.2514	0.3596	0.0717	67.84
M8	Type III	9.24	0.0881	2.812	5.274	0.2613	0.1394	74.72
M9	Type III	5.33	0.0777	2.99	7.889	0.2458	0.0932	98.59
M10	Type III	3.73	0.0089	2.989	8.521	0.2459	0.0863	23.43

MICP measurements were performed with an AutoPore IV 9520 automated mercury porosimeter (Micromeritics Instrument Corporation, Norcross, GA, USA). The capillary-pressure curves provided displacement pressure (P_d), median capillary pressure (P_{50}),

median pore-throat radius (r_{50}), maximum mercury intrusion saturation ($S_{\text{Hg,max}}$), and stage-dependent intrusion responses; pore-throat radius was calculated from capillary pressure [39]. Samples were classified as Type I, II, or III primarily from curve morphology and the quantitative criteria P_d , P_{50} , and r_{50} , with $S_{\text{Hg,max}}$ and permeability used as supplementary indicators. Mercury-saturation increments between adjacent pressure steps were assigned to the corresponding pore-throat radius intervals and normalized for differences in logarithmic interval width. Changes in the normalized increments were used to identify functional boundaries and define large-pore-throat-dominated, transitional, and fine-throat-limited regimes for physical interpretation; the fractal dimensions were then obtained from sample-specific quasi-linear segments of the log–log MICP curves, whose exact fitting transitions were allowed to vary among samples rather than being forced to coincide with the two common functional boundaries. Types I–III describe differences in overall pore-throat architecture, whereas the three functional intervals distinguish scale-dependent responses during mercury intrusion. Only positive mercury-saturation increments, representing net mercury intrusion, were retained for the functional-contribution and population-response calculations. For cross-sample aggregation, the normalized increments were evaluated on a common 0.1-decade $\log_{10}(r)$ radius grid.

The MICP measurements were conducted by a specialized analytical testing facility, and formal test reports were retained to ensure traceability of the instrument outputs and reported capillary-pressure data. Systematic replicate MICP measurements on identical core plugs were not available for the complete dataset; accordingly, repeatability-based measurement uncertainty could not be quantified. The boundary-perturbation analysis evaluates the sensitivity of the functional interpretation to deliberate changes in boundary placement, whereas the leave-one-out analysis evaluates the dependence of the data-derived transition scales on sample composition. Neither analysis provides an estimate of instrumental measurement uncertainty, which would require replicate measurements and instrument-specific uncertainty characterization.

For the correlation analysis presented later, permeability was $\log_{10}$ -transformed. To provide a common statistical basis across samples, all MICP curves considered for this analysis were processed using a standardized sample-specific three-segment regression of $\log_{10}(\text{SHg})$ versus $\log_{10}(\text{Pc})$. Two breakpoints were selected by minimizing the total sum of squared errors, at least four data points with $\text{Pc} > 0$ and $\text{SHg} > 0$ were required in each segment, and only fits with $0 < K \leq 1$ ($2 < D \leq 3$) were retained. R^2 was recorded as a measure of fit quality but was not used as a screening threshold. Samples with complete petrophysical/MICP variables and admissible D_L , D_T , and D_B fits yielded 27 complete cases. This standardized complete-case refit was used specifically for the correlation analysis, whereas Table 2 summarizes the descriptive sample-specific segmented fits. Pearson correlations were evaluated using two-sided tests, and the regression panels report n , r , p , the regression equation, R^2 , and 95% confidence bands; statistical significance was assessed at $p < 0.05$.

Spearman rank correlations were additionally calculated as a nonparametric robustness check on the Pearson results. All significance tests were two-sided. The reported p -values are nominal (unadjusted) values. As a multiple-comparison robustness check, the Benjamini–Hochberg false-discovery-rate correction was additionally applied across the 18 Pearson correlation tests, and the set of statistically significant associations was unchanged at $q < 0.05$.

To evaluate the sensitivity of the functional interpretation to boundary placement, the two data-derived boundaries, $r_{L/T}$ and $r_{T/B}$, were independently perturbed by $\pm 5\%$ and $\pm 10\%$ around their nominal values. Each perturbed radius was converted to the corresponding capillary pressure using Equation (1), and the resulting pressure ranges

were compared with the sample-specific P_d and P_{50} values. This perturbation analysis was used to determine whether moderate shifts in boundary position altered the principal functional distinction among the three pore-throat structure types. The perturbation ranges represent sensitivity intervals rather than statistical confidence intervals.

Table 2. Segment-specific fractal parameters derived from MICP for Type I–III samples. D_L , D_T , and D_B denote the large-pore-throat-related, transitional, and fine-throat-related fractal dimensions, respectively; R_L^2 , R_T^2 , and R_B^2 are the corresponding coefficients of determination.

Sample Type	D_L	R_L^2	D_T	R_T^2	D_B	R_B^2
Type I	2.827 ± 0.113	0.988	2.693	0.966	2.055 ± 0.024	0.854
Type II	2.603 ± 0.178	0.928	2.586 ± 0.174	0.948	2.349 ± 0.256	0.952
Type III	2.535 ± 0.158	0.913	2.568 ± 0.193	0.968	2.369 ± 0.191	0.914

Note: When multiple sample-specific fits were available for a given functional regime within a type, D is reported as the mean $\pm$ standard deviation; a single value indicates that only one fit was available. R^2 is the mean coefficient of determination for the corresponding segment and is used only to assess fit reliability. These descriptive segment summaries are distinct from the standardized complete-case refit used for the correlation analysis presented later.

To assess whether the population-level transition scales were dominated by individual samples, a leave-one-out jackknife analysis was performed on the 59-sample MICP population. In each of 59 iterations, one sample was removed, the population-averaged normalized mercury-intrusion response was recalculated on the same 0.1-decade $\log_{10}(r)$ radius grid, and both transition locations were re-identified using the same local-maximum criterion as for the full dataset. Boundary stability was evaluated from the frequency with which the full-data transition locations were retained at the adopted radius-grid resolution.

On the basis of their MICP responses and petrophysical characteristics, S1, S2, and S3 were selected from Types I, II, and III, respectively, for micro-CT-based digital-rock analysis. Scanning was conducted with an UltraXRM-L200 system (Xradia, Inc., Pleasanton, CA, USA) at 20 °C and an exposure time of 120 s. Three-dimensional volumes of interest (VOIs) were cropped from the complete reconstructed datasets for pore segmentation, connectivity analysis, and pore-network extraction. The S1 and S3 VOIs each comprised $500 \times 500 \times 500$ voxels at 2.000 and 1.000 $\mu\text{m}/\text{voxel}$, corresponding to approximately 1.00 and 0.50 mm per side, respectively. The S2 VOI comprised $400 \times 400 \times 400$ voxels at 2.06546 $\mu\text{m}/\text{voxel}$, corresponding to approximately 0.83 mm per side. The voxel size represents the nominal spatial sampling of each reconstructed volume; pore features approaching or falling below this scale cannot be reliably distinguished as independent geometric objects.

Following filtering, threshold segmentation, and extraction of the three-dimensional pore space, CT porosity, the fraction of the largest connected pore cluster, and connected porosity were calculated [40]. Image processing and segmentation were performed using Thermo Scientific PerGeos 2023.1 (Thermo Fisher Scientific, Waltham, MA, USA). For each VOI, an initial pore-solid threshold was determined using the software's built-in automatic thresholding function and was then interactively fine-adjusted by comparing the segmented pore boundaries with the grayscale images on representative slices. The resulting binary pore-space volume was used for subsequent connectivity analysis and pore-network extraction. Pore-network models were extracted from the segmented pore space to quantify equivalent pore-body and throat radii, pore-throat configuration, and network-flow parameters [41]. The built-in Pore Network Model Extraction workflow was applied using the Statistics and Single Phase method, which represents the segmented pore space as an equivalent network of spherical pore bodies connected by cylindrical throats. For the single-phase network calculation, the macroscopic flow direction was specified in

PerGeos, and the generated network properties were used to obtain absolute permeability (K_{PNM}) and tortuosity. Permeabilities obtained from PNM and direct-flow simulation were used to compare the flow capacity of the three-dimensional networks and were evaluated together with the MICP and segment-specific fractal parameters. Direct-flow permeability (K_{DF}) was independently calculated from the connected segmented pore space using the built-in single-phase absolute-permeability solver in PerGeos. These two permeability estimates were treated as complementary rather than interchangeable: K_{DF} retains the connected voxel-resolved pore geometry, whereas K_{PNM} is calculated after reduction to an equivalent pore-body–throat network.

Apart from specifying the macroscopic flow direction, no user-defined pore-scale conductance relation or additional network-flow boundary-condition scheme was imposed; permeability and tortuosity were calculated using the built-in single-phase PerGeos workflow.

4. Results

4.1. Petrographic Characteristics, Reservoir Space, and Porosity–Permeability Response

Benxi Formation sandstones in the Gaoqiao area are dominated by quartz sandstone and lithic quartz sandstone, with subordinate lithic sandstone (Figure 2). These rock types account for 51.39%, 30.56%, and 18.06% of the samples, respectively. Quartz is the principal detrital component, with mean contents of 83.70%, 70.36%, and 55.82%; feldspar contents are low (0, 0.50%, and 2.86%), whereas rock-fragment contents increase from 3.96% to 16.14% and 27.21%. The fragments are mainly chert and metamorphic lithics, accompanied locally by minor igneous and sedimentary fragments. The Benxi Formation sandstones are therefore quartz rich and feldspar poor but vary markedly in lithic content. Quartz-rich compositions favor a mechanically stable framework, whereas variations in lithic grains, matrix, and cement produce contrasting degrees of primary-pore preservation, dissolution modification, and pore-throat connectivity.

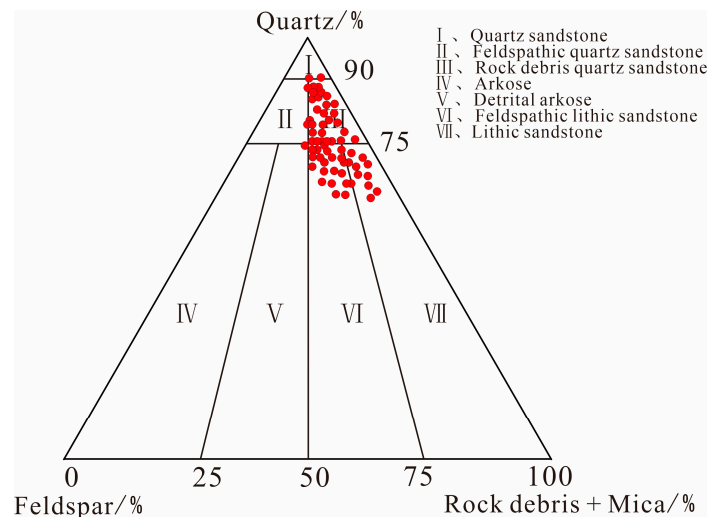


Figure 2. Ternary classification of tight sandstone types in the Benxi Formation, Gaoqiao area.

Observations of standard and cast thin sections indicate that the main reservoir spaces comprise residual intergranular pores, intergranular and intragranular dissolution pores, intercrystalline pores in kaolinite aggregates, and sparse microfractures (Figure 3). Residual intergranular pores occur as irregular or narrow-rimmed voids along grain boundaries and are locally constricted by quartz overgrowths, authigenic quartz, and carbonate cement. Intergranular and intragranular dissolution pores formed mainly through dissolution of

feldspar, lithic grains, and local cements; their irregular margins commonly merge with residual intergranular pores to form local storage domains. Intercrystalline pores within kaolinite aggregates are small and dispersed. Sparse microfractures occur along grain boundaries, within brittle grains, or at cement margins and may locally connect adjacent pores, although their continuity and aperture are strongly modified by later filling.

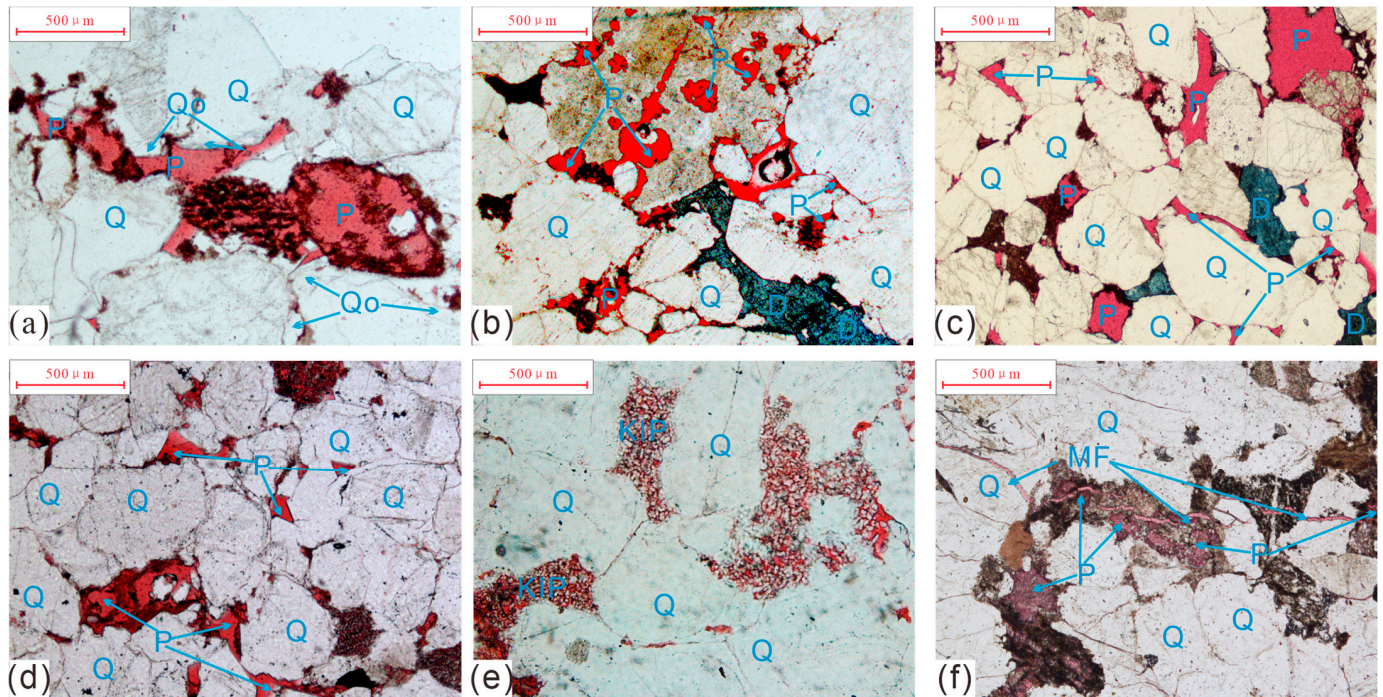


Figure 3. Reservoir-space types and petrographic features of Benxi Formation sandstones in the Gaoqiao area. (a) Well S290, 3569.17 m: residual intergranular pores with pronounced quartz overgrowths; (b) Well S291, 3800.12 m: intergranular dissolution pores accompanied by authigenic quartz cement; (c) Well S469, 3226.28 m: well-preserved primary intergranular pores with local quartz and dolomite cement; (d) Well S301, 3272.02 m: coexisting intergranular and secondary dissolution pores; (e) Well S281, 3634.36 m: intercrystalline pores in kaolinite aggregates and strong quartz cementation; (f) Well S458, 3091.24 m: microfractures affected by strong siliceous and carbonate cementation. Scale bars = 500 µm. In the annotations, Q = quartz, Qo = quartz overgrowth, P = red-epoxy-filled pore space, D = dolomite cement, KIP = intercrystalline pores within kaolinite aggregates, and MF = microfractures.

Intergranular dissolution pores are comparatively abundant in samples from wells S291 and S301, where localized dissolution enlarged intergranular space. Pronounced quartz overgrowths in the S290 sample reduced many residual intergranular pores to narrow-rimmed voids. The S281 sample contains small, dispersed intercrystalline pores within kaolinite aggregates. Sparse microfractures are present in the S458 sample, but their margins and adjacent pores remain affected by siliceous and carbonate cementation. Dissolution primarily enlarged pore bodies, whereas siliceous and carbonate cementation and clay-mineral filling preferentially affected pore margins and throats, causing constriction, segmentation, and local blockage. A pore type contributes to reservoir performance only when it is effectively connected to the network. Residual intergranular pores, intergranular dissolution pores, and local microfractures are more likely to participate in connected flow, whereas kaolinite intercrystalline pores, intragranular micropores, and isolated dissolution pores mainly increase local pore volume.

Porosity ranges from 1.61% to 15.40%, with a mean of 7.21%, whereas permeability ranges from 0.0089 to 34.7794 mD, with a mean of 2.3276 mD and a median of 0.1693 mD

(Figure 4). The division lines in Figure 4 are used only to illustrate the distribution of petrophysical properties and do not define the pore-throat structure types. Most samples have low porosity and permeability, although a few are comparatively permeable. The large difference between mean and median permeability reflects the influence of a small number of high-permeability samples. The porosity–permeability data exhibit substantial scatter: samples with similar porosity differ in permeability by one to several orders of magnitude, some high-porosity samples remain poorly permeable, and several samples with moderate or low porosity retain appreciable flow capacity.

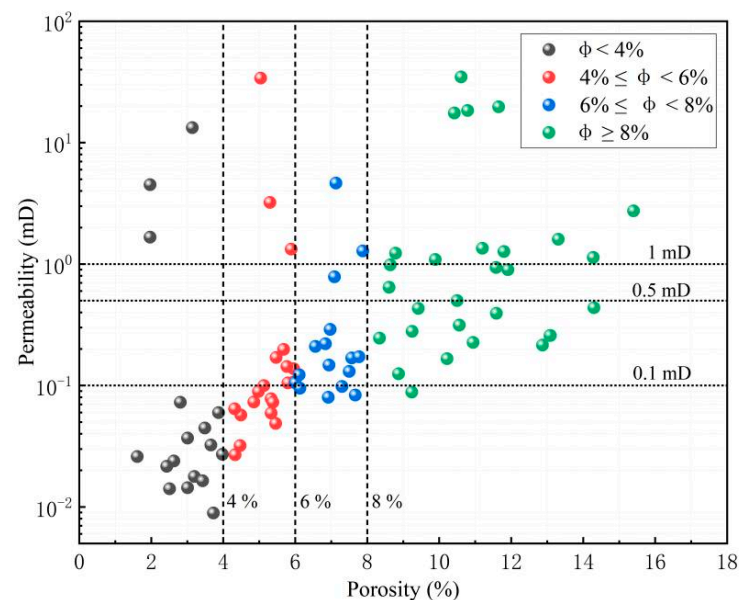


Figure 4. Relationship between porosity and permeability in Benxi Formation tight sandstones.

The dispersed porosity–permeability relationship reflects differences in pore type, throat preservation, and pore-throat connectivity. High-porosity but low-permeability samples commonly contain kaolinite intercrystalline pores, intragranular dissolution pores, or dispersed micropores. These pores increase local pore volume, but their small size and weak connectivity prevent the formation of continuous flow pathways. Comparatively permeable samples are generally associated with effective connections among residual intergranular pores, intergranular dissolution pores, and local microfractures. Quartz overgrowths, authigenic quartz, carbonate cement, and clay-mineral filling commonly occur along intergranular pore margins or within throats, where they constrict the pore-throat system and interrupt local connectivity. Reservoir effectiveness in the Benxi Formation therefore depends primarily on whether pore bodies are connected by throats of sufficient size to form continuous pathways, rather than on pore volume alone.

4.2. MICP Responses and Functional Pore-Throat Boundaries

Capillary-pressure curve morphology, together with P_d , P_{50} , and r_{50} as the principal quantitative criteria and $S_{Hg,max}$ and permeability as supplementary indicators, distinguishes three pore-throat structure types (Figure 5; Table 1). Type I comprises M1 and M2. Both samples have $P_d = 0.020$ MPa, $P_{50} = 0.210$ – 0.259 MPa, $r_{50} = 2.840$ – 3.498 μm , and permeability = 17.54–19.73 mD. Mercury enters rapidly at low capillary pressure, producing a steep initial segment of the intrusion curve. Maximum mercury intrusion saturation reaches 88.66–88.83%, consistent with an intrusion process dominated by comparatively large pore throats.

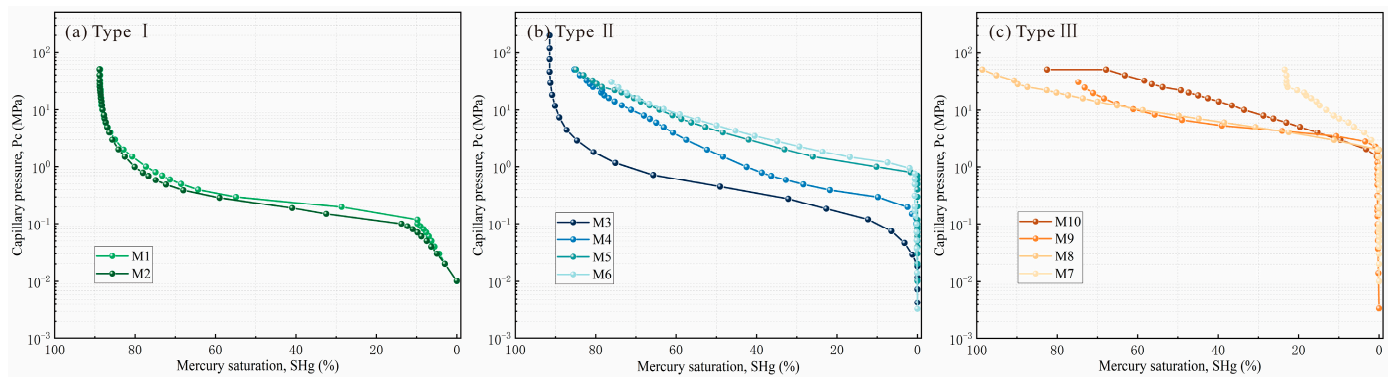


Figure 5. Mercury-intrusion capillary-pressure (MICP) curves for Type I–III pore-throat structures.

Type II includes M3–M6, with $P_d = 0.029\text{--}0.949$ MPa, $P_{50} = 0.418\text{--}3.207$ MPa, $r_{50} = 0.229\text{--}1.757$ μm , and permeability = $0.2895\text{--}1.325$ mD. Relative to Type I, low-pressure intrusion is less pronounced, the pressure range is broader, and mercury continues to enter throughout the intermediate- and high-pressure stages. Type III comprises M7–M10. Their P_d values increase to $2.044\text{--}2.990$ MPa, P_{50} ranges from 5.274 to 10.251 MPa, r_{50} decreases to $0.072\text{--}0.139$ μm , and permeability falls to $0.0089\text{--}0.0998$ mD. Little mercury enters at low pressure, and most intrusion occurs at higher capillary pressures, reflecting the increasingly strong restriction imposed by fine throats.

Pore-throat radius was calculated from capillary pressure using Equation (1):

$$r_i = \frac{0.735}{P_{c,i}}, \quad (1)$$

where r_i is the pore-throat radius corresponding to the i th pressure point (μm), and $P_{c,i}$ is the capillary pressure (MPa). The coefficient in Equation (1) follows the mercury surface-tension/contact-angle convention used for the MICP calculation. The mercury-saturation increment between adjacent pressure points was calculated using Equation (2):

$$\Delta S_i = S_{Hg,i} - S_{Hg,i-1}, \quad (2)$$

where ΔS_i is the mercury-saturation increment assigned to the i th pore-throat radius interval, and $S_{Hg,i}$ and $S_{Hg,i-1}$ are the cumulative mercury saturations at adjacent pressure points. Only positive ΔS_i values, representing net mercury intrusion, were retained in the subsequent functional-contribution and population-response calculations. The representative radius of each interval was defined as the geometric mean on the logarithmic scale using Equation (3):

$$r_i^* = (r_i r_{i-1})^{1/2}. \quad (3)$$

Pore-throat radii resolved by MICP span several orders of magnitude, and successive pressure points represent unequal radius intervals. Direct comparison of mercury-saturation increments would therefore be biased by interval width. To compare intrusion responses among radius intervals, each increment was normalized by the corresponding logarithmic pore-throat radius width using Equation (4):

$$F_i = \frac{\Delta S_i}{|\Delta \lg r_i|}, \quad (4)$$

where F_i is the normalized mercury-intrusion increment for the i th pore-throat radius interval, and $|\Delta \lg r_i|$ is the spacing between adjacent radii on the logarithmic scale. For cross-sample aggregation, the normalized increments were mapped to a common

0.1-decade $\log_{10}(r)$ radius grid. The mean normalized increment for each grid interval across samples was then calculated using Equation (5):

$$\bar{F}_k = \frac{1}{m_k} \sum_{s=1}^{m_k} F_{s,k}, \quad (5)$$

where F_k is the mean normalized mercury-intrusion increment for the k th radius interval, and m_k is the number of samples contributing to that interval. The rate of change between adjacent intervals was calculated using Equation (6):

$$G_k = \frac{|\bar{F}_{k+1} - \bar{F}_k|}{|\lg r_{k+1}^* - \lg r_k^*|}. \quad (6)$$

Two prominent local maxima occur near 0.708 and 0.141 μm (Figure 6a); these radii define the functional boundaries given in Equations (7) and (8):

$$r_{L/T} = 0.708, \quad (7)$$

$$r_{T/B} = 0.141. \quad (8)$$

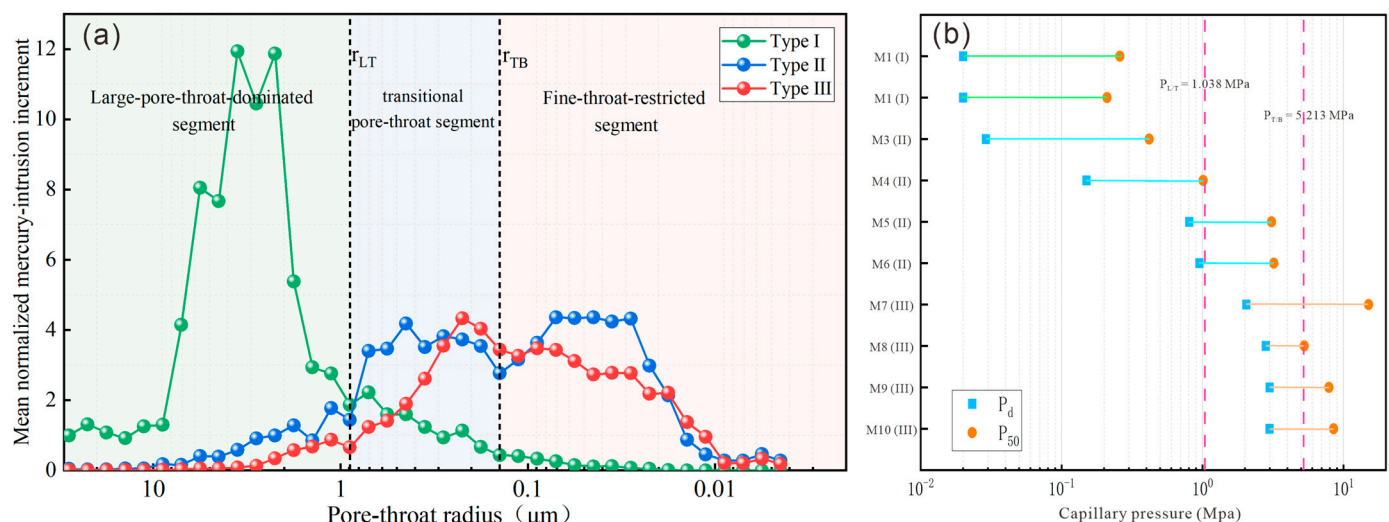


Figure 6. Data-derived functional pore-throat boundaries and sensitivity to boundary perturbation based on MICP. (a) Variation in mean normalized mercury-intrusion increment with pore-throat radius; dashed lines denote the nominal functional boundaries at $r_{L/T} = 0.708 \mu\text{m}$ and $r_{T/B} = 0.141 \mu\text{m}$. (b) Sample-specific displacement pressure (P_d) and median capillary pressure (P_{50}) relative to the equivalent capillary-pressure ranges produced by $\pm 10\%$ perturbation of the two functional boundaries. Panel (a) displays the mean normalized intrusion profiles grouped by pore-throat structure type for comparison; the dashed boundary locations were identified from the 59-sample population-level response using Equations (5) and (6).

Using Equation (1), the corresponding capillary pressures were calculated and are given in Equations (9) and (10):

$$P_{L/T} = \frac{0.735}{0.708} = 1.04, \quad (9)$$

$$P_{T/B} = \frac{0.735}{0.141} = 5.21. \quad (10)$$

Both pressures are expressed in MPa. The MICP data can therefore be partitioned into three functional intervals. The large-pore-throat-dominated interval ($r > 0.708 \mu\text{m}$) represents intrusion controlled by comparatively large pore throats at low capillary pressure. The transitional pore-throat interval ($0.141 < r \leq 0.708 \mu\text{m}$) records the shift from large-pore-throat dominance to progressively stronger fine-throat control. The fine-throat-limited interval ($r \leq 0.141 \mu\text{m}$) represents restriction of fluid entry by fine throats under high capillary pressure.

The sensitivity of the two functional boundaries was further evaluated by perturbing each nominal radius by $\pm 5\%$ and $\pm 10\%$. For $r_{L/T} = 0.708 \mu\text{m}$, the $\pm 5\%$ and $\pm 10\%$ radius ranges are $0.673\text{--}0.743 \mu\text{m}$ and $0.637\text{--}0.779 \mu\text{m}$, corresponding to capillary-pressure ranges of $0.989\text{--}1.093 \text{ MPa}$ and $0.944\text{--}1.153 \text{ MPa}$, respectively. For $r_{T/B} = 0.141 \mu\text{m}$, the corresponding radius ranges are $0.134\text{--}0.148 \mu\text{m}$ and $0.127\text{--}0.155 \mu\text{m}$, equivalent to $4.965\text{--}5.487 \text{ MPa}$ and $4.739\text{--}5.792 \text{ MPa}$.

These perturbations do not alter the principal functional distinctions among the three pore-throat types. The P_{50} values of Type I samples ($0.210\text{--}0.259 \text{ MPa}$) remain well below the pressure range of the perturbed $r_{L/T}$, whereas the P_d values of Type III samples ($2.044\text{--}2.990 \text{ MPa}$) remain well above it. The complete P_{50} range of Type II ($0.418\text{--}3.207 \text{ MPa}$) also lies below the pressure range of the perturbed $r_{T/B}$. Among Type III samples, three P_{50} values lie above the entire $\pm 10\%$ range of the second boundary, whereas M8 ($P_{50} = 5.274 \text{ MPa}$) falls within this range. The latter therefore represents a locally boundary-sensitive sample near the transitional scale, rather than a change in the overall fine-throat-limited character of Type III.

The leave-one-out analysis retained both transition locations at 0.708 and $0.141 \mu\text{m}$ in all 59 iterations at the adopted 0.1 -decade radius-grid resolution. Thus, removal of any single sample did not shift either identified grid-scale transition. This jackknife stability complements the boundary-perturbation test but does not quantify instrumental measurement uncertainty or imply zero physical uncertainty.

The proportion of total mercury intrusion assigned to each functional interval was calculated using Equation (11):

$$\eta_j = \frac{\sum_{i \in I_j} \Delta S_i}{\sum_{i=1}^n \Delta S_i} \times 100\%, \quad j = L, T, B, \quad (11)$$

where η_j is the mercury-intrusion fraction of functional interval j , and I_L , I_T , and I_B denote the large-pore-throat-dominated, transitional, and fine-throat-limited intervals, respectively. The interval-specific proportions were calculated first for each individual sample rather than from a pooled type-averaged intrusion curve. Under the nominal boundaries, Type I is strongly dominated by the large-pore-throat interval, which accounts for an average of 88.7% of total intrusion in the two Type I samples. Type II samples exhibit a broader distribution of intrusion across the large-pore-throat and transitional intervals, whereas Type III samples show negligible intrusion within the large-pore-throat interval and markedly stronger restriction associated with finer throats. Equation (11) was evaluated over positive intrusion increments only.

Comparison among Types I–III indicates systematic differences in the pressure ranges over which mercury enters the pore-throat system. These differences are consistent with the relative positions of P_d and P_{50} with respect to the two functional boundaries and remain evident after moderate perturbation of the boundary positions. The values of 0.708 and $0.141 \mu\text{m}$ are therefore interpreted as dataset-derived transition scales in mercury-intrusion behavior rather than universal or empirically prescribed pore-size thresholds.

4.3. Functional Pore-Throat Segmentation and Fractal Characteristics

The common boundaries at 0.708 and 0.141 μm define the large-pore-throat-dominated, transitional, and fine-throat-limited regimes used for physical interpretation, but they were not imposed as fixed regression nodes on individual MICP curves. For each sample, quasi-linear segments in the log-log relationship between capillary pressure and cumulative mercury saturation were identified from sample-specific changes in slope, and the corresponding D_L , D_T , and D_B values were associated with the large-pore-throat-related, transitional, and fine-throat-related regimes, respectively (Figure 7; Table 2).

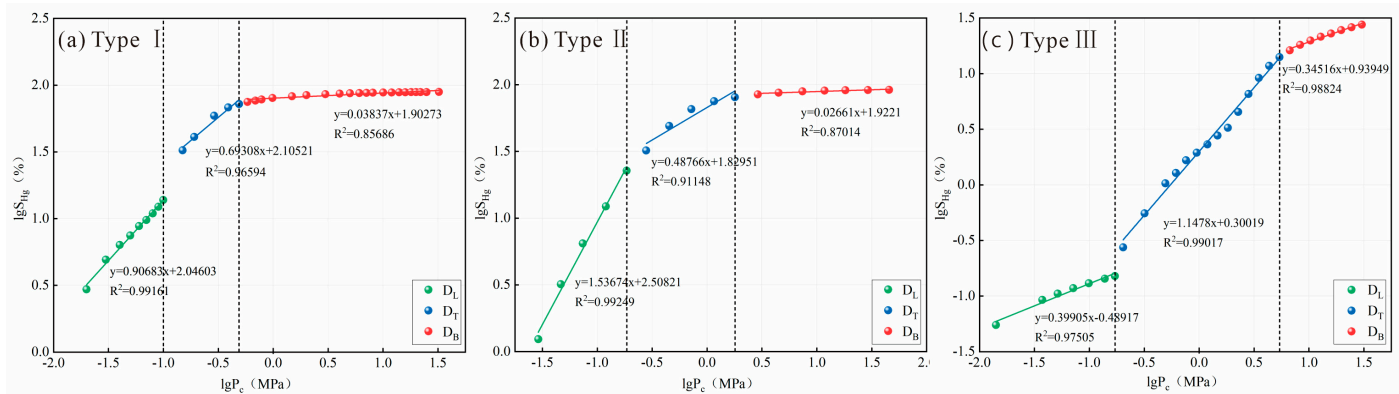


Figure 7. Segment-specific fractal fits for samples with different pore-throat structure types. The vertical dashed lines denote sample-specific fitting transitions and are not required to coincide exactly with the common functional boundaries at 0.708 and 0.141 μm .

The log-transformed variables were defined using Equations (12) and (13):

$$x_i = \lg P_{c,i}, \quad (12)$$

$$y_i = \lg S_{Hg,i}, \quad (13)$$

where $P_{c,i}$ is the capillary pressure at the i th intrusion data point and $S_{Hg,i}$ is the cumulative mercury saturation. A separate linear relationship was fitted within each sample-specific quasi-linear segment using Equation (14):

$$y_i = K_j x_i + C_j, \quad i \in I_j, \quad j = L, T, B, \quad (14)$$

where K_j is the fitted slope for sample-specific segment j and C_j is the intercept. The fitting parameters were obtained by minimizing the least-squares objective in Equation (15):

$$(K_j, C_j) = \arg \min \sum_{i \in I_j} [y_i - (K_j x_i + C_j)]^2, \quad j = L, T, B. \quad (15)$$

The corresponding functional fractal dimension was calculated using Equation (16):

$$D_j = K_j + 2, \quad j = L, T, B \quad (16)$$

The fitted segments generally exhibit strong linear relationships. R^2 is reported only to assess the reliability of the segmented fits; it is neither interpreted as an independent pore-throat parameter nor used as a screening threshold.

D_L ranges from 2.384 to 2.907, with a mean of 2.585, a median of 2.523, and a coefficient of variation of 0.068 (Figure 8). It describes structural complexity within the large-pore-throat-dominated interval. The large-pore-throat interval dominates mercury intrusion in Type I but contributes progressively less in Types II and III; accordingly, D_L is interpreted

as a descriptor of the large-pore-throat-related component rather than as a stand-alone measure of bulk flow capacity.

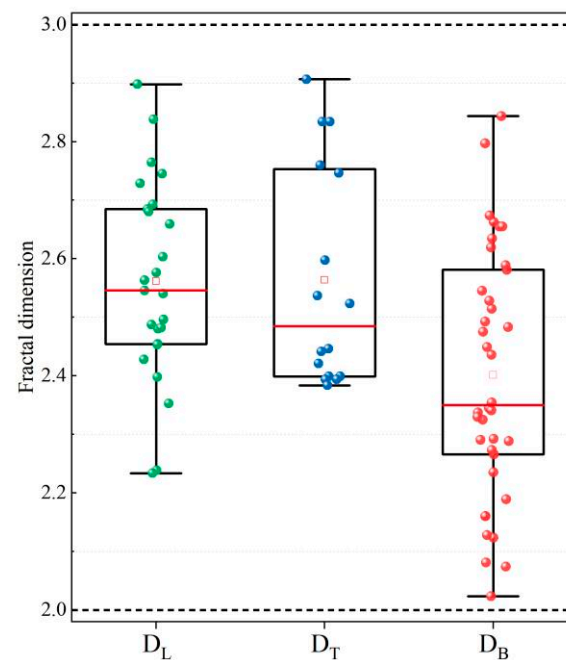


Figure 8. Distribution of the segment-specific fractal dimensions D_L , D_T , and D_B across the analyzed samples.

D_T ranges from 2.234 to 2.898, with a mean of 2.583, a median of 2.570, and a coefficient of variation of 0.068. The transitional interval lies between declining large-pore-throat dominance and increasing fine-throat control; D_T therefore records structural complexity across the pore-throat scale transition. Type II exhibits a broader mercury-intrusion response across the large-pore-throat and transitional intervals, consistent with stronger scale mixing and the joint participation of multiple pore-throat sizes.

D_B ranges from 2.023 to 2.844, with a mean of 2.346, a median of 2.325, and a coefficient of variation of 0.097. It describes the complexity of the fine-throat system under high capillary pressure. Fine-throat restriction is most pronounced in Type III, where mercury intrusion is shifted toward higher capillary pressures; D_B is therefore interpreted as a descriptor associated with structural complexity under fine-throat bottleneck conditions.

The three fractal parameters describe distinct functional parts of the pore-throat spectrum. D_L characterizes structural complexity within the large-pore-throat-related regime, D_T describes heterogeneity across the scale-transition zone, and D_B characterizes structural complexity associated with fine-throat bottleneck restriction. The progressive redistribution of mercury intrusion from large-pore-throat dominance toward transitional and fine-throat control shifts the interpretive emphasis from large-pore-throat complexity to scale-transition heterogeneity and fine-throat limitation.

4.4. Micro-CT-Based Digital-Rock Reconstruction and Pore-Network Connectivity of Different Pore-Throat Types

S1, S2, and S3 represent Type I, II, and III pore-throat structures, respectively, and were used for micro-CT-based digital-rock reconstruction and PNM analysis. Their reconstructed pore spaces differ markedly in abundance and connectivity (Figure 9(a1)–(c3); Table 3). CT porosity denotes the volume fraction of pores resolvable at the respective imaging resolution and is used here only to compare resolvable pore space among the three samples. Accordingly, all CT-derived porosity and connectivity metrics in this study refer to the

pore space resolvable at the respective voxel sizes and do not represent the complete submicrometer pore-throat system. Because the VOI dimensions and voxel sizes differ among S1–S3, the absolute CT-derived values are resolution- and volume-conditioned; they are used here as within-study type contrasts and are not directly interchangeable with plug-scale laboratory porosity.

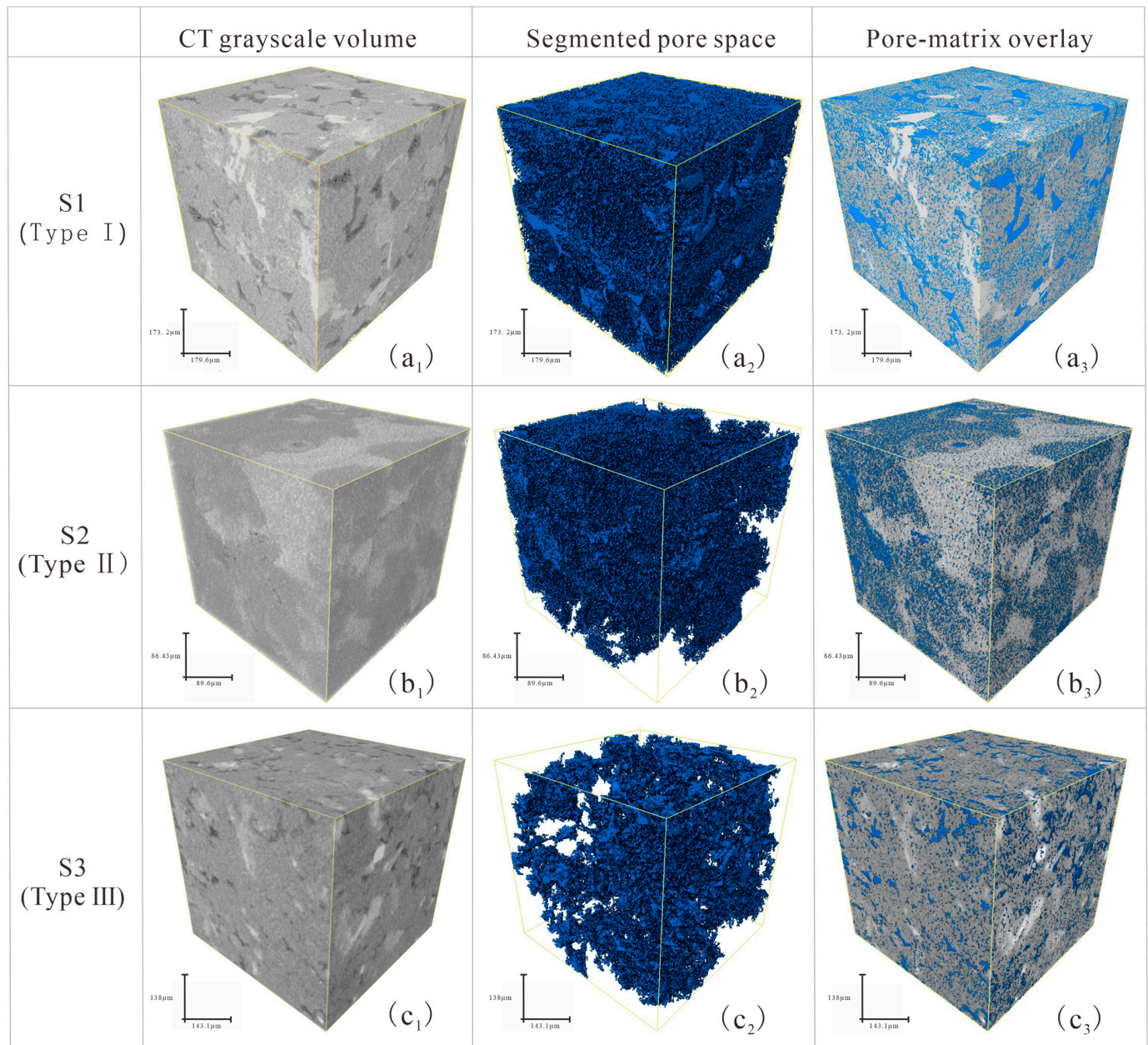


Figure 9. Three-dimensional micro-CT reconstruction of pore space in representative Type I–III samples. Panels (a1–a3), (b1–b3), and (c1–c3) correspond to S1 (Type I), S2 (Type II), and S3 (Type III), respectively. Panels in the first column (a1,b1,c1) show the reconstructed CT grayscale volumes; those in the second column (a2,b2,c2) show the segmented pore spaces; and those in the third column (a3,b3,c3) show the pore–matrix overlays. Scale bars are shown within the individual panels, and the same rendering convention is used across S1–S3 within each column. Blue denotes the segmented pore space in the segmentation and overlay panels.

CT porosities for S1, S2, and S3 are 22.29%, 11.34%, and 9.51%, respectively. The largest connected pore-cluster fractions are 90.26%, 72.56%, and 64.65%, yielding connected porosities of 20.12%, 8.23%, and 6.15%. Most resolvable pores in S1 belong to the connected

network, whereas both resolvable pore volume and connected fraction decline in S2 and S3 and are lowest in S3. These values document systematic differences in pore space and geometric connectivity at the current micro-CT resolutions (Figure 9(a1)–(c3); Table 3).

Table 3. Digital-rock connectivity parameters and permeability of representative Type I–III sandstone samples. K_{DF} denotes permeability from direct-flow simulation in connected pore space, and K_{PNM} denotes permeability predicted by the pore-network model. K_{DF} is calculated directly within the segmented connected pore space, whereas K_{PNM} is obtained after reducing that space to an equivalent pore-body–throat network; the two estimates therefore represent different numerical descriptions of the same resolvable pore geometry and are not expected to coincide in absolute magnitude. Here, ϕ_{CT} denotes CT-resolved porosity, F_{max} the percentage of CT-resolved pore volume belonging to the largest connected cluster, and ϕ_{conn} ($=\phi_{CT} \times F_{max}/100$) the connected porosity. The connectivity class is a qualitative within-study descriptor of the combined connectivity contrast and is not a universal threshold-based classification.

Structure Type	Sample	Voxel Size (μm)	ϕ_{CT} (%)	F_{max} (%)	ϕ_{conn} (%)	K_{DF} (mD)	K_{PNM} (mD)	Tortuosity, τ	Connectivity Class
Type I	S1	2.000	22.29	90.26	20.12	238.96	64.32	1.761	High
Type II	S2	2.06546	11.34	72.56	8.23	23.50	0.850	1.728	Moderate
Type III	S3	1.000	9.51	64.65	6.15	12.347	0.121	1.830	Restricted

Direct-flow simulation permeabilities for S1, S2, and S3 are 238.96, 23.50, and 12.347 mD, whereas the corresponding PNM permeabilities are 64.32, 0.850, and 0.121 mD (Table 3). Although their absolute magnitudes differ substantially, both approaches yield the same flow-capacity ranking of $S1 > S2 > S3$. This difference reflects their distinct geometric representations: K_{DF} is calculated directly on the connected voxel-resolved pore space, whereas K_{PNM} is obtained from the reduced equivalent pore-body–throat network. The pronounced decline in K_{PNM} across S1–S3, compared with the smaller changes in CT porosity and connected porosity, is consistent with strong sensitivity of the reduced network to throat size and pore-body–throat configuration.

Tortuosities of S1, S2, and S3 are 1.761, 1.728, and 1.830, respectively, and vary only slightly (Table 3). In contrast to the pronounced differences in permeability and connected porosity, tortuosity alone cannot explain the variation in network flow capacity. Network flow capacity should therefore be interpreted jointly from pore-body size, throat radius, pore-body–throat size matching, and the extent of the largest connected pore cluster.

5. Discussion

5.1. Depositional and Diagenetic Controls on Pore-Throat Structure

The broad scatter in the porosity–permeability relationship is evident across porosities of 1.61–15.40% and permeabilities of 0.0089–34.7794 mD (Figure 4). Samples with similar porosity differ in permeability by one to several orders of magnitude; some comparatively porous samples remain poorly permeable, whereas some samples with moderate or low porosity retain appreciable flow capacity. This scatter is consistent with differences in pore type, throat preservation, and the manner in which pore bodies are connected.

Quartz sandstone and lithic quartz sandstone together constitute 81.95% of the Benxi Formation samples, whereas lithic sandstone accounts for 18.06% (Figure 2). Quartz content decreases from 83.70% in quartz sandstone to 70.36% in lithic quartz sandstone and 55.82% in lithic sandstone, while lithic content increases from 3.96% to 27.21%. Quartz-rich compositions promote a stable grain-supported framework and favor preservation of residual intergranular pores. As lithic grains, matrix, and mud-rich components increase, compaction and cementation more readily reduce pore volume and partition throats. Hydrodynamic conditions varied rapidly across the mixed tidal-flat–lagoon system: relatively

high-energy tidal channels and sand flats were more likely to preserve a sandy framework, whereas transitional zones with stronger argillaceous or calcareous influence favored fine-grained filling and weakly connected pore-throat assemblages.

The reservoir space observed in cast thin sections comprises residual intergranular pores, intergranular and intragranular dissolution pores, intercrystalline pores in kaolinite aggregates, and sparse microfractures (Figure 3). Residual intergranular and intergranular dissolution pores are comparatively favorable for effective storage and connectivity. Intragranular dissolution pores and kaolinite intercrystalline pores are commonly dispersed and may increase local pore volume without substantially improving flow. Dissolution enlarged pore bodies, whereas siliceous and carbonate cementation and clay-mineral filling were concentrated along pore margins and within throats, where they narrowed constrictions and reduced connectivity.

MICP provides a complementary pressure-domain expression of these pore-throat assemblages (Figures 5 and 6; Table 1). Type I is characterized by $P_d = 0.020$ MPa, $P_{50} = 0.210$ – 0.259 MPa, and $r_{50} = 2.840$ – 3.498 μm , and mercury intrusion is concentrated in the large-pore-throat-dominated interval. Type II has $P_d = 0.029$ – 0.949 MPa and $P_{50} = 0.418$ – 3.207 MPa, with r_{50} decreasing to 0.229 – 1.757 μm ; its broader intrusion response reflects the joint participation of large and transitional pore-throat scales. Type III has $P_d = 2.044$ – 2.990 MPa, $P_{50} = 5.274$ – 10.251 MPa, and $r_{50} = 0.072$ – 0.139 μm . Because the displacement pressures of all Type III samples exceed the first functional-boundary pressure, intrusion through pore throats larger than $r_{L/T}$ is negligible, while the higher P_{50} values indicate substantially stronger control by finer throats.

The boundaries $r_{L/T}$ and $r_{T/B}$, identified from the rate of change in mean normalized mercury intrusion, mark the pore-throat scales at which the dominant contribution to intrusion shifts. The large-pore-throat-dominated interval is mainly associated with residual intergranular pores, intergranular dissolution pores, and comparatively open throats. The transitional interval reflects changes in connections among larger pore bodies, whereas the fine-throat-limited interval is more closely associated with kaolinite intercrystalline pores, small intragranular pores, narrow throats, and pore-throat space constricted by cement. Depositional fabric and grain composition established the initial potential for pore preservation; subsequent compaction, cementation, and dissolution modified pore-body size, throat width, and connectivity, progressively transforming relatively open assemblages into weakly connected networks controlled by fine throats.

Mineralogical variability, dissolution, and microfracture development are not excluded as controls on reservoir quality. Rather, they represent geological processes that generate or modify the observed pore-throat architecture: framework-grain composition, clay minerals, and cement influence compaction resistance and throat preservation; dissolution mainly enlarges local pore bodies; and sparse microfractures may locally improve connectivity (Figures 2 and 3). Because these attributes were not quantified for the complete MICP population at the same sample scale, their independent contributions to the fractal parameters cannot be statistically separated in the present study. Within this dataset, the consistent relationships among throat-related MICP parameters, segment-specific fractal responses, and three-dimensional network characteristics therefore support fine-throat restriction as the proximate hydraulic expression of reservoir-quality deterioration rather than as its sole geological cause.

5.2. Functional Fractal Segmentation and Constraints from Micro-CT/PNM-Derived Pore-Throat Radii

The two functional boundaries coincide with the principal local maxima in the rate of change in mean normalized mercury intrusion and therefore locate major shifts in the pore-throat scales controlling intrusion. With reference to these three functional regimes, D_L ,

D_T , and D_B describe the complexity associated with the large-pore-throat-related regime, pore-throat scale transition, and fine-throat bottleneck restriction, respectively; their exact fitting transitions remain sample specific. Their relationships with porosity, permeability, and MICP parameters differ substantially (Figure 10).

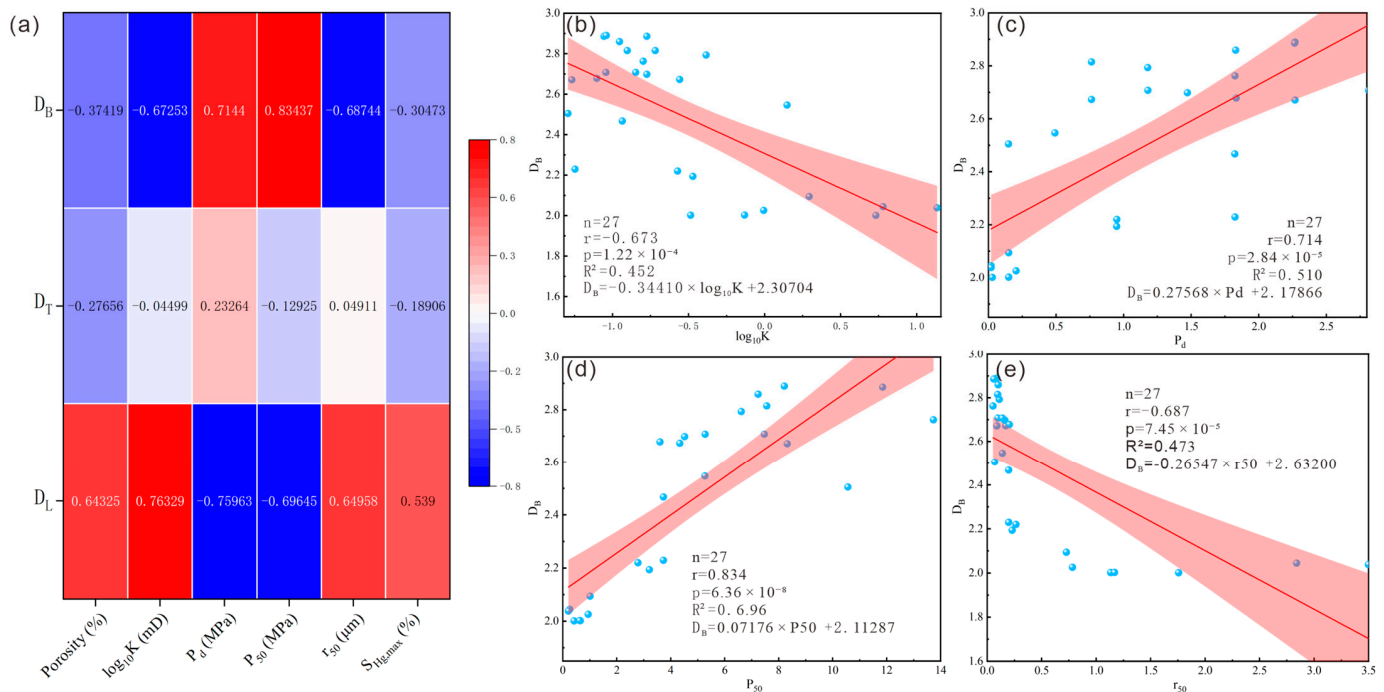


Figure 10. Relationships of segment-specific fractal dimensions with porosity, permeability, and MICP parameters. (a) Pearson correlation matrix of D_L , D_T , and D_B with porosity, $\log_{10}K$, P_d , P_{50} , r_{50} , and $S_{Hg,max}$. (b–e) Linear regressions of D_B against $\log_{10}K$, P_d , P_{50} and r_{50} , respectively. All correlation and regression analyses are based on the same complete-case dataset ($n = 27$), and the shaded bands in panels (b–e) represent 95% confidence intervals.

The perturbation analysis further constrains the interpretation of the two functional boundaries. Even when $r_{L/T}$ is shifted by $\pm 10\%$, its equivalent pressure range remains well above the P_{50} values of Type I and well below the P_d values of Type III. The first boundary therefore robustly separates large-pore-throat-dominated intrusion from pore-throat systems in which large throats make little contribution to mercury entry. The second boundary is more sensitive because it lies within the scale-transition region: M8 has a P_{50} value within the $\pm 10\%$ pressure range of $r_{T/B}$, whereas the other Type III samples lie above it. This local sensitivity is consistent with the transitional nature of the boundary and does not alter the broader contrast among the three pore-throat structure types. Accordingly, 0.708 and 0.141 μm should be regarded as characteristic transition scales derived from the present Benxi Formation dataset, rather than universal pore-size thresholds applicable to all tight sandstones.

Using the 27 complete cases, D_L is positively correlated with porosity, $\log_{10}K$, r_{50} , and $S_{Hg,max}$ and negatively correlated with P_d and P_{50} ($|r| = 0.539\text{--}0.763$, $p \leq 0.0037$). D_T remains weakly related to all six variables ($|r| \leq 0.277$, $p > 0.05$). By contrast, D_B shows the strongest relationship with P_{50} ($r = 0.834$, $p < 0.001$, $R^2 = 0.696$) and is also significantly correlated with P_d ($r = 0.714$, $p < 0.001$), r_{50} ($r = -0.687$, $p < 0.001$), and $\log_{10}K$ ($r = -0.673$, $p < 0.001$); its correlations with porosity ($r = -0.374$, $p = 0.0545$) and $S_{Hg,max}$ ($r = -0.305$, $p = 0.122$) are not statistically significant. The same set of significant Pearson associations was retained after Benjamini–Hochberg false-discovery-rate correction across the 18 tests ($q < 0.05$). These contrasting statistical associations are consistent with D_L

reflecting broader variations in pore-throat openness, D_T representing the scale-transition regime, and D_B serving as a sensitive indicator associated with fine-throat bottleneck restriction and reduced permeability.

The nonparametric sensitivity check supports the same interpretation: Spearman correlations retained significant relationships for all six D_L comparisons, while all D_T comparisons remained non-significant. For D_B , the strongest rank relationships were with P_{50} ($\rho = 0.855$, $p < 0.001$) and r_{50} ($\rho = -0.855$, $p < 0.001$), with significant associations also retained for P_d ($\rho = 0.722$, $p < 0.001$) and $\log_{10}K$ ($\rho = -0.563$, $p = 0.002$).

Within the pore-network models extracted from the micro-CT-resolved segmented pore space, the equivalent pore-body and throat-radius distributions differ systematically among the Type I–III representatives (Figure 11). In S1 (Type I), pore-body radii are concentrated between 6.31 and 17.78 μm . The 8.91–12.59 μm interval has the highest relative frequency (29.39%), followed by 6.31–8.91 μm (25.82%) and 12.59–17.78 μm (19.23%). Throat radii are concentrated between 2.24 and 6.31 μm , with a maximum frequency of 20.48% at 3.16–4.47 μm and frequencies of 17.12% and 16.56% at 2.24–3.16 and 4.47–6.31 μm , respectively. The coexistence of large pore bodies and comparatively wide throats is consistent with S1's high connected-cluster fraction and with the large mercury-intrusion contribution from the large-pore-throat-dominated interval.

Pore bodies in S2 (Type II) remain comparatively large. The 6.31–8.91 μm interval accounts for 39.15%, followed by 8.91–12.59 μm (26.62%) and 4.47–6.31 μm (17.64%). Relative to S1, however, throat radii are more strongly concentrated in intermediate intervals: 4.47–6.31 and 3.16–4.47 μm account for 22.97% and 22.78%, respectively, while 2.24–3.16 μm contributes 15.46%. Pore bodies thus retain appreciable volume, but their interconnection is increasingly controlled by throats, consistent with the reduced large-pore-throat contribution and greater participation of the transitional and fine-throat-limited intervals. In S3 (Type III), the pore-body mode shifts to smaller radii. The 3.16–4.47 μm interval accounts for 32.45%, followed by 4.47–6.31 μm (23.52%) and 2.24–3.16 μm (18.33%). Throat-size reduction is more pronounced: 1.58–2.24 μm has the highest relative frequency (24.80%), followed by 1.12–1.58 μm (20.44%) and 2.24–3.16 μm (16.14%). Equivalent throat radii of 0.1–1 μm collectively account for 35.13%, compared with 10.15% in S1 and 7.39% in S2. The resulting mismatch between pore-body and throat sizes prevents larger local pores from being linked by persistently wide throats and provides a geometric basis for the low flow capacity of Type III. These 0.1–1 μm values are equivalent radii calculated by the PNM and do not imply direct micro-CT resolution of subvoxel throats. More specifically, these submicrometer values are model-derived equivalent radii assigned to PNM network elements and should not be interpreted as direct observations of the submicrometer throat population identified by MICP.

The micro-CT/PNM radius distributions neither replace MICP identification of submicrometer pore throats nor redefine the functional boundaries at 0.708 and 0.141 μm . MICP segmentation captures transitions in pore-throat contribution within the pressure domain, whereas micro-CT/PNM distributions describe equivalent pore-body–throat geometry in networks extracted from the resolvable segmented pore space. From S1 to S2 and S3, the modal pore-body radius shifts toward smaller intervals, throat contraction is more pronounced, and pore-body–throat size matching progressively deteriorates. These changes are consistent with increasing P_{50} , decreasing r_{50} , a greater intrusion contribution from the fine-throat-limited interval, and the stronger response of D_B in low-permeability samples.

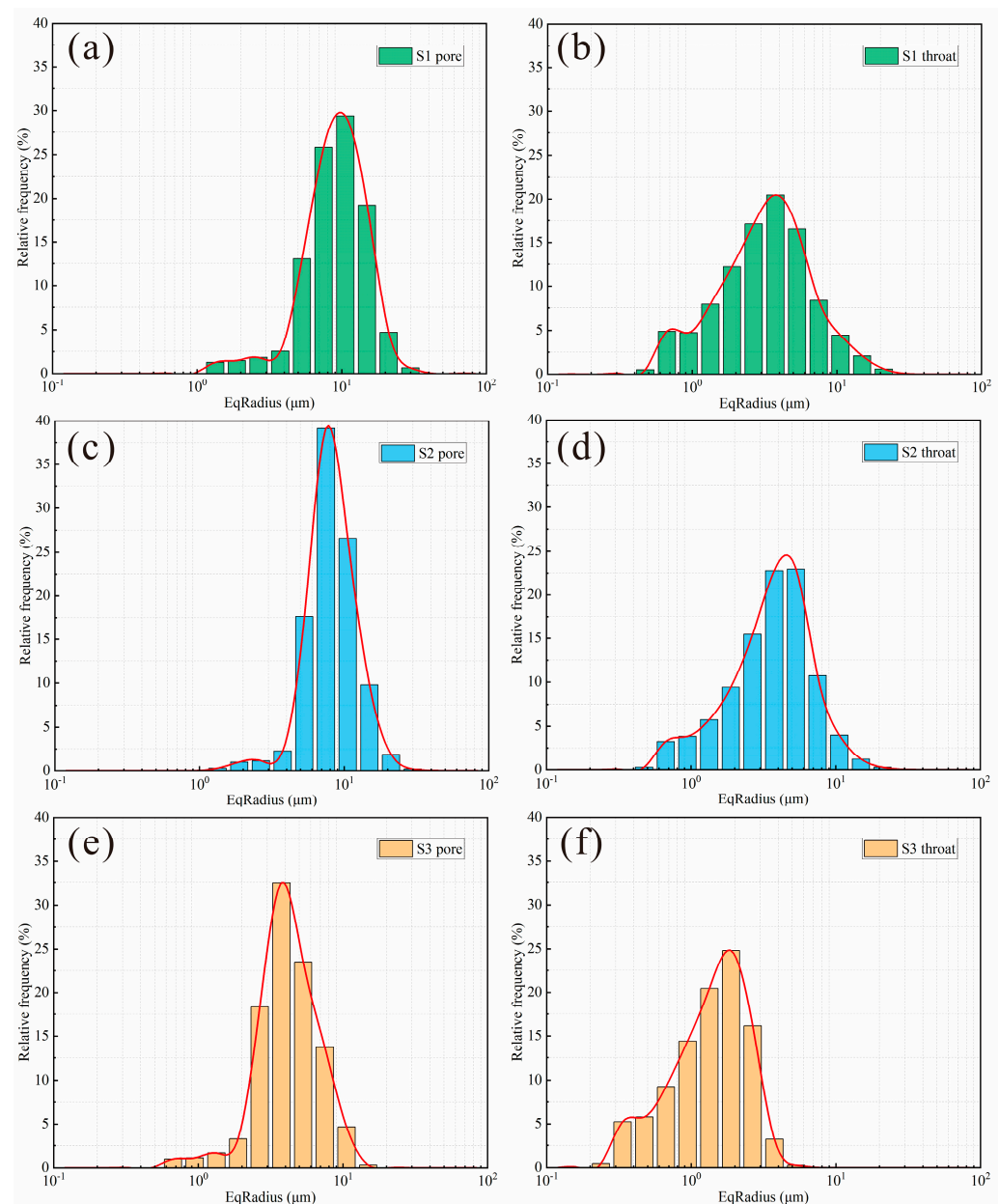


Figure 11. Equivalent pore-body and throat radius distributions of representative samples. (a,b) Pore-body and throat-radius distributions of S1 (Type I), respectively; (c,d) pore-body and throat-radius distributions of S2 (Type II), respectively; (e,f) pore-body and throat-radius distributions of S3 (Type III), respectively. Red curves indicate the smoothed distribution trends of the corresponding histograms. Submicrometer throat radii are model-derived equivalent radii from the extracted PNM rather than directly resolved micro-CT throat sizes.

In functional-fractal terms, D_L primarily characterizes structural complexity associated with the large-pore-throat-related regime, D_T characterizes structural complexity across the pore-throat scale-transition regime, and D_B is most strongly associated with the fine-throat bottleneck signature observed in the MICP and flow-related parameters. Large pore bodies and comparatively wide throats coexist in S1, producing a network close to large-pore-throat dominance. Pore bodies remain developed in S2, but throat connections become increasingly restrictive, consistent with stronger transitional control. In S3, marked throat contraction and poor pore-body–throat matching produce the clearest fine-throat-limited response. Combining the functional fractal parameters with micro-CT/PNM radius

distributions links scale-dependent mercury-intrusion responses to geometric features of the resolvable pore network.

Previous studies have approached reservoir pore-space heterogeneity from complementary perspectives. Cheng et al. [42] demonstrated that tight-sandstone permeability is strongly scale dependent and identified the pore-throat radius at 10% mercury saturation (r_{10}) as a particularly effective permeability predictor, emphasizing that characteristic pore-throat scales may be more informative than bulk porosity alone. Wang et al. [43] classified tight-sandstone reservoir space into combined, isolated-grain, and clay-dominated pore types and documented systematic differences in connectivity and fractal characteristics among these pore-space types. Jouini et al. [44] further showed that experimental mercury-intrusion data and three-dimensional digital-rock fractal/multifractal descriptors can be combined to quantify pore-space heterogeneity. The present study builds on these complementary concepts but addresses a different question. Rather than replacing morphology-based classifications or introducing multifractal parameters as an additional discrimination layer, the proposed workflow identifies functional transition scales from changes in mercury-intrusion contribution, quantifies regime-specific structural responses using D_L , D_T , and D_B , and constrains these responses using pore-body–throat radii, connected pore volume, permeability, and three-dimensional network connectivity. The methodological extension therefore lies in linking scale-specific intrusion function, segment-specific complexity, and hydraulic connectivity within a single reservoir-effectiveness framework.

5.3. Fine-Throat Bottleneck Effects and Three-Dimensional Connectivity Constraints

CT porosity, the largest connected pore-cluster fraction, and connected porosity all decrease from S1 to S2 and S3 (Figure 12(a1)–(c3); Table 3). Throat contraction and deteriorating pore-throat matching, recorded by the radius distributions, are expressed in three dimensions by shrinkage of the connected cluster and increasing isolation of local pores. K_{PNM} declines from 64.32 mD in S1 to 0.850 mD in S2 and 0.121 mD in S3, a much greater reduction than that in CT porosity or connected porosity. The stronger decline in flow capacity relative to pore volume is therefore more consistent with sensitivity to throat radius, pore-body–throat size matching, and the number of effective flow pathways than with pore volume alone. In the following network-scale interpretation, K_{PNM} is emphasized because it is derived from the extracted pore-body–throat topology and is therefore directly linked to throat-controlled network flow; K_{DF} is retained as a complementary direct-flow estimate from the connected voxel-resolved pore space rather than as an interchangeable absolute-permeability value.

The large fraction of the largest connected pore cluster and the comparatively wide throats in S1 support a continuous flow network. S2 retains local connectivity, but its principal pathways depend increasingly on a limited number of critical throats. Although S3 preserves some resolvable pores and geometric connections, its K_{PNM} is only 0.121 mD, illustrating that geometric connectivity is not equivalent to effective flow (Figure 12(a1)–(c3)). Under fine-throat bottleneck control, local pore bodies form narrow-throat connections associated with localized retention and weak flow, so part of the connected pore volume contributes little to throughflow.

Tortuosity varies only slightly among the three samples, whereas K_{PNM} differs by more than two orders of magnitude. Tortuosity therefore does not, by itself, explain the contrast in flow capacity. In these representative digital-rock models, simulated flow is concentrated along a limited set of relatively open and continuous pore-throat pathways. When these critical pathways are narrowed or partitioned by fine throats, bulk flow capacity decreases sharply even where measurable connected pore volume remains.

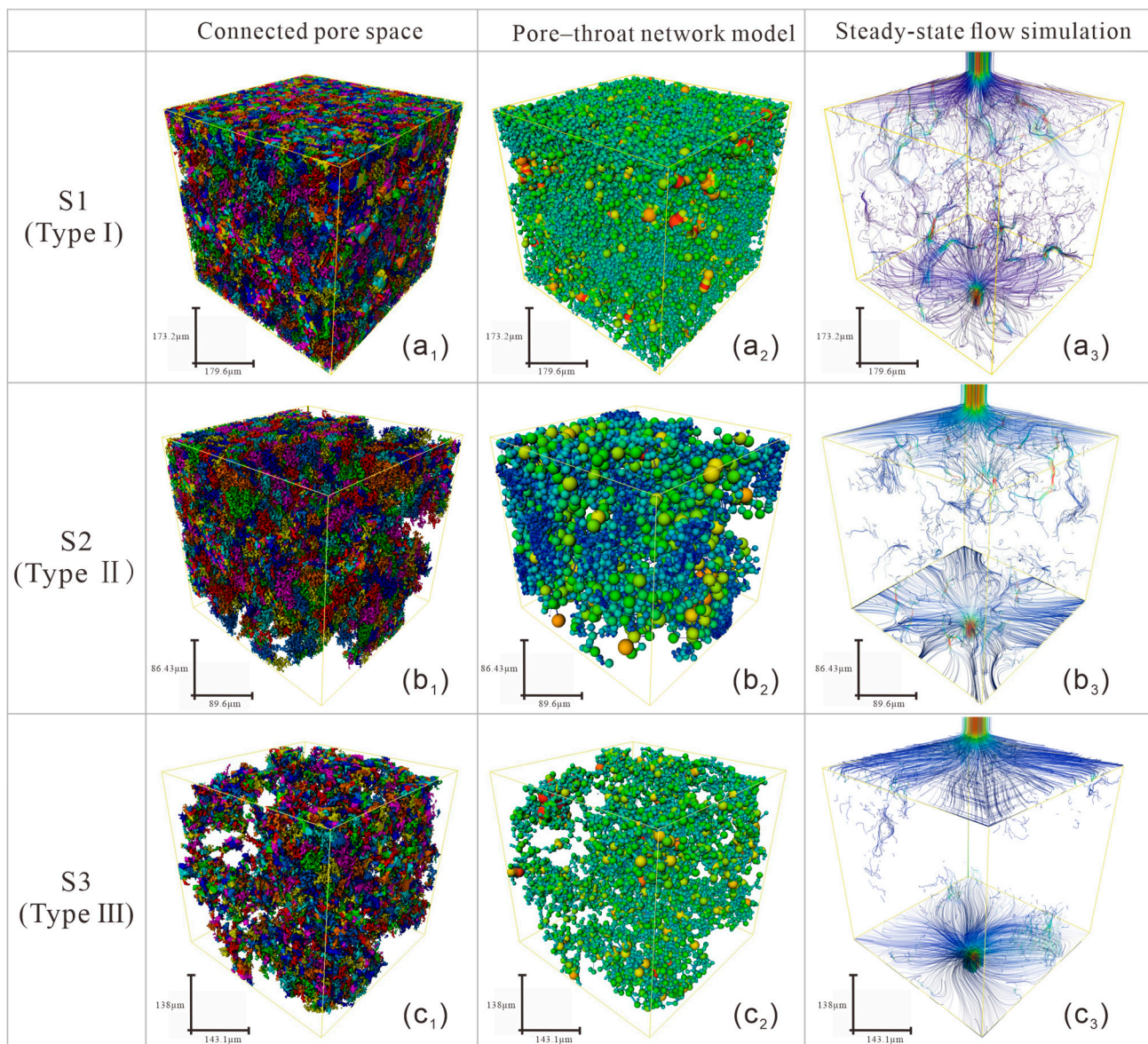


Figure 12. Pore-network extraction and flow simulation constrained by connected pore space in representative samples. Panels (a1–a3), (b1–b3), and (c1–c3) correspond to S1 (Type I), S2 (Type II), and S3 (Type III), respectively. Panels in the first column (a1,b1,c1) show the connected pore space; those in the second column (a2,b2,c2) show the extracted pore-body–throat network; and those in the third column (a3,b3,c3) show the steady-state single-phase flow simulation. The same rendering convention is used across S1–S3 within each column. Quantitative connectivity and permeability parameters are summarized in Table 3, and the corresponding pore-body and throat radius distributions are shown in Figure 11.

The combined MICP and digital-rock results are consistent with a fine-throat bottleneck mechanism that translates differences in pore-throat scale and configuration into differences in three-dimensional flow capacity. Type I contains an effective network formed jointly by larger pore bodies and comparatively wide throats. Type II retains appreciable pore-body development, but critical throats exert stronger control over the principal pathways. Type III is characterized by poorly matched and weakly connected pore–throat pathways dominated by fine throats, reducing the number of effective pathways. Identifying an effective reservoir therefore requires more than confirming the presence of pores; it requires determining whether pore bodies are connected by throats of sufficient size and whether those connections form stable, continuous, dominant flow pathways.

Uncertainty in the MICP-based interpretation also arises from representing irregular pore-throat constrictions by equivalent capillary radii and from the exact placement of the functional transition boundaries; the latter was therefore evaluated using the $\pm 5\%$ and $\pm 10\%$ perturbation tests described above. Segment-specific fractal dimensions remain dependent on the sample-specific quasi-linear fitting intervals, and the reported R^2 values are used only to describe fitting reliability rather than as independent physical parameters.

The micro-CT/PNM results should be interpreted within the spatial-resolution, segmentation, and model-abstraction limits of the digital-rock workflow. The voxel sizes of 1.000–2.065 μm restrict direct geometric characterization to the resolvable pore system; smaller pores and throats identified by MICP are not explicitly represented in the segmented volumes. Although automatic thresholding followed by interactive fine-adjustment reduces obvious pore-solid misclassification, voxels close to the pore-matrix grayscale boundary remain sensitive to threshold placement and may affect local connectivity. PNM further reduces the segmented pore space to idealized pore bodies and throats, so equivalent radii and K_{PNM} are model-dependent quantities. The relative separation between K_{DF} and K_{PNM} becomes larger from S1 to S3. This trend is consistent with increasing sensitivity to the representation of narrow throats and pore-body–throat mismatch: the direct-flow calculation retains the continuous geometry of the resolved connected pore space, whereas PNM reduces that geometry to idealized pore bodies and throats. Consequently, the two permeability estimates are not treated as interchangeable absolute values, and their difference is interpreted as model dependence rather than as evidence that one method is intrinsically more accurate. Nevertheless, both simulations yield the same relative flow-capacity ranking ($S1 > S2 > S3$), consistent with the independent MICP shift from large-pore-throat dominance toward fine-throat restriction. The digital-rock results are therefore used primarily to constrain relative differences in three-dimensional connectivity and flow-network organization rather than to recover the complete submicrometer pore-throat system or provide unique formation-scale permeability estimates.

5.4. Multiscale Integrated Model for Reservoir-Effectiveness Discrimination

Spatial variations in terrigenous sediment supply, carbonate participation, and hydrodynamic energy across the marine–continental transitional mixed siliciclastic–carbonate system produced sand flats, tidal flats, mixed flats, lime flats, and lagoons. Differences in grain composition, primary fabric, and argillaceous–calcareous content among these sand bodies established the depositional basis for pore-throat differentiation. Compaction, siliceous and carbonate cementation, and clay-mineral filling subsequently modified primary intergranular space, while dissolution locally generated and enlarged secondary pores. Sandstones formed in different settings consequently developed contrasting pore-body sizes, throat widths, and three-dimensional connection patterns. The Type I–III pore-throat structures are interpreted as end-member expressions of these depositional–diagenetic controls, whereas S1–S3 illustrate the corresponding contrast in three-dimensional network configuration.

Relatively strong hydrodynamic conditions in sand flats and tidal flats favored enrichment of sandy components and development of grain-supported fabrics, while argillaceous and calcareous influences were limited. These settings are interpreted as providing a favorable initial framework for Type I-like pore-throat architectures. Primary intergranular space was comparatively well preserved, and residual intergranular pores formed the basis of the reservoir space. Local dissolution generated intergranular and intragranular pores that enlarged effective pore bodies and remained spatially associated with preserved primary pores (Figure 13a–c). Low P_d and P_{50} , large r_{50} , and the high intrusion contribution from the large-pore-throat-dominated interval are consistent with this open configuration. In S1,

large pore bodies are continuously linked by relatively wide throats. Flow is distributed through interconnected intergranular and dissolution-pore networks and follows several communicating preferential pathways rather than relying on a single narrow constriction, producing an effective network jointly controlled by large pore bodies and wide throats (Figure 13d).

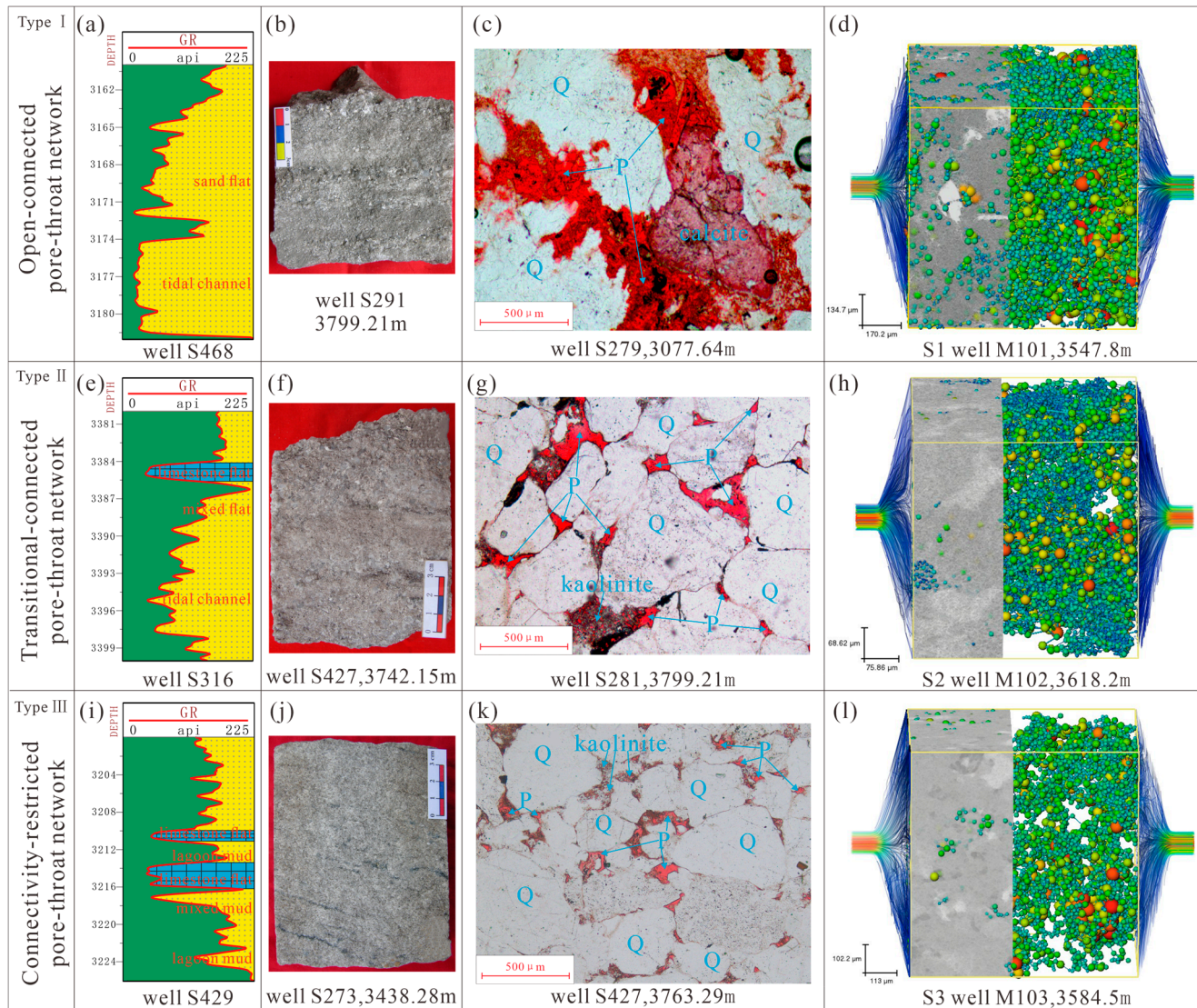


Figure 13. Multiscale integrated model for discriminating effective reservoirs in Benxi Formation tight sandstones. Panels (a–d), (e–h), and (i–l) correspond to Types I, II, and III pore structures, respectively. Panels in the first column (a,e,i) illustrate the depositional and sand-body context; those in the second column (b,f,j) show representative core appearances; those in the third column (c,g,k) show representative petrographic pore features; and those in the fourth column (d,h,l) show the corresponding digital-rock/network representations. Petrographic symbols follow the definitions given for Figure 3.

Lime flats, mixed flats, and transitional parts of some tidal flats were influenced jointly by terrigenous clastics and carbonate components. Compositional heterogeneity was greater, and grain support and preservation of primary intergranular pores were less favorable than in Type I settings. Compaction and cementation reduced primary intergranular space, while residual intergranular pores coexisted with secondary pores generated by later dissolution. Local pore bodies could remain relatively large, but their connections were increasingly affected by cement filling and throat narrowing (Figure 13e–g). The

reduced large-pore-throat contribution and greater participation of transitional and fine throats in Type II record a growing decoupling between pore-body development and throat connectivity. S2 retains local storage in comparatively large pore bodies, but these bodies are connected mainly by a limited number of intermediate and small throats. Preferential pathways coexist with narrow-throat control: continuous migration remains possible, but critical throats exert stronger control on bulk flow, and some stored pore volume contributes little to effective transport (Figure 13h).

In lower-energy lagoons and lime flats with stronger argillaceous and calcareous influence, development of the sandy framework and lateral continuity of sand bodies were further reduced. Increased mud and carbonate contents promoted intense compaction and cementation. Primary intergranular pores were strongly destroyed during diagenesis, residual intergranular pores became scarce, and the remaining reservoir space was dominated by intragranular dissolution pores, intercrystalline pores in kaolinite aggregates, and locally dispersed secondary dissolution pores. These pores preserve some volume but are spatially scattered and poorly matched in scale to the connecting throats, so even locally large pore bodies rarely form continuous connections through effective throats (Figure 13i–k). High P_{50} , small r_{50} , and the large contribution from the fine-throat-limited interval in Type III reflect stronger restriction on fluid entry and transport. The S3 flow simulation is dominated by small-throat pathways and is characterized by narrow-throat control, localized weak connectivity, and isolated pore bodies. Some pores are geometrically linked to the main network but contribute little to total flow; transport is concentrated in a few restricted pathways, producing a pronounced separation between storage space and effective flow space (Figure 13l).

Depositional environment and sand-body type establish the initial grain composition and primary fabric, whereas diagenesis modifies primary-pore preservation, secondary-pore development, and throat width. Together, these processes shape the pore-body–throat configuration that governs continuity of the three-dimensional flow network. In Type I, large pore bodies are well matched with comparatively wide throats, allowing preserved primary pores and dissolution-enhanced secondary pores to function jointly as effective flow space. Type II retains appreciable storage, but flow capacity becomes increasingly dependent on critical throats. Type III contains local pore volume but lacks sufficient effective throats, so fine-throat restriction decouples geometric connectivity from effective transport. For the Gaoqiao Benxi sandstones, the combined evidence therefore supports a hierarchical interpretation in which depositional framework and diagenesis shape pore-throat architecture, while reservoir effectiveness is expressed by whether pores and throats form a size-matched, spatially continuous, hydraulically effective network.

For practical core-scale reservoir evaluation, routine petrophysical measurements and MICP can serve as the first screening level to identify pore-throat structure type and quantify mercury-intrusion contributions across the three functional intervals. Segment-specific fractal parameters can then help identify whether the dominant structural signature is associated with large-pore-throat openness, scale-transition heterogeneity, or fine-throat bottlenecks, whereas micro-CT/PNM can be applied selectively to representative or ambiguous samples to constrain three-dimensional connectivity and flow-network organization. This staged workflow supports comparative ranking of cores or reservoir intervals; extension to production forecasting would require additional calibration and validation using independent log-, field-, and dynamic-production data.

At the present level of validation, the proposed workflow is intended for core-scale reservoir-effectiveness characterization and comparative ranking rather than as a stand-alone production-forecasting model. Its conceptual procedure may be transferable to other tight-sandstone systems, but the numerical boundaries of 0.708 and 0.141 μm are

specific to the present dataset and should be re-derived from formation-specific MICP data before application elsewhere. The limited number of micro-CT/PNM specimens also means that the three-dimensional results constrain type-level mechanisms rather than represent the full spatial variability of the Benxi Formation; broader transferability requires larger independent sample sets and additional core-, log-, or field-scale validation. The workflow has not yet been evaluated in strongly weathered, faulted, or fracture-dominated sandstone systems, where weathering alteration or structural anisotropy may become first-order controls on connectivity. Contrasting sandstone end members illustrate why separate validation is necessary: tropical weathering can modify sandstone pore-related and material properties through repeated water–rock interaction and wetting–drying processes, whereas dynamic stressing in fractured sandstone can modify fracture permeability through particle mobilization and aperture changes [45,46]. These processes are not represented by the deeply buried, structurally gentle Gaoqiao dataset. Future work should include replicate MICP measurements and sample-matched quantitative two-dimensional petrographic analysis to evaluate boundary reproducibility and to quantify more directly the relationships among pore-type proportions, diagenetic attributes, and segment-specific fractal parameters.

6. Conclusions

- (1) Benxi Formation sandstones in the Gaoqiao area are dominated by quartz sandstone and lithic quartz sandstone, which together account for 81.95%. Reservoir space comprises residual intergranular pores, intergranular and intragranular dissolution pores, intercrystalline pores in kaolinite aggregates, and sparse microfractures. Porosity ranges from 1.61% to 15.40% and permeability from 0.0089 to 34.7794 mD; samples with similar porosity may differ in permeability by one to several orders of magnitude. Pore type, throat preservation, and pore-throat connectivity provide a structural explanation for the dispersed porosity–permeability relationship, indicating that pore volume alone does not define reservoir effectiveness.
- (2) Capillary-pressure curve morphology and the key MICP parameters P_d , P_{50} , and r_{50} distinguish Type I, II, and III pore-throat structures. Variations in normalized incremental mercury intrusion define functional boundaries at 0.708 and 0.141 μm , corresponding to capillary pressures of 1.04 and 5.21 MPa, and separate large-pore-throat-dominated, transitional, and fine-throat-limited intervals. A leave-one-out analysis of all 59 MICP samples retained both transition locations in every iteration at the adopted 0.1-decade radius-grid resolution, indicating that neither boundary was driven by any single sample. Perturbing the two boundaries by $\pm 10\%$ gives radius ranges of 0.637–0.779 and 0.127–0.155 μm , respectively, without altering the principal functional distinctions among the three pore-throat types. Type I remains strongly large-pore-throat dominated, Type II exhibits a mixed large-to-transitional response, and Type III remains strongly constrained by fine throats. The two boundaries therefore represent characteristic transition scales for the investigated dataset rather than universal pore-size thresholds.
- (3) Across the descriptive segmented-fit distributions, mean D_L , D_T , and D_B values are 2.585, 2.583, and 2.346, respectively, and describe large-pore-throat structural complexity, pore-throat scale transition, and fine-throat bottleneck characteristics. In the standardized complete-case correlation analysis ($n = 27$), D_L varies systematically with several petrophysical and MICP parameters, whereas D_T remains weakly correlated with all six tested variables ($p > 0.05$). D_B is most strongly correlated with P_{50} ($r = 0.834$, $p < 0.001$, $R^2 = 0.696$) and is also significantly related to P_d ($r = 0.714$), r_{50} ($r = -0.687$), and $\log_{10}K$ ($r = -0.673$) (all $p < 0.001$). These contrasting statistical

responses are consistent with D_L reflecting broader variations in pore-throat openness, D_T representing the scale-transition regime, and D_B serving as a sensitive indicator associated with fine-throat bottleneck restriction.

- (4) Three-dimensional network connectivity differs markedly among the representative samples. The largest connected pore-cluster fractions of S1, S2, and S3 are 90.26%, 72.56%, and 64.65%, with connected porosities of 20.12%, 8.23%, and 6.15%. K_{PNM} decreases from 64.32 to 0.850 and 0.121 mD. Systematic differences in pore-body size, throat development, and pore-throat matching are consistent with the observed contrast in flow through the connected network; geometric pore connectivity does not necessarily imply effective transport. Because the CT segmentation and PNM are constrained by voxel-scale resolution and model abstraction, these values are interpreted primarily in terms of relative network differences. Although their absolute magnitudes differ, direct-flow and PNM simulations consistently rank flow capacity as $S1 > S2 > S3$. K_{PNM} is used primarily as a network-sensitive indicator of throat-controlled flow, whereas K_{DF} provides a complementary voxel-scale flow estimate; neither value is interpreted as a unique absolute reference permeability.
- (5) Type I is characterized by low P_d and P_{50} , large r_{50} , a high intrusion contribution from the large-pore-throat-dominated interval, and favorable three-dimensional connectivity, a combination consistent with favorable storage and flow capacity. Type II retains appreciable pore-body development, but throat control is stronger and reservoir effectiveness is intermediate. Type III is characterized by high P_{50} , small r_{50} , a high contribution from the fine-throat-limited interval, and low K_{PNM} ; fine-throat bottlenecks, reduced network connectivity, and fewer effective pathways jointly restrict fluid migration. Pore-body–throat configurations shaped by deposition and diagenesis provide a primary structural basis for reservoir effectiveness in Benxi Formation tight sandstones of the Gaoqiao area. The proposed workflow therefore provides a core-scale evaluation framework for the investigated Benxi Formation sandstones; its numerical functional boundaries and discrimination performance require formation-specific re-derivation and independent validation before application to other formations or reservoir-scale prediction.

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Definition
MICP	Mercury intrusion capillary pressure
micro-CT	X-ray micro-computed tomography
PNM	Pore-network model
RMI	Rate-controlled mercury intrusion
NMR	Nuclear magnetic resonance
SEM	Scanning electron microscopy
VOI	Volume of interest
K_{DF}	Direct-flow permeability
K_{PNM}	Pore-network-model permeability

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