

Article

Occurrence Types of Chlorite and Their Association with Reservoir Quality in Emeishan Basalts

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Abstract

Volcanic reservoirs are critical deep hydrocarbon exploration targets, but the complex relationship between chlorite occurrence types and reservoir quality in mafic volcanic successions remains poorly constrained. This study investigates Emeishan basalts from Well A (southwestern Sichuan Basin) using integrated geochemical, mineralogical, and petrophysical methods. Four chlorite occurrence types are identified, with distinct Fe/(Fe+Mg) compositional variations. A three-stage alteration sequence is delineated, and a ~3 m thick tight barrier layer formed by dense matrix replacement and pervasive amygdale-filling chlorite vertically compartmentalizes the reservoir. Chlorite exerts context-dependent effects: matrix replacement and pseudomorphic chlorite generally are preferentially associated with intervals exhibiting higher porosity; fracture-filling and amygdale-filling chlorite commonly occur in intervals characterized by reduced porosity and permeability. This study proposes an occurrence-based framework for interpreting reservoir heterogeneity in mafic volcanic rocks, providing practical reference for volcanic reservoir evaluation.

Keywords: chlorite occurrence; reservoir space; Emeishan basalt; SEM-EDS; volcanic reservoir

1. Introduction

As hydrocarbon exploration expands into deep and ultra-deep strata, volcanic reservoirs have become an increasingly important global target [1–3]. The Emeishan Large Igneous Province (ELIP) is characterized by widespread basalts of great thickness and considerable resource potential. Commercial oil and gas flows have recently been discovered in the Emeishan basalts in the southwestern Sichuan Basin, confirming their prospectivity as a mafic volcanic play [4,5]. However, volcanic reservoirs are typically highly heterogeneous. Their pore systems are extensively modified by post-magmatic hydrothermal alteration, which complicates reservoir characterization and prediction [6–8].

Chlorite is the most abundant and characteristic hydrothermal alteration mineral in mafic volcanic rocks, forming throughout the syn-diagenetic to epi-diagenetic stages. It can either preserve or destroy reservoir spaces, exerting both constructive and destructive effects on reservoir quality [7,9–11]. Previous studies have largely focused on chlorite geochemistry, geothermometry, or its effects on reservoirs [12–15]. The significance of chlo-

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rite occurrence types in basalts has received comparatively little attention. Few studies have quantitatively linked chlorite occurrence types to the evolution of porosity and permeability, and a comprehensive model integrating chlorite occurrence, composition, and reservoir properties has not been established.

This study aims to (1) establish a reproducible classification scheme for chlorite occurrence types in Emeishan basalts; (2) characterize compositional variations among occurrence types; (3) evaluate the relationship between chlorite occurrence and reservoir properties; and (4) develop an occurrence-based reservoir quality model. To achieve these objectives, we integrate whole-rock geochemistry, X-ray diffraction mineralogy, SEM-EDS microanalysis, and core plug porosity–permeability measurements from Well A in the southwestern Sichuan Basin. The results of this study provide an occurrence-based framework for interpreting reservoir heterogeneity in mafic volcanic rocks, offering practical guidance for diagenetic evaluation and reservoir prediction in the ELIP and analogous volcanic basins worldwide.

2. Geological Setting

The study area is located in the southwestern Sichuan Basin, on the northwestern margin of the Yangtze Paraplatform [16]. During the Late Permian Dongwu Movement, intense mantle plume activity triggered large-scale flood basalt eruptions, forming the world-famous Emeishan Large Igneous Province [17]. The region can be divided into inner, intermediate, and outer zones, with the southwestern Sichuan Basin situated in the outer zone (Figure 1a).

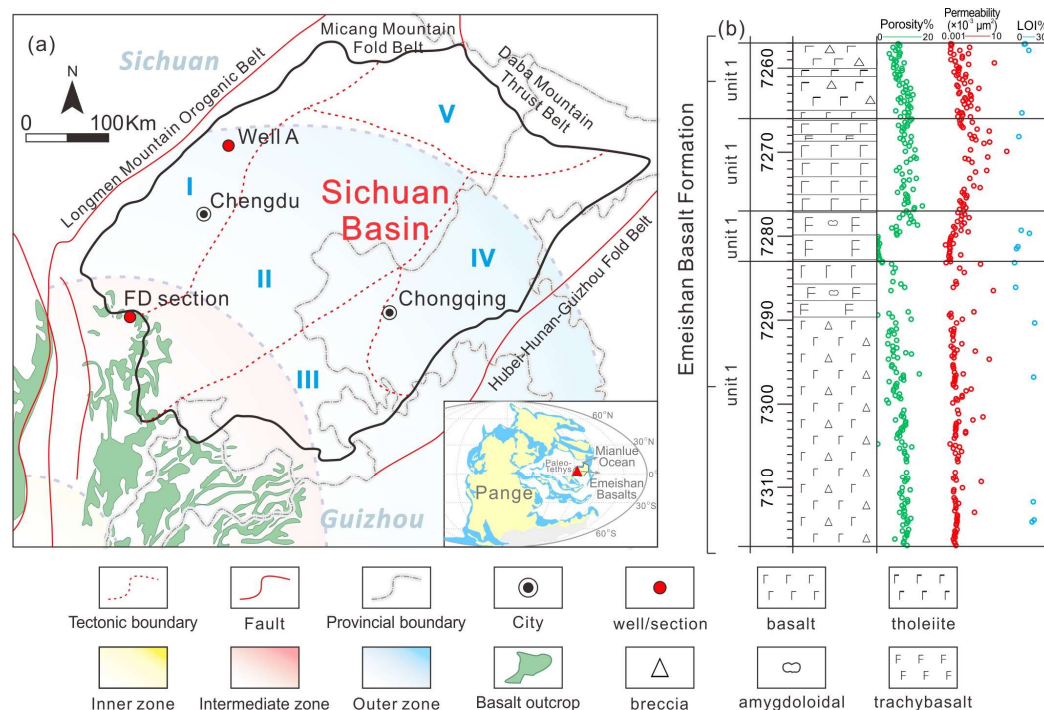


Figure 1. (a) Regional geological setting of the southwestern Sichuan Basin (after [18]) and Middle–Late Permian paleogeographic plate reconstruction (after [19]). I: the western depression; II: the central uplift; III: the southeastern gentle structural zone; IV: the eastern steep structural zone; V: the northern gentle structural zone. (b) Composite lithological column of Well A (7257–7317 m).

Primary Fe–Mg-rich minerals such as pyroxene and olivine provided abundant material for extensive later hydrothermal alteration [20,21]. After the Indosinian orogeny, regional fault systems acted as pathways for focused fluid flow. Fluids migrated along

fractures and unconformities, resulting in strong fluid–rock interactions and widespread alteration [22–25].

Well A is located in a structurally stable region of the basin (Figure 1), and it penetrated the Emeishan basalt succession from 7257 to 7317 m. The lithology is dominated by tholeiitic basalt, interbedded with basaltic breccia, amygdaloidal basalt, and trachybasalt (Figure 1b). Core and thin-section observations reveal that the rocks have been extensively altered by hydrothermal fluids, among which chloritization is the most developed, followed by carbonatization, zeolitization, and silicification. Controlled by fracture systems and primary rock textures, the alteration types and chlorite occurrences vary distinctly with depth: fracture zones and amygdale-rich intervals are dominated by filling-type chlorite, whereas relatively intact matrix intervals are dominated by replacement-type chlorite. The composite column in Figure 1b also presents depth profiles of porosity, permeability, and loss on ignition (LOI), providing the macro-scale background for subsequent alteration classification and analysis of reservoir space differentiation.

The study interval (7257–7317 m) is currently at a depth where formation temperatures are estimated at ~220 °C based on a regional geothermal gradient of ~25 °C/km [18,26]. At these temperatures, the reservoir fluid, if present, is expected to be dry gas or condensate rather than liquid oil. The late Permian Emeishan Large Igneous Province (ELIP) event provided the heat source for widespread hydrothermal circulation [18], which likely drove the chloritization and carbonatization observed in the studied basalts.

3. Materials and Methods

3.1. Materials Selection

A total of 196 core samples were collected from the Emeishan basalt interval of Well A (7257–7317 m). All samples were first examined in thin sections under a polarizing microscope to systematically document lithology, alteration characteristics, and chlorite occurrence types. Based on this comprehensive petrographic screening, representative subsamples were selected for subsequent geochemical, mineralogical, and petrophysical analyses. The selection strategy was designed to maximize coverage of (1) all four lithological alteration units; (2) the full range of alteration grades; and (3) all four chlorite occurrence types identified during the initial screening.

Whole-rock geochemistry: 19 samples covering the full LOI range (1.39–22.92 wt%) were selected, with sample size limited by analytical budget.

XRD samples were chosen from representative intervals showing contrasting alteration intensities, distributed as Unit 1 ($n = 4$), Unit 2 ($n = 4$), Unit 3 ($n = 5$), Unit 4 ($n = 3$). Potential sampling bias is discussed in Section 5.3.

EDS analyses were distributed among the four chlorite occurrence types, with 42 valid spot measurements obtained: fracture-filling ($n = 17$), matrix replacement ($n = 19$), pseudomorph ($n = 4$), amygdale-filling ($n = 2$). Pseudomorph and amygdale-filling chlorite are naturally rare in the intensely altered Well A interval.

Porosity and permeability: 236 core plugs were analyzed at ambient conditions, reflecting the routine nature and lower cost of these measurements.

3.2. Analytical Methods

Petrographic analysis: Thin sections were examined under a Leica DM2500 polarizing microscope (Leica Microsystems, Wetzlar, Germany) to determine rock types, textural features, and alteration mineral distribution.

SEM-EDS analysis: Polished samples were carbon-coated and analyzed using an FEI Quanta 650 FEG SEM (Thermo Fisher Scientific, Hillsboro, OR, USA) equipped with an X-MAX50 EDS spectrometer (Oxford Instruments, Abingdon, UK). Operating conditions:

15 kV accelerating voltage, 10 mm working distance, and 124 μ A beam current. SEM-EDS analysis provides semi-quantitative chemical data. It cannot distinguish Fe^{2+} from Fe^{3+} , and absolute concentrations of Fe and Mg carry inherent analytical uncertainty. The EDS results in this study are used exclusively for relative comparison of compositional trends among chlorite occurrence types, not for precise stoichiometric calculation.

Major and trace element analysis: Major elements were determined on a PANalytical PW2424 X-ray fluorescence spectrometer (Malvern Panalytical, Almelo, The Netherlands) using fused glass discs. Loss on ignition (LOI) was measured gravimetrically after ignition at 1000 °C. Trace elements were analyzed on an Agilent 7900 ICP-MS (Agilent Technologies, Singapore) and a 5100 ICP-OES (Agilent Technologies, Penang, Malaysia). Samples were prepared by acid digestion and lithium borate fusion prior to analysis.

X-ray diffraction: Bulk and clay fraction mineralogy were analyzed on a Rigaku SmartLab diffractometer (Cu $K\alpha$ radiation, 5–70° 2 θ , 0.02° step size, 1.5 s per step; Rigaku Corporation, Tokyo, Japan). Rietveld refinement was performed using RockQuan-2021 (developed by Lin Xisheng, Research Institute of Petroleum Exploration and Development, Beijing, China) with NIST SRM 676a alumina powder (corundum, α - Al_2O_3 ; National Institute of Standards and Technology, Gaithersburg, MD, USA) serving as the external standard, with a crystalline phase detection limit of ~1 wt%. Clay minerals were analyzed after ethylene glycol solvation and heating treatments.

Porosity and permeability measurements: Porosity was measured using a KX-07F gas porosimeter (Coretest Systems, Beijing, China), and permeability using a DX-07G gas permeameter (Coretest Systems, Beijing, China), with helium and nitrogen as working media at ambient conditions. Core samples were weighed using an electronic balance (ME204E, Mettler Toledo, Zurich, Switzerland) for pre-treatment.

Enrichment factors (EFs) were calculated to evaluate element mobility relative to unaltered protolith, using Zr as the immobile reference element [27,28]:

$$EF = (\text{Element}_x/\text{Zr})_{\text{sample}} / (\text{Element}_x/\text{Zr})_{\text{Background}}$$

where Element_x is the target element content in the sample; Background refers to the average composition of unaltered Emeishan basalt. $EF \approx 1$ indicates negligible mobilization; $EF > 1$ indicates enrichment; $EF < 1$ indicates depletion.

Isocon analysis was used to quantify element mass transfer during alteration, taking the average unaltered Emeishan basalt composition as protolith and Al_2O_3 and TiO_2 as immobile reference elements [29]. The isocon slope (k) measures mass change relative to protolith: $k = 1$ indicates isochemical conditions; $k < 1$ indicates net mass gain.

3.3. Chlorite Identification and Classification Criteria

Chlorite identification was performed via an integrated petrographic and geochemical approach, following standard criteria for clay minerals in altered volcanic rocks [30,31]:

Optical criteria: Under plane-polarized light, chlorite shows pale-green to dark-green pleochroism; under cross-polarized light, it exhibits typical first-order-grey to anomalous-blue interference colors, with low relief and perfect cleavage.

Morphological criteria: Under SEM, chlorite occurs as characteristic hexagonal platy, fibrous, or rosette aggregates, consistent with typical chlorite crystal habits.

Compositional criteria: EDS semi-quantitative analysis shows the mineral is dominated by Si, Al, Fe and Mg, with Si/Al ratios of 1.4–1.6, falling within the compositional range of trioctahedral chlorite. Other Fe-bearing silicates (e.g., epidote, celadonite, smectite) were excluded based on their distinct morphological and compositional features.

XRD verification: Oriented clay fraction XRD analysis confirms that chlorite accounts for 99%–100% of the clay fraction in all samples, further verifying that chlorite is the dominant clay-sized alteration mineral.

Chlorite occurrence was classified based on four criteria observable in thin section and SEM images: (i) host site (fracture, vesicle, phenocryst, or matrix); (ii) crystal morphology (fibrous, platy, or hexagonal); (iii) relationship to precursor minerals (replacement vs. filling); and (iv) presence of associated minerals (e.g., calcite, quartz). A decision tree summarizing the classification scheme is shown in Figure 2.

The classification follows a hierarchical logic. First, chlorite occurring exclusively within microfractures or macrofractures is classified as fracture-filling chlorite. Second, chlorite not located in fractures, disseminated in the groundmass matrix without preserving precursor mineral morphology, is classified as matrix replacement chlorite. Third, chlorite not belonging to the above two types, which fully preserves the euhedral to subhedral crystal morphology of primary olivine or pyroxene phenocrysts, is classified as pseudomorphous chlorite. Finally, chlorite filling primary volcanic vesicles (amygdales) is classified as amygdale-filling chlorite.

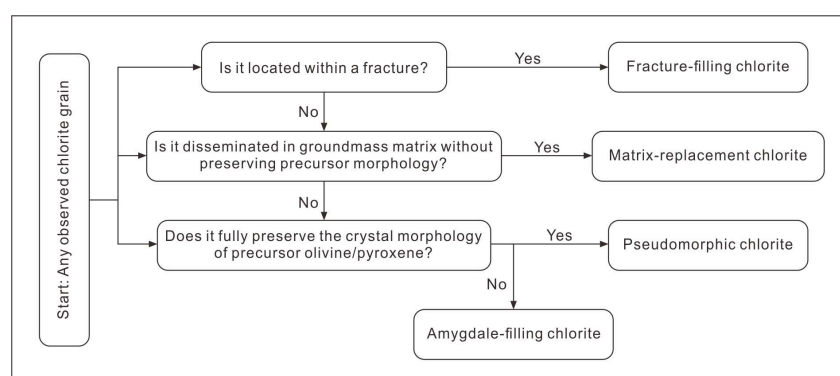


Figure 2. Decision tree for reproducible classification of four chlorite occurrence types, based on petrographic and SEM observations.

4. Results

4.1. Whole-Rock Geochemistry and Alteration Grade Classification

4.1.1. Loss on Ignition and Element Mobility

The LOI values of the 19 whole-rock samples range from 1.39 to 22.92 wt% (Table 1), reflecting highly heterogeneous hydrothermal alteration. Enrichment factors (EFs) normalized to Zr were calculated as described in Section 3.2, using the unaltered background composition defined from 10 fresh FD section samples (Supplementary Table S1). Noteworthy, the LOI-based alteration grade reflects comprehensive alteration intensity rather than pure chloritization, as LOI incorporates both structural hydroxyl from chlorite and CO₂ from carbonates, and the strong alteration interval is dominated by carbonatization with superimposed chloritization.

Table 1. Alteration grade classification and isocon parameters.

Alteration Grade	LOI (wt%)	Number	Isocon Slope k	95% CI	R ²	Mass Change	EF Characteristics	Dominant Process
Weak	<5%	3	≈1.02	(0.98, 1.06)	0.99	~−1.5% gain	All elements ≈ 1	Near-fresh
Moderate	5%–15%	9	≈0.91	(0.85, 0.97)	0.99	~10% gain	Ca > 1, K/Na < 1	Chloritization
Strong	>15%	7	≈0.62	(0.57, 0.68)	0.98	~60% gain	Ca ≫ 1, K/Na ≪ 1	Carbonatization

Plotting CaO-EF (carbonatization proxy) and K₂O-EF (alkali depletion proxy) against LOI (Figure 3a) reveals two distinct natural inflection points at 5 wt% and 15 wt% LOI, rather than a continuous trend:

LOI < 5 wt% ($n = 3$): CaO-EF and K₂O-EF remain near 1, indicating negligible element mobilization; 5–15 wt% LOI ($n = 9$): CaO-EF increases to 1–3, K₂O-EF decreases to 0.1–0.5, marking moderate element differentiation; and LOI > 15 wt% ($n = 7$): CaO-EF jumps to 10–40, K₂O-EF drops below 0.1, indicating intense Ca enrichment and alkali depletion.

The enrichment factor spider diagram (Figure 3b) shows three distinct sample clusters corresponding to the three LOI ranges, with consistent internal EF patterns.

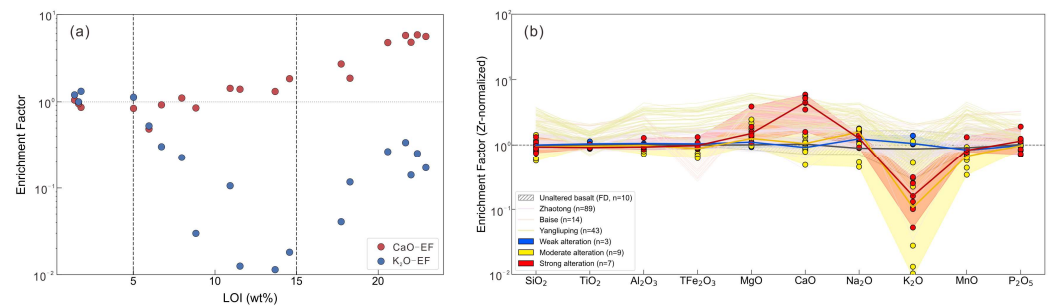


Figure 3. (a) CaO-EF and K₂O-EF (Zr-normalized) versus LOI for the 19 Well A samples, with dashed lines marking transition thresholds at 5% and 15%. (b) Enrichment factor spider diagram normalized to Zr. The background reference line (EF = 1) is based on the 10 FD section samples (this study). Literature data from Zhaotong [32], Baise [33] and Yangliuping [34] (grey symbols) are plotted for regional context only and were not included in the background calculation.

4.1.2. Alteration Grade Classification

Cross-plots of Zr vs. Al₂O₃ and Zr vs. TiO₂ for all 29 samples (Supplementary Figure S1) show overall good positive correlations, supporting the relative immobility of these elements during alteration. Al₂O₃ and TiO₂ are therefore used as the primary immobile references for isocon analysis.

Based on the two natural inflection points, the samples are divided into three objective alteration grades (Table 1): weak (LOI < 5%, $n = 3$), moderate (LOI 5%–15%, $n = 9$), and strong (LOI > 15%, $n = 7$). The thresholds do not represent pure chloritization intensity. LOI includes both OH-bearing chlorite and carbonate-derived CO₂.

Using the average unaltered Emeishan basalt composition as a protolith reference and Al₂O₃ and TiO₂ as immobile elements, element mobility was quantified for the three grades via isocon analysis and EF calculations (Figure 3; Table 1):

Weak alteration: Isocon slope $k \approx 1.02$ (Figure 4a), nearly coinciding with the 1:1 line, indicating an isochemical process with no net mass change. Moderate alteration: $k \approx 0.91$ (Figure 4b), corresponding to ~10% net mass gain. CaO plots above the isocon, Na₂O and K₂O below, forming a “Ca-enrichment–alkali-depletion” pattern, while SiO₂, Fe₂O₃, and MgO remain near the isocon, reflecting chlorite-alteration-dominated conditions. Strong alteration: $k \approx 0.62$ (Figure 4c), corresponding to ~60% net mass gain. CaO is highly enriched, Na₂O and K₂O are almost completely depleted, and SiO₂ falls below the isocon due to carbonate dilution, indicating carbonate-dominated conditions.

The progressive decrease in isocon slope and increasing differentiation of element mobility patterns across the three grades are consistent with the thresholds identified from EF trends, providing independent mass balance support for the classification.

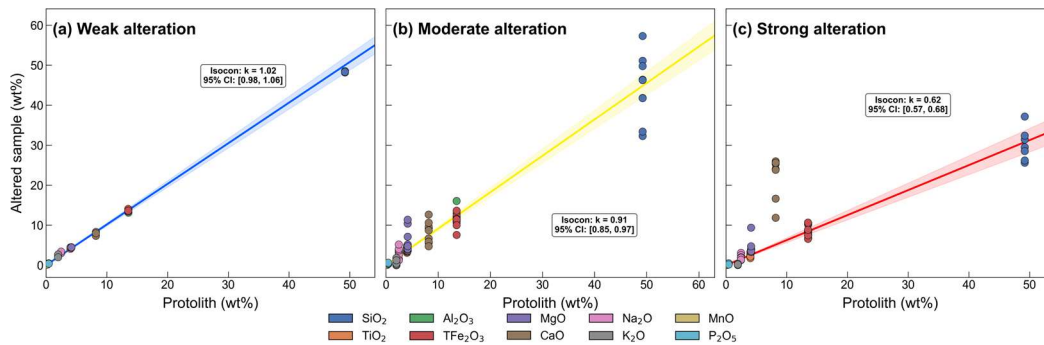


Figure 4. Isocon scatter diagrams for the three alteration grades, with Al_2O_3 and TiO_2 as immobile reference elements. (a) Weak alteration; (b) Moderate alteration; (c) Strong alteration. Notes: Unaltered background composition is based on 10 fresh basalt samples from the FD section (see Supplementary Table S1). Isocon slopes and 95% confidence intervals (CIs) were calculated by weighted least-squares regression through the origin using Al_2O_3 and TiO_2 as immobile reference elements. R^2 values indicate the goodness of fit of the isocon. Mass change ($\Delta M/M^0 = 1/k - 1$; positive values indicate net mass gain relative to protolith. Weak alteration shows a slight mass loss (~1.5%), which is within analytical uncertainty and considered negligible.

4.2. Mineral Assemblage and Chlorite Content

Systematic core and thin-section observations divide the studied interval into four lithological alteration units (Figure 5). Bulk mineral compositions from 16 XRD samples agree well with this zonation, and the full dataset is summarized in Supplementary Table S2.

Unit 1 (7257–7266 m): Strongly altered plagioclase-phyric basalt containing limestone breccia. Residual feldspar phenocrysts are common, and brecciation is widespread. Bulk mineralogy consists mainly of calcite (24.2%–43.0%) and chlorite (28.1%–47.1%), both showing wide variations reflecting heterogeneous alteration.

Unit 2 (7266–7277 m): Strongly altered basalt with balanced albite–calcite–chlorite assemblages. Primary igneous fabric is partially preserved. Chlorite content reaches the highest values in the profile (mean ~42 wt%, maximum 60.0 wt%), while calcite content is significantly lower than in Unit 1. Samples at 7265.32 m (47.1 wt% chlorite) and 7257.13 m (39.8 wt% chlorite) are representative of this unit.

Unit 3 (7277–7283 m): Brecciated trachybasalt in the upper part, and trachybasalt with abundant amygdals filled by albite, calcite, and chlorite in the lower part. The lower part (7280–7283 m) contains mainly cryptocrystalline alteration minerals and corresponds to the low-porosity, low-permeability barrier layer described in Section 4.4. Chlorite content varies between 25.8 and 49.9 wt%, and calcite content is typically below 20 wt%.

Unit 4 (7283–7317 m): Intensely fractured altered basalt containing bioclastic limestone breccia, showing cryptoexplosive breccia features. Calcite content increases sharply to 41.6–46.5 wt%, while chlorite content decreases to 22.5–34.4 wt%. Carbonatization becomes the dominant alteration type, replacing chlorite alteration. Samples at 7290.33 m, 7296.78 m, and 7313.87 m fall within this unit, consistent with the strong alteration grade defined in Section 4.1.

The bulk mineral assemblage of the 16 XRD samples includes quartz (3.2%–49.4%), plagioclase (7.5%–49.7%), calcite (0%–65.8%), and clay minerals (22.5%–60.0%). Oriented clay fraction XRD analysis confirms that chlorite makes up 99%–100% of the clay fraction in all samples; thus, bulk clay mineral content effectively equals chlorite content. Stacked mineral abundance profiles (Figure 4) show a clear inverse relationship between calcite and chlorite: Unit 2, with the highest chlorite abundance, has the lowest calcite content, while Unit 4, with extensive calcite precipitation, shows the weakest chlorite alteration.

Chlorite content and whole-rock TFe_2O_3 show generally similar variations along the depth profile.

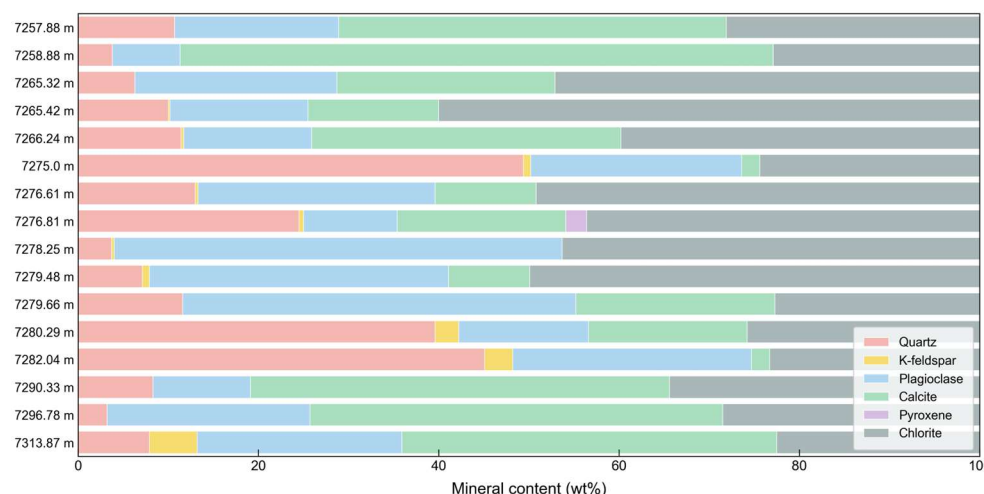


Figure 5. Stacked bar chart of XRD mineral compositions with depth annotations.

4.3. Chlorite Occurrence Types and Micro-Area Composition

4.3.1. Chlorite Occurrence and Mineralogical Characteristics

Integrated optical microscopy and SEM-BSE observations identify four distinct chlorite occurrence types (Figure 6):

- (1) **Fracture-filling chlorite:** Under plane-polarized light, microfractures are sequentially filled from margin to core by pale-yellow chlorite, albite, and calcite (Figure 6a). SEM images show chlorite crystals growing perpendicularly to fracture walls, forming comb-like textures; they are needle-like or fibrous (1–20 μm wide), extending along or normal to the fracture direction (Figure 6b,c). This type is more abundant in Units 1 and 4, and less common in Units 2 and 3.
- (2) **Matrix replacement chlorite:** In plane-polarized light, brownish-green turbid chlorite is disseminated throughout the matrix (Figure 6d). Under SEM, it appears as tiny platy (hexagonal) crystals (1–10 μm in diameter) that are randomly oriented or form moss-like aggregates (Figure 6e,f). This type is most abundant in Units 1 and 2.
- (3) **Pseudomorphic chlorite:** Under crossed polars, plagioclase crystal outlines are clearly visible but show uneven interference colors, indicating partial compositional alteration (Figure 6g). SEM observations reveal that chlorite completely inherits the morphology of precursor minerals, commonly exhibiting rhombic olivine or short prismatic pyroxene outlines (Figure 6h,i). Interiors are entirely replaced by micro-crystalline chlorite aggregates. This type occurs mainly in Units 2 and 3.
- (4) **Amygdale-filling chlorite:** Under crossed polars, chlorite filling amygdaloids displays blue interference colors and an uneven distribution (Figure 6j). In SEM, fibrous crystals grow inward from vesicle walls or radiate from a center, forming rosette or spherulitic aggregates (Figure 6k,l). It is commonly intergrown with quartz and calcite. This type is concentrated in Unit 3 (7280–7283 m).

4.3.2. Chlorite Micro-Area Composition

A total of 42 valid EDS spot measurements were obtained from the four chlorite occurrence types (Table 2), and the detailed raw data are provided in Supplementary Table S3. Because EDS cannot distinguish Fe^{2+} from Fe^{3+} and has limited precision for light elements, the reported $\text{Fe}/(\text{Fe}+\text{Mg})$ atomic ratios are semi-quantitative and are used only for relative comparison among occurrence types.

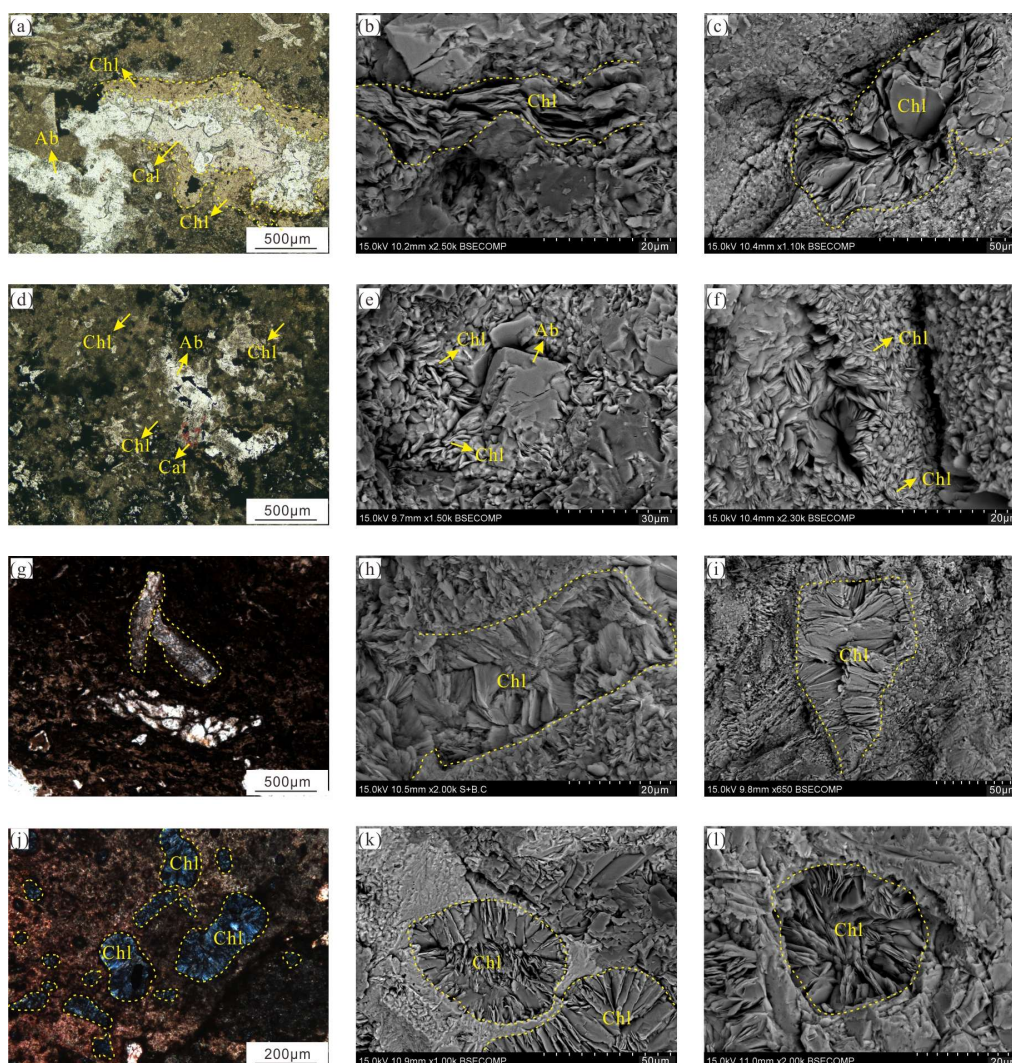


Figure 6. Chlorite occurrence types in Well A. (a–c) Fracture-filling chlorite (7274.43 m, 7257.16 m, 7283.16 m). (d–f) Matrix replacement chlorite (7277.19 m, 7286.48 m, 7293.69 m). (g–i) Pseudomorphous chlorite (7263.37 m, 7264.71 m, 7315.94 m). (j–l) Amygdale-filling chlorite (7281.84 m, 7270.85 m, 7280.06 m). Ab—albite; Cal—calcite; Chl—chlorite. Areas circled by yellow dashed lines represent chlorite.

Fracture-filling chlorite ($n = 17$) shows $\text{Fe}/(\text{Fe}+\text{Mg})$ ranging from 0.31 to 0.80 (median = 0.49). Matrix replacement chlorite ($n = 19$) ranges from 0.33 to 0.71 (median = 0.45). For pseudomorphous chlorite ($n = 4$), the ratio varies between 0.39 and 0.89 (median = 0.48). Only two analyses were obtained for amygdale-filling chlorite ($n = 2$), with values of 0.39 and 0.55. Si/Al ratios show no systematic differences among the four types (range 1.43–1.61, Figure 7a, Table 2).

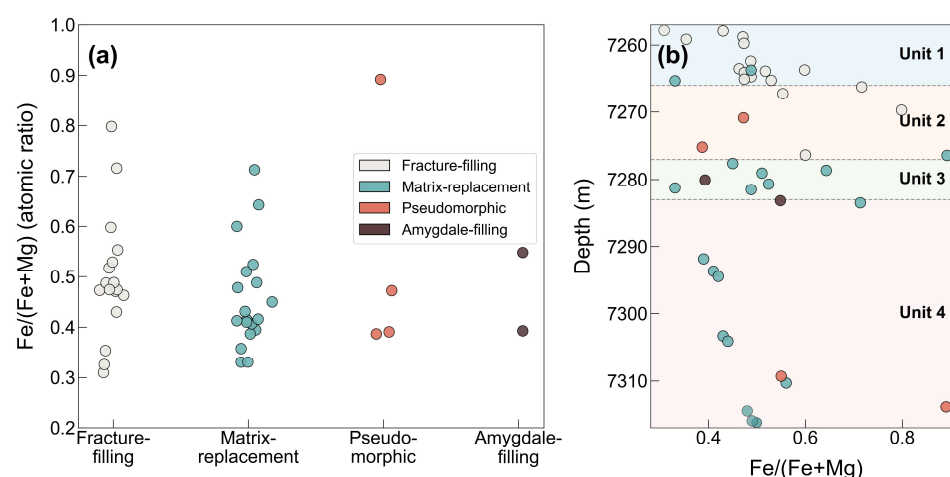
Pseudomorphous chlorite ($n = 4$) and amygdale-filling chlorite ($n = 2$) are naturally rare in the studied interval, resulting in very limited EDS datasets. Due to the insufficient sample size, no statistically robust differentiation of compositional parameters can be performed among occurrence types. The compositional features of these two types are presented solely as preliminary descriptive observations, not as statistically validated conclusions.

Plotting the 42 measurements against depth (Figure 7b) reveals an ordered vertical succession of chlorite occurrence types, but the small sample sizes for some types preclude robust correlation with depth.

Table 2. EDS compositional statistics of chlorite by occurrence type (atomic ratios).

Occurrence Type	Number	Fe/(Fe+Mg) Mean $\pm$ SD	Range	Si/Al Mean $\pm$ SD
Fracture-filling	17	0.52 ± 0.13	0.31–0.80	1.58 ± 0.17
Matrix replacement	19	0.46 ± 0.09	0.33–0.71	1.61 ± 0.15
Pseudomorph	4	0.54 ± 0.23	0.39–0.89	1.43 ± 0.09
Amygdale-filling	2	/	0.39, 0.55	1.58, 1.52

$n = 4$: range and median reported for descriptive purposes only; no statistical inference. $n = 2$: only two measurements, reported as individual values.

**Figure 7.** (a) Fe/(Fe+Mg) scatter plot by occurrence type; (b) Fe/(Fe+Mg) depth profile with lithological alteration unit bands and unit boundary dashed lines.

In summary, no robust compositional distinction among the four chlorite occurrence types can be demonstrated based on the current EDS dataset. The observed trends in Fe/(Fe+Mg) range are only tentatively suggested and require verification with larger sample sets and higher-precision analytical methods.

Chlorite geothermometry was considered for this study, but was not applied. Traditional chlorite geothermometers require accurate Fe²⁺ contents and full structural formula calculations, neither of which can be reliably obtained from semi-quantitative EDS data with unresolved iron valence. Application of these data to geothermometry would produce highly unreliable temperature estimates.

4.4. Petrophysical Characteristics

Porosity and permeability measurements on 236 core plugs using helium and nitrogen as working fluids under ambient laboratory conditions (room temperature, atmospheric pressure). All reported permeability values are air permeability at zero effective stress and do not represent in situ reservoir permeability. Under reservoir stress, permeability is likely 1–2 orders of magnitude lower [22]. The data are used primarily for relative comparison between depth intervals.

Porosity varies between 0.18% and 14.47% and permeability between 0.0026 and $8.77 \times 10^{-3} \mu\text{m}^2$. Most samples fall in the low-porosity, low-permeability range. Some samples with relatively low porosity show higher permeability, suggesting a minor contribution from microfractures.

The porosity–permeability relationship plotted against depth (Figure 8), with depth represented by a color scale, reveals vertical zonation of petrophysical properties consistent with the lithological-alteration units defined in Section 4.2. The statistical petrophysical characteristics of Units 1–4 are listed in Table 3 (detailed raw data in Supplementary Table S4).

Unit 1 (7257–7266 m): Porosity varies between 4.64% and 10.71% (mean $\sim 7.1\%$) and permeability between 0.006 and $8.77 \times 10^{-3} \mu\text{m}^2$ (mean $\sim 0.36 \times 10^{-3} \mu\text{m}^2$). This unit shows significant petrophysical heterogeneity and contains the highest single permeability value in the profile ($8.77 \times 10^{-3} \mu\text{m}^2$ at 7259.37 m).

Unit 2 (7266–7277 m): Porosity varies between 3.18% and 14.47% (mean $\sim 8.5\%$), and permeability between 0.003 and $3.99 \times 10^{-3} \mu\text{m}^2$ (mean $\sim 0.25 \times 10^{-3} \mu\text{m}^2$). This unit has the highest mean porosity in the profile.

Unit 3 (7277–7283 m): This unit shows clear internal differentiation. The upper part (7277–7280 m) has porosity of 4.76%–12.94% (mean $\sim 7.8\%$) and permeability of 0.010–0.112 $\times 10^{-3} \mu\text{m}^2$ (mean $\sim 0.034 \times 10^{-3} \mu\text{m}^2$). The lower part (7280–7283.8 m) shows an abrupt drop in porosity to 0.18%–1.83% (mean $\sim 1.04\%$) and permeability to 0.0026–0.033 $\times 10^{-3} \mu\text{m}^2$ (mean $\sim 0.008 \times 10^{-3} \mu\text{m}^2$), forming a ~ 3 m thick tight barrier layer.

Unit 4 (7283–7317 m): Porosity varies between 3.18% and 13.50% (mean $\sim 7.8\%$) and permeability between 0.005 and $7.41 \times 10^{-3} \mu\text{m}^2$ (mean $\sim 0.44 \times 10^{-3} \mu\text{m}^2$). Excluding the barrier interval, this unit has slightly higher mean permeability than Units 1 and 2.

Table 3. Summary of porosity and permeability measurements by lithological alteration unit (Well A, ambient conditions).

Unit	Depth (m)	Porosity (%)	Permeability ($\times 10^{-3} \mu\text{m}^2$)
Unit1	7257–7266	4.64–10.71 (7.1 ± 1.8)	0.006–8.77 (0.36 ± 1.02)
Unit2	7266–7277	3.18–14.47 (8.5 ± 2.5)	0.003–3.99 (0.25 ± 0.67)
Unit3	7277–7280	4.76–12.94 (7.8 ± 2.1)	0.010–0.112 (0.034 ± 0.028)
Unit4	7280–7283.8	0.18–1.83 (1.04 ± 0.58)	0.0026–0.033 (0.008 ± 0.010)
Unit5	7283–7317	3.18–13.50 (7.8 ± 2.3)	0.005–7.41 (0.44 ± 1.21)

The barrier layer (7280–7283.8 m) is the most prominent anomaly in the petrophysical profile. With a mean porosity of $\sim 1.04\%$ and a mean permeability of $\sim 0.008 \times 10^{-3} \mu\text{m}^2$, it is roughly one order of magnitude lower than the overlying and underlying intervals. This layer occurs in the lower part of Unit 3 and vertically compartmentalizes the reservoir into upper and lower sections.

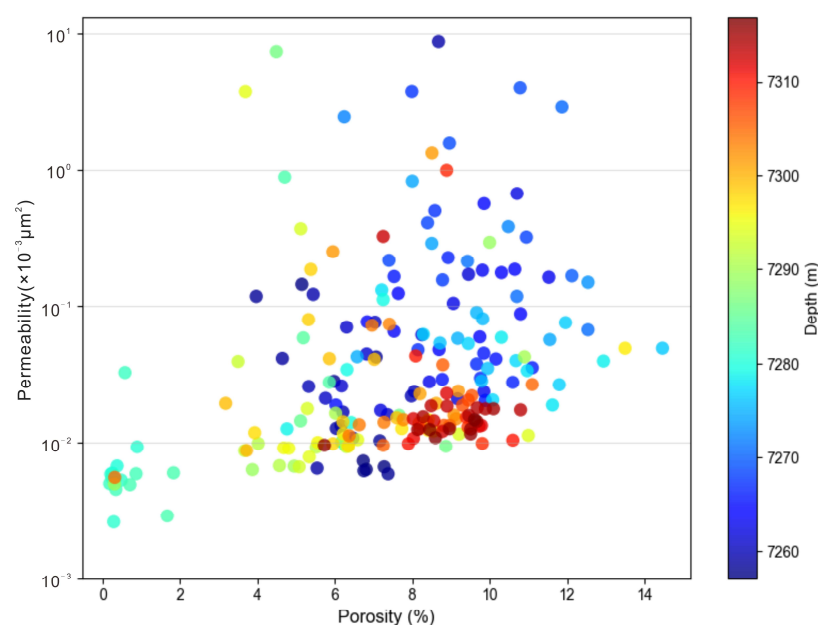


Figure 8. Porosity–permeability relationship with depth as color scale.

5. Discussion

5.1. Effects on Chlorite Distribution and Evolution

The vertical distribution of chlorite occurrence types is largely independent of lithological boundaries (Figure 7b), indicating that chloritization was controlled by the combined effects of fluid evolution, thermal history, and structural modification rather than primary lithology alone [11,14,35]. Multi-stage chlorite formation in volcanic reservoirs, driven by post-emplacement cooling and hydrothermal modification of primary minerals [36,37], is genetically tied to the ELIP hydrothermal event, with Late Permian mantle plume heat flow powering large-scale basalt hydrothermal circulation.

Matrix replacement chlorite is interpreted as the earliest chloritization product, formed during post-eruptive cooling through alteration of volcanic glass and fine-grained groundmass under relatively closed-system conditions [38]. With increasing hydrothermal circulation, fluid–rock interaction became more intense and preferentially affected ferromagnesian phenocrysts, producing pseudomorphic chlorite through dissolution–precipitation processes while preserving precursor crystal morphologies [39].

A later stage of chloritization was associated with fracture-controlled fluid migration. Reactivation of pre-existing structures during regional tectonic events likely enhanced permeability and facilitated localized mineral precipitation along fracture networks [13,40]. The common association of fracture-filling chlorite with carbonate minerals suggests progressive cooling and chemical evolution of hydrothermal fluids [41,42]. Amygdale-filling chlorite represents the latest alteration stage and reflects localized precipitation within pre-existing vesicular pore systems [43]. Therefore, chlorite occurrence records a transition from early rock-buffered alteration to structurally focused fluid flow during reservoir evolution.

5.2. Implications of Chlorite Occurrence for Reservoir Quality

The links between chlorite occurrence types and reservoir properties described in this section are qualitative, established based on interval-scale petrophysical trends and petrographic interpretation, not on quantitative one-to-one matching at the individual plug scale.

The four occurrence types generally exert complex and context-dependent effects on reservoir quality, depending on their growth mechanisms, spatial settings, and degree of filling. This observation is consistent with previous studies showing that chlorite may either preserve or destroy reservoir properties depending on its textural relationship with pore systems [8,9,44].

Matrix replacement and pseudomorphic chlorite are generally associated with improved pore development. Their formation may generate intercrystalline and intracrystalline microporosity while preserving parts of the original rock framework, thereby contributing to storage capacity [44,45]. In contrast, extensive chloritization can progressively reduce pore connectivity when newly formed chlorite aggregates occupy available pore space.

Fracture-filling chlorite primarily affects permeability through fracture occlusion [46,47]. Partially mineralized fractures may remain effective flow conduits, whereas complete sealing substantially restricts fluid migration. Amygdale-filling chlorite generally exerts a negative influence on reservoir performance because mineral precipitation within vesicles reduces effective pore volume and contributes little to pore connectivity [47]. These observations indicate that reservoir quality is governed by the spatial configuration and interaction of chlorite occurrence types rather than by total chlorite content alone.

To make the reservoir quality classification reproducible, explicit numerical thresholds are defined based on the petrophysical distribution of the study interval and conven-

tional volcanic reservoir evaluation criteria (Figure 9). These thresholds are defined based on the statistical distribution of petrophysical data in the study interval, and are consistent with conventional classification criteria for volcanic tight reservoirs in the Sichuan Basin and analogous basins [3,48,49].

Favorable reservoir: porosity $> 8.0\%$ and permeability $> 0.2 \times 10^{-3} \mu\text{m}^2$, typically developed in intervals with abundant pseudomorphic chlorite and incompletely filled fractures; ordinary reservoir: porosity $3.0\%–8.0\%$ and permeability $0.01–0.2 \times 10^{-3} \mu\text{m}^2$, mainly composed of matrix replacement chlorite with moderate alteration intensity; and tight barrier: porosity $< 2.0\%$ and permeability $< 0.01 \times 10^{-3} \mu\text{m}^2$, corresponding to intervals with dense matrix replacement and pervasive amygdale-filling chlorite.

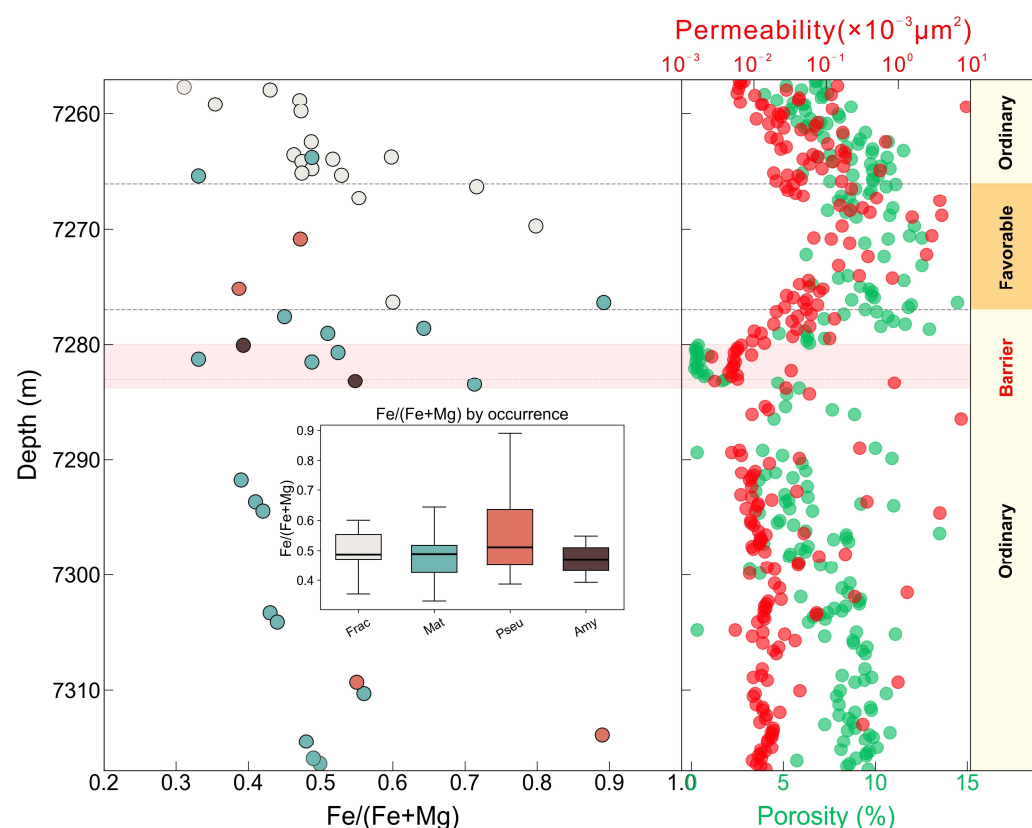


Figure 9. Integrated depth profile of chlorite composition, petrophysical properties, and reservoir quality assessment.

5.3. Implications for Reservoir Architecture

The occurrence-based distribution of chlorite contributes directly to reservoir heterogeneity at both pore and reservoir scales. A ~ 3 m thick tight zone at the base of Unit 3 hydraulically separates the basalt reservoir into upper and lower segments with divergent hydrocarbon accumulation and production characteristics (Figure 9). Pervasive pore-filling chlorite forms local permeability baffles that further strengthen reservoir compartmentalization [11,12,50].

Based on the integrated analysis of chlorite occurrence types and petrophysical properties (Figure 8), Unit 2 appears to be the most favorable reservoir target, combining the highest mean porosity ($\sim 8.5\%$), moderate permeability, and a favorable assemblage of pseudomorphic and incompletely filled fracture-filling chlorite. Unit 1 also shows good reservoir potential in intervals where fractures are only partially sealed by chlorite. Unit 4 exhibits high porosity associated with matrix replacement chlorite, but its permeability is generally lower than that of Unit 1 and Unit 2.

From an exploration perspective, this study proposes a revised occurrence-based evaluation framework for mafic volcanic reservoirs, which addresses the novelty gap that most previous studies treated chlorite as a single alteration variable without distinguishing occurrence types. The core implication is that no single chlorite occurrence type can be universally classified as “favorable” or “unfavorable”; instead, reservoir quality depends on the specific combination of occurrence. These results suggest that characterization of chlorite occurrence should be incorporated into reservoir evaluation workflows because occurrence-based analysis provides more meaningful information than mineral abundance alone.

This framework clarifies chlorite’s dual role in volcanic reservoirs and offers a petrography-based reservoir quality prediction tool. Beyond the ELIP, this model applies to global chloritization-dominated mafic volcanic successions, aiding reservoir heterogeneity analysis.

Future work should carry out plug-scale modal quantification of chlorite occurrence types via image analysis to establish a one-to-one dataset matching petrophysical properties. With a suitably structured paired dataset, multivariate statistical methods or machine learning approaches (e.g., multiple regression, random forest) can be applied to quantitatively disentangle the contributions of different controlling factors to reservoir quality.

6. Conclusions

The following conclusions can be drawn from this study:

- (1) Four chlorite occurrence types were identified in the Emeishan basalt reservoir, including matrix replacement, pseudomorphic, fracture-filling, and amygdale-filling chlorite. Their distribution records a multi-stage chloritization history involving post-eruptive alteration, hydrothermal fluid–rock interaction, and fracture-controlled mineralization.
- (2) Chlorite exerts contrasting effects on reservoir properties depending on its occurrence. Matrix replacement and pseudomorphic chlorite are generally associated with pore development, whereas amygdale-filling chlorite commonly reduces reservoir quality. The effect of fracture-filling chlorite depends on the degree of fracture sealing.
- (3) Chlorite occurrence is an important control on reservoir heterogeneity and compartmentalization. Intervals containing pseudomorphic chlorite and partially preserved fracture networks represent the most favorable reservoir targets, highlighting the importance of occurrence-based chlorite characterization in volcanic reservoir evaluation.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/min16070684/s1>, Figure S1: Cross-plots of (a) Zr vs. Al_2O_3 and (b) Zr vs. TiO_2 for the 10 FD background samples (grey) and 19 Well A samples (coloured by alteration grade). Overall positive correlations indicate that Zr, Al_2O_3 and TiO_2 can be used as immobile references for mass-balance calculations. Table S1: Major and trace element compositions for enrichment factor (EF) calculation. Table S2: Whole-rock mineral X-ray diffraction analysis. Table S3: Chlorite EDS Analysis: Atomic Percentage Data. Table S4: Porosity and Permeability Data.

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