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«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық рефеpативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық рефеpативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылымды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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COMPREHENSIVE EVALUATION OF HYDROCHLORIC ACID TREATMENT EFFICIENCY FOR PRODUCTIVITY ENHANCEMENT IN WESTERN KAZAKHSTAN TERRIGENOUS RESERVOIRS

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Abstract. *Relevance.* The development of hard-to-recover oil reserves in tight fractured terrigenous reservoirs remains a major challenge for the oil and gas industry of Western Kazakhstan due to low matrix permeability, complex mineral composition, and unfavorable geomechanical conditions. *Objective.* This study aims to precisely substantiate the selection of an effective stimulation technology for a newly discovered, deeply buried fractured terrigenous reservoir through an integrated laboratory and geomechanical assessment. *Methods.* A multidisciplinary workflow was applied, including X-ray computed tomography, lithological and petrographic analyses, scanning electron microscopy with energy-dispersive spectroscopy, geomechanical testing, acid–rock interaction studies, and dynamic filtration experiments under reservoir conditions. *Results.* CT imaging revealed that fluid flow is controlled predominantly by a network of vertical and subvertical fractures, whereas effective intergranular porosity is negligible. Geomechanical modeling indicated a reverse stress regime at depth, which limits the effectiveness of conventional hydraulic fracturing because of the tendency to generate horizontal fractures rather than vertical ones under high breakdown pressures. Detailed laboratory experiments performed on 117 core samples demonstrated that HF-based acid systems promote the rapid formation of secondary precipitates, including calcium fluorides and fluorosilicates, resulting in severe pore-space blockage and permeability impairment within the matrix. In contrast, an optimized 12 % hydrochloric acid solution selectively dissolved calcite fracture fillings with minimal secondary mineral precipitation. Dynamic core-flooding tests, conducted under realistic reservoir temperatures and confining pressures, confirmed a substantial permeability enhancement of fractured samples, from 0.3×10^{-3} to 330×10^{-3} μm^2. *Conclusions.* The primary scientific novelty of this study lies in the comprehensive integration of tomographic, mineralogical, geomechanical, and filtration data to establish a scientifically grounded framework for stimulation technology selection. The findings demonstrate that hydrochloric acid treatment is a highly effective alternative to hydraulic fracturing in fractured terrigenous reservoirs and provide critical practical guidance for the development of analogous tight sandstone reservoirs under similar geological and geomechanical conditions.

Keywords: fractured terrigenous reservoir, hydrochloric acid treatment, geomechanical modeling, reverse stress mode, oil production intensification

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БАТЫС ҚАЗАҚСТАННЫҢ ЖАРЫҚШАҚТЫ ТЕРРИГЕНДІ КОЛЛЕКТОРЛАРЫНЫҢ ӨНІМДІЛІГІН АРТТЫРУ ҮШІН ТҰЗ ҚЫШҚЫЛЫМЕН ӨҢДЕУ ТИІМДІЛІГІН КЕШЕНДІ БАҒАЛАУ

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Аннотация. *Өзектілігі.* Тығыз жарықшақты терригендік коллекторға коллекторларға шоғырланған қиын өндірілетін мұнай қорларын игеру Батыс Қазақстанның мұнай-газ саласындағы ең өзекті мәселелерінің бірі болып табылады. Мұндай объектілерді игерудің тиімділігі матрицаның төмен өтімділігімен, тау жыныстарының күрделі минералдық құрамымен және қолайсыз геомеханикалық жағдайлармен айтарлықтай күрделене түседі. *Мақсаты.* Кешенді зертханалық және геомеханикалық талдау негізінде жаңа жарықшақты терригендік коллектор үшін өнімділікті ынталандыру технологиясын таңдауды ғылыми түрде дәлелдеу осы зерттеудің мақсаты болып табылады. *Әдістері.* Қойылған міндетті шешу үшін келесі пәнаралық тәсілдер қолданылды, рентгендік компьютерлік томография, литологиялық-петрографиялық зерттеулер, энергия-дисперсиялық талдауы бар сканерлеуші электронды микроскопия, геомеханикалық сынақтар, қышқылдық жүйелердің ерігіштігін зерттеу және қабат жағдайларындағы динамикалық сүзілгіштік эксперименттері. *Нәтижелері.* Компьютерлік томография нәтижелері қабат флюидтерінің сүзілуі негізінен тік және субвертикальды жарықшақтар жүйесімен бақыланатынын, ал тиімді түйіршікаралық кеуектіліктің іс жүзінде жоқ екендігін көрсетті. Геомеханикалық модельдеу кері кернеулі күйдің бар екенін дәлелдеді, бұл негізінен көлденең жарықшақтардың түзілуі салдарынан қабатты гидравликалық жарудың дәстүрлі әдісінің тиімділігін шектейді. Кернің 117 үлгісінде жүргізілген статикалық зерттеулер құрамындағы HF-қышқылының жүйелері кальций фториді мен фторосиликаттардың қайта шөгінділерінің түзілуі, кеуек кеңістігінің бітелуіне әкелетінін көрсетті. Оған қарағанда, 12 % тұз қышқылының сулы ерітіндісі қайта шөгінділер түзбей, жарықшақтардың кальцитті толтырғыштарын іріктеп ерітуді қамтамасыз етеді. Динамикалық сүзілгіштік эксперименттері жарықшақты үлгінің өтімділігін $0,3 \times 10^{-3}$ мкм^2-ден 330×10^{-3} мкм^2-ге дейін артқанын растады. *Қорытынды.* Жұмыстың ғылыми жаңалығы – қабатқа әсер ету технологиясын таңдауды негіздеу үшін томографиялық, минералогиялық, геомеханикалық және фильтрациялық мәліметтерді біріктіруде жатыр. Алынған нәтижелер селективті тұз-қышқылымен өңдеудің жоғары тиімділігін көрсетеді және ұқсас геологиялық-геомеханикалық жағдайлары ұқсас тығыз жарықшақты терригендік коллекторларды игеру кезінде қолданылуы мүмкін.

Түйін сөздер: жарықшақты терригендік коллектор, тұз-қышқылымен өңдеу, геомеханикалық модельдеу, кері кернеу режимі, мұнай өндіруді қарқындату

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КОМПЛЕКСНАЯ ОЦЕНКА ЭФФЕКТИВНОСТИ СОЛЯНО-КИСЛОТНОЙ ОБРАБОТКИ ДЛЯ ПОВЫШЕНИЯ ПРОДУКТИВНОСТИ ТРЕЩИНОВАТЫХ ТЕРРИГЕННЫХ КОЛЛЕКТОРОВ ЗАПАДНОГО КАЗАХСТАНА

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Аннотация. *Актуальность.* Разработка трудноизвлекаемых запасов нефти, приуроченных к плотным трещиноватым терригенным коллекторам, является одной из актуальных задач нефтегазовой отрасли Западного Казахстана. Эффективное освоение подобных объектов существенно осложняется низкой матричной проницаемостью, сложным минеральным составом пород и неблагоприятными геомеханическими условиями. *Цель*. Научно обосновать выбор технологии интенсификации притока для плотного трещиноватого терригенного коллектора на основе комплексного лабораторного и геомеханического анализа. *Методы*. Для решения поставленной задачи применён междисциплинарный подход, включающий рентгеновскую компьютерную томографию (КТ), литолого-петрографические исследования, сканирующую электронную микроскопию с энергодисперсионным анализом (SEM–EDS), геомеханические испытания, исследования растворяющей способности кислотных систем и динамические фильтрационные эксперименты в пластовых условиях. *Результаты*. По данным КТ установлено, что фильтрация пластовых флюидов контролируется преимущественно системой вертикальных и субвертикальных трещин, тогда как эффективная межзерновая пористость практически отсутствует. Геомеханическое моделирование подтвердило наличие реверсного напряжённого состояния (Sv < Shmin < SHmax), ограничивающего эффективность традиционного гидравлического разрыва пласта вследствие преимущественного формирования горизонтальных трещин. Статические исследования 117 образцов керна показали, что HF-содержащие кислотные системы вызывают интенсивное образование вторичных осадков фторида кальция и фторосиликатов, приводящих к кольматации порового пространства. В отличие от них, 12 %-ный водный раствор соляной кислоты обеспечивает селективное растворение кальцитового заполнения трещин без образования значительного количества вторичных осадков. Динамические фильтрационные эксперименты подтвердили увеличение проницаемости трещиноватого образца с $0{,}3 \times 10^{-3}$ до 330×10^{-3} мкм^2. *Выводы*. Научная новизна исследования заключается в комплексной интеграции томографических, минералогических, геомеханических и фильтрационных данных для обоснования выбора технологии воздействия на пласт. Полученные результаты свидетельствуют о высокой эффективности селективной солянокислотной обработки и могут быть использованы при разработке плотных трещиноватых терригенных коллекторов со сходными геолого-геомеханическими условиями.

Ключевые слова: трещиноватый терригенный коллектор, солянокислотная обработка, геомеханическое моделирование, реверсный режим напряжений, интенсификация добычи нефти

Introduction. Development of hard-to-recover reserves in low-permeability fractured reservoirs is a priority for Western Kazakhstan. Conventional production methods are ineffective due to low matrix permeability, complex geology, and secondary mineralization.

In fractured reservoirs, natural fractures are the main flow paths. However, their conductivity is often reduced by calcite filling during secondary processes.

This study aims to substantiate stimulation technology for fractured terrigenous reservoirs using integrated laboratory and geomechanical analysis. The novelty is in linking CT, SEM-EDS, geomechanical and filtration data to select acid treatment and prevent secondary damage.

The following methods were used: X-ray computed tomography, SEM-EDS analysis, geomechanical testing, and dynamic filtration of acid systems under reservoir conditions.2. Literature Review.

Literature review. Effective development of low-permeability reservoirs requires overcoming high filtration resistance. The two main stimulation methods are hydraulic fracturing and matrix acid treatments (Qassabi et al., 2022; Wei et al., 2022).

The success of these methods depends on mineral composition, fracture morphology, and the current stress state. For fractured reservoirs, an integrated assessment of geological and geomechanical factors is required to select the optimal technology.

Application of standard hydraulic fracturing in deep dense formations is often limited by geomechanics. Under normal stress, fractures propagate vertically. However, in regions with reverse stress regime $S_v < Sh_{min} < SH_{max}$, injection leads to horizontal fractures or bedding plane opening (Li et al., 2022; Li et al., 2023). These fractures close rapidly under overburden pressure and provide poor drainage, making conventional fracturing inefficient.

Matrix acid treatments are an alternative. HF/HCl blends are used to dissolve silicates and clays (Gao et al., 2025). However, reaction of HF with polymict sandstones forms secondary insoluble precipitates (Qamruzzaman et al., 2021; Wei et al., 2022). Direct contact of HF with carbonates causes instant precipitation of CaF2 with very low solubility (Bin et al., 2022):

$$CaCO3 + 2HF \rightarrow CaF2\downarrow + H2O + CO2\uparrow$$

This gel-like CaF2 together with fluorosilicates blocks pore throats and causes colmatage (Zhang et al., 2020). To avoid this, pre-flush with HCl is recommended (Xie et al., 2025 Gomaa et al., 2020).

For purely fractured reservoirs, HF is risky due to destruction of the silicate framework. Therefore, selective treatments with HCl or organic acids are discussed. HCl does not react with the quartz skeleton but effectively dissolves calcite bridges in fractures, restoring conductivity without fluoride precipitation.

Despite extensive studies, there is a gap linking calcite dissolution kinetics with geomechanical behavior under reverse stress. Most filtration models assume isotropic matrix and are not applicable to fractured systems of Western Kazakhstan.

This work proposes an interdisciplinary approach combining CT, geomechanical analysis, and dynamic modeling.

Materials and Methods. Core samples were taken from a new deep deposit in Western Kazakhstan. The reservoir consists of dense fine-grained polymict sandstones and siltstones with carbonate-clay cement.

The key feature of the deposit is intense tectonic fracturing with almost no matrix porosity. To avoid damage during transport, diagnostics were performed directly in aluminum core tubes. The complex of lab studies included CT, SEM-EDS, geomechanical tests, solubility tests, and filtration experiments.

X-ray CT and petrography: High-resolution CT-scan CTSKAN-300 (Core Laboratories, USA) was used for 3D visualization of void space and fracture geometry.

Geomechanical testing**:** Strength and elastic properties were measured on Autolab 2000 (New England Research, USA) under triaxial and uniaxial loading at reservoir pressures. Dynamic elastic moduli E and Poisson ratio ν were calculated from acoustic velocities Vp and Vs. Static moduli and rock strength were measured at 5 MPa confining pressure. Dynamic moduli were also determined under hydrostatic pressures of 5, 10, 15 MPa using 1 MHz ultrasonic sensors.

Dynamic Poisson ratio and Young's modulus were calculated using acoustoelastic equations:

$$\upsilon_{dyn} = \frac{V_p^2 - 2V_s^2}{2V_p^2 - V_s^2}$$

$$E_{dyn} = \frac{\rho V_p^2 \cdot \left(3V_p^2 - 4V_s^2\right)}{V_p^2 - V_s^2}$$

where ρ is bulk density, kg/m³.

Acid solubility: Tests were done on 117 representative samples by gravimetric method. Solutions tested: 6%, 9%, 12% HCl; HCl/HF blends; and organic acid systems with 3-5% retarders. All tests used fixed hydraulic module and temperature for comparison. Secondary products were analyzed on SEM-EDS Quanta 650 (Thermo Fisher, USA).

Dynamic filtration: Performed on FDES-650 (LLC KEN Dynamics, USA) under conditions close to reservoir.

Dynamic filtration procedure**:** Cylindrical cores with macroscopic cracks sealed by secondary calcite were tested in 4 steps:

1. Thermobaric stabilization: T=85°C, P=15 MPa, backpressure 5 MPa to simulate reservoir conditions.

2. Initial brine filtration: Formation water 28 g/L injected at 0.5 mL/min to determine initial permeability.

3. Acid injection: 12% HCl with corrosion inhibitors and surfactants, 45 mL at 0.3 mL/min. Pressure drop ΔP recorded continuously.

4. Final brine filtration: Formation water injected in forward and reverse directions to assess change in crack conductivity and removal of reaction products.3.1 Results

Results. Lithology: The reservoir consists of dense fine-grained silty polymict sandstones and siltstones with carbonate-clay cement. Grains are angular to sub-rounded with medium sorting.

Fracture system**:** CT scanning showed vertical and subvertical tectonic fractures. A significant part is sealed by secondary calcite. Open conductive fractures have dip angles of 30° to 80° and contain signs of mobile oil Figure 1. The main feature is fractured-type filtration with extremely low matrix porosity.

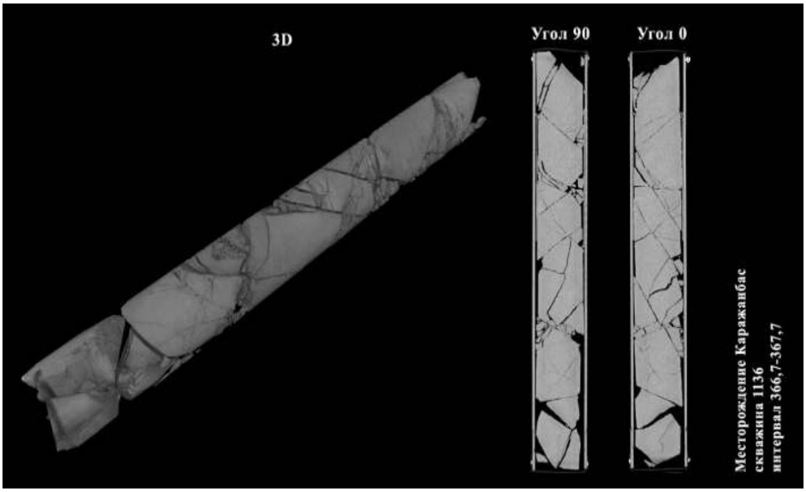

Figure 1. Fracture Geometry and Dip Angles Identified in Core Samples.

Geomechanical tests under triaxial loading were used to assess deformation and strength for predicting bottomhole treatment behavior. Results are given in Table 1.

Table 1. Results of Acoustic Wave Velocity Measurements Used for the Calculation of Dynamic Young's Modulus and Poisson's Ratio.

Bulk Density, $\times 10^3$, kg/m^3	Confining Pressure, MPa	Compressional-Wave Velocity (V_p), m/s	Shear-Wave Velocity Vs_1, m/s	Shear-Wave Velocity Vs_2, m/s	Young's Modulus (E), GPa	Poisson's Ratio (υ)
2,643	5	5915	3469	3450	78.4	0.240
	10	5952	3510	3441	79.3	0.241
	15	5999	3551	3451	80.5	0.242
2,654	5	5673	3310	3255	71.4	0.248
	10	5684	3328	3239	71.5	0.250
	15	5713	3328	3236	71.7	0.254

Dynamic Young's modulus of 71.4–80.5 GPa indicates high stiffness and ability to accumulate elastic stress. Low Poisson's ratio 0.240–0.254 shows limited ductility and high brittleness. This combination forms a mechanically stable fractured massif where behavior under hydraulic action depends mainly on the stressed state.

Table 2. Measured Static Bulk Modulus, Compressibility Coefficient, and Shear Modulus of the Studied Reservoir Rocks.

Bulk Density, $\times10^3$, kg/m³	Bulk Modulus, GPa	Compressibility Coefficient, $\times10^{-5}$ MPa^{-1}	Shear Modulus, GPa
2.643	31.28	3.20	14.55
2.654	32.38	3.09	13.78
2.657	31.15	3.21	11.56
2.672	30.13	3.32	15.64

Таблица 3. Results of Uniaxial Compressive Strength (UCS) Testing of the Studied Reservoir Rocks.

Sample Density, g/cm³	Confining Pressure, MPa	Uniaxial Compressive Strength (σ_c), MPa
2.672	5	156.8
2.671	5	134.5
2.691	5	148.3
2.677	5	150.6
2.688	5	145.1

Compressive strength reaches 135–157 MPa, comparable to dense carbonates. High strength combined with high Young's modulus means high energy is needed to initiate and propagate fractures. This limits effectiveness of conventional hydraulic fracturing and increases requirements for stimulation tech.

Based on elastic-strength data, logs and density, a 1D geomechanical model was built. It allowed calculating current stress distribution, verifying the tectonic regime Sv < Shmin < SHmax, and predicting geometry of artificial fractures under hydraulic or acid treatment [Fig. 2-4].

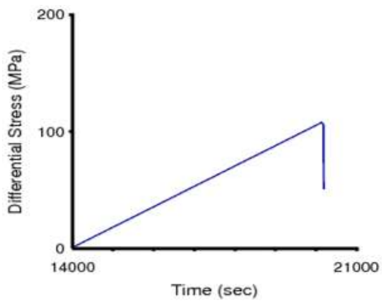

Figure 2. Representative Failure Pattern Observed During Uniaxial Compressive Strength (UCS) Testing.

Before After

Figure 3. Representative Core Sample Before and After Uniaxial Compressive Strength (UCS) Testing.

Figure 4. Secondary Precipitation on the Rock Surface Induced by Treatment with an HF-Containing Acid System.

The reservoir is in a pronounced reverse thrust tectonic regime: $S_v < Sh_{min} < SH_{max}$, where vertical stress is the minimum.

Integration of elastic-strength data with density logs confirmed this regime. Under such conditions, fractures during hydraulic fracturing propagate perpendicular to Sh_{min}, i.e. mainly in the horizontal plane. High-rate injection will not create effective vertical drainage fractures. This confirms that conventional hydraulic fracturing is ineffective for this deposit. Acid treatment targeting dissolution of calcite-filled fractures is the preferred approach to restore conductivity without creating new horizontal fractures.

This confirms that conventional hydraulic fracturing is ineffective for this deposit. Acid treatment targeting dissolution of calcite-filled fractures is the preferred approach to restore conductivity without creating new horizontal fractures.

Geomechanical modeling showed limited effectiveness of conventional hydraulic fracturing. Due to reverse stress regime, injection causes opening of bedding planes and microcracks instead of a vertical drainage channel. High rock strength (σ_{pph}>130 MPa) increases risk of premature proppant "stop".

Acid composition selection. Solubility tests on 117 cores were done to select optimal HMO. Since the reservoir has carbonate-clay cement and calcite-filled cracks, the goal was selective dissolution of calcite without destroying the silicate skeleton.

HF/HCl blends: Caused destruction of both carbonate and silicate minerals. SEM-EDS showed critical side effect: HF reacts with Ca in cement to instantly precipitate CaF_2 with very low solubility:

$$CaCO_3 + 2HF \rightarrow CaF_2\downarrow + H_2O + CO_2\uparrow$$

In narrow fractures, local Ca^{2+} concentration rises and causes dense CaF_2, Na_2SiF_6, K_2SiF_6 deposits. These seal pore throats and create colmatage barriers Figure 4.

HCl solutions: Testing 6%, 9%, 12% HCl showed controlled dissolution kinetics. 12% HCl gave best results. It fully dissolves calcite to form highly soluble $CaCl_2$:

$$CaCO_3 + 2HCl \rightarrow CaCl_2 + H_2O + CO_2\uparrow$$

SEM showed clean fracture walls with intact silicate framework. No secondary precipitation.

Organic retardants: 3-5% acetic acid reduced corrosion at high T. Base solubility was still controlled by HCl.

Results agree with (Mahmoud et al., 2020; Almubarak et al., 2022). HF systems aggressively attack the rock but risk secondary precipitation. 12% HCl provides selective calcite dissolution without secondary solids.

Comparative results are shown in Figure 5 – Acid System Effectiveness.

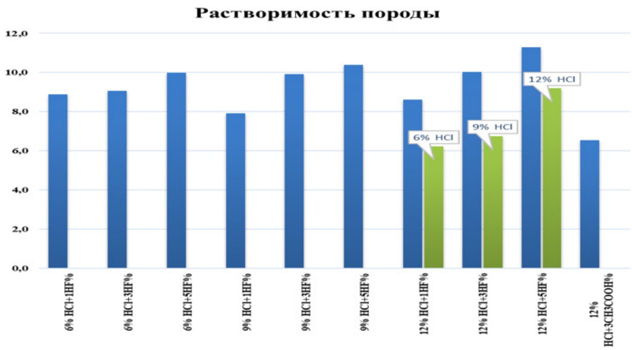

Figure 5. Comparative Dissolution Efficiency of the Investigated Acid Systems.

Key structural feature: Almost complete absence of matrix porosity. Traditional matrix filtration is extremely poorly developed and cannot provide industrial oil flow.

SEM-EDS and XRD results: Analysis confirmed polymict sandstones with quartz, feldspar, calcite and clay minerals Figure 6. SEM-EDS confirmed that CaF_2 precipitation is the main damage mechanism in HF-containing systems. This supports using selective HCl treatments instead.

Fracture role: A significant part of tectonic cracks is sealed by secondary calcite. Open conductive channels with oil saturation have dip angles 30° to 80° and trace through the entire productive section. Fractures play a dominant role in hydrocarbon migration and are the main filtration channels.

Dynamic filtration verification: Tests on cores with calcite-sealed cracks were done with 12% HCl.

During the first minutes of contact, a short-term jump in ΔP occurred due to active CO2 release and gas-liquid resistance (Jamin effect). As the acid front progressed and calcite bridges dissolved, differential pressure dropped to minimal stable values. This indicates acid breakthrough and restoration of fracture hydraulic connectivity Figure 8-9.

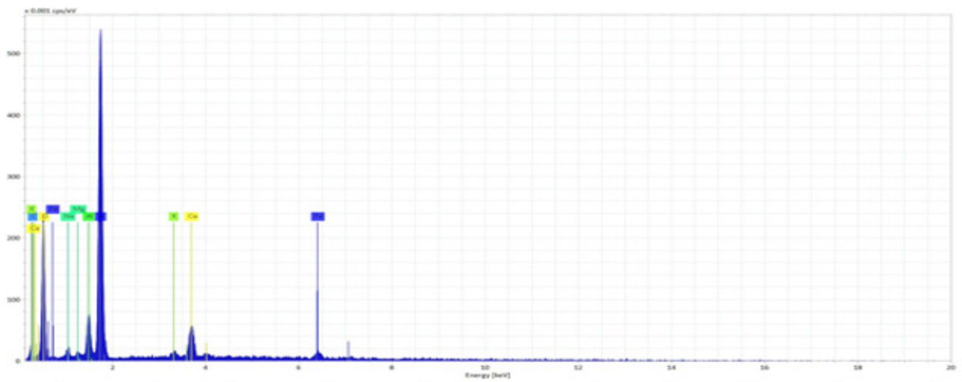

Figure 6. Mineralogical Composition of the Reservoir Rock Based on XRD and SEM–EDS Analyses Prior to Acid Treatment.

Spectrum	O, %	C, %	Al, %	Si, %	K, %	Na, %	Fe, %	Ti, %	Mg, %	Ca, %	Total, %
Spectrum 1	52,02	1,28	3,11	27,79	1,02	2,59	2,63	–	0,65	8,91	100

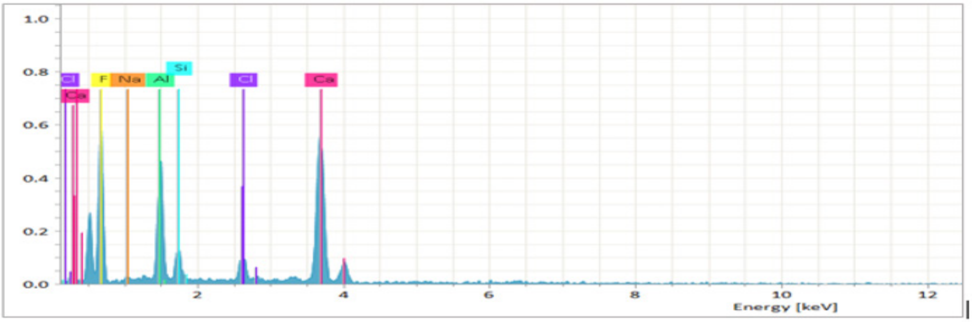

Figure 7. EDS Characterization of Secondary Precipitates Formed Following Exposure to an HF-Containing Acid System.

Spectrum	Fe, %	Na, %	Al, %	Ca, %	Si, %	Cl, %	F, %	Total, %
Spectrum 1	–	2,31	6,93	34,29	1,56	4,36	50,55	100

Dynamic filtration results:

Final filtration with model brine 28 g/L at 0.5 mL/min showed permeability increase from $0.3\times10{-}3$ to $330\times10{-}3$ μm².

That is a growth of >1,100 times.

This increase is not due to new channels, but to restoration of hydraulic connectivity of previously calcitized natural cracks.

Conclusion: The main factor limiting productivity is mineralized filling of cracks, not low matrix permeability.

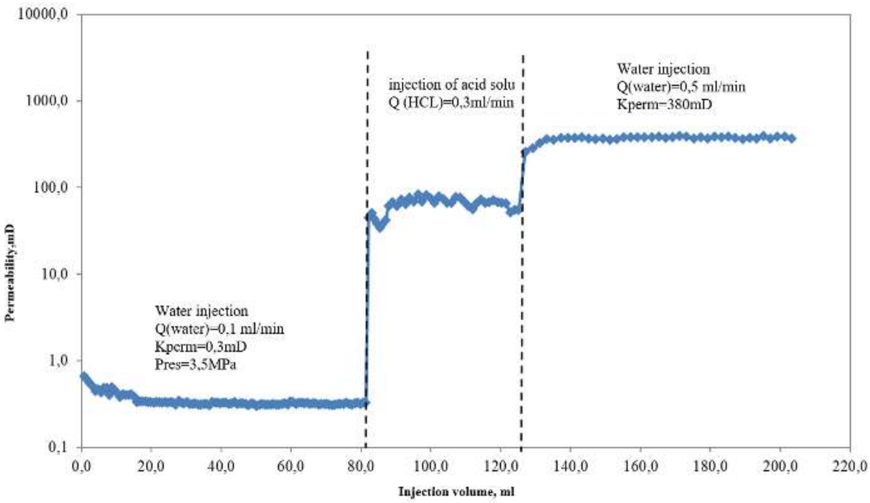

Figure 8. Comparison of Permeability Measurements Before and After Hydrochloric Acid Treatment (HAT).

Depth: 326.26 m Fine-grained silty polymictic sandstone, brownish-gray in color, massive, dense, and mechanically strong, cemented by a carbonate–clay matrix. A vertical fracture with an aperture of 0.7 mm is present, partially healed by calcite and exhibiting an open-fracture character.	
Water Permeability Before and After Hydrochloric Acid Treatment (HAT), $\times10^{-3}$ μm^2	
0.3	**330.0**
	

Figure 9. Results of Core-Flooding Experiments Demonstrating Fracture Conductivity Enhancement Following Hydrochloric Acid Treatment.

Analysis of oil production rate Figure 10 shows steady increase in well productivity. Cleaning of the fracture network from calcite allowed stable decrease in water cut and multiple increase in productivity coefficient.

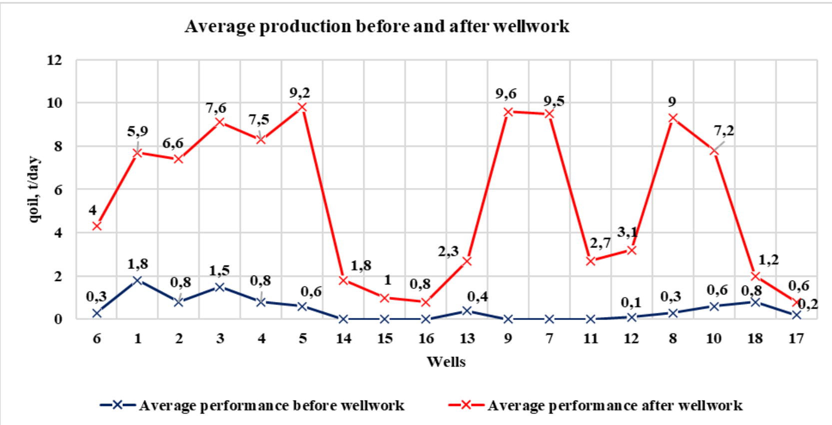

Figure 10. Well results before and after RMS.

Field data correlate with lab studies and confirm reliability of the proposed integrated approach for dense fractured terrigenous reservoirs in Western Kazakhstan.

Discussion. Geomechanical conditions are a key factor limiting effectiveness of traditional hydraulic fracturing. The identified reverse stress regime S_v<Sh_{min}<SH_{max} leads to development of horizontal fractures with limited drainage, reducing expected effect.

For the studied reservoir, filtration is controlled mainly by the fracture system. Matrix porosity and permeability have almost no role. In such reservoirs, technologies focused on creating new matrix channels have limited effectiveness. Similar conclusions for ultra-low permeability sandstones are reported by (Yang et al., 2023; Zheng et al., 2025).

Geomechanical modeling showed that hydraulic impact mainly opens existing cracks instead of creating new conductive channels, forming complex T-shaped structures with low conductivity. Due to this, modern literature focuses more on matrix acid treatments as an alternative to HF in complicated geomechanical conditions (Qassabi et al., 2022; Wei et al., 2022).

Success of hydraulic fracturing is strictly controlled by orientation of minimum principal stress, which agrees with our results for the reverse stress regime.

An additional factor reducing acid effectiveness is formation of secondary precipitates with HF-containing systems. SEM showed that HF reacts with carbonates and aluminosilicates to form Ca, Na, K fluorides and fluoroaluminates. This causes colmatation of fracture space and deterioration of filtration properties (Gao et al., 2025; Qamruzzaman et al., 2021; Zhang et al., 2020).

To prevent this, chelated and organic acid systems are used (Gomaa et al., 2020; Hassan et al., 2021; Almubarak et al., 2022; Barri et al., 2022). Results are consistent with literature (Qamruzzaman et al., 2021; Almubarak et al., 2022;2022-2023; Gao et al., 2025).

However, in fractured reservoirs with reverse stress, negative impact of secondary sedimentation is significantly enhanced because filtration is controlled by fractures. Alternative ways include delayed acid systems and gemini-surfactant compositions (Mahmoud et al., 2020; Zhao et al., 2021; Yan et al., 2021; Abdallah et al., 2022; Zhao et al., 2022; Xie et al., 2025).

Filtration studies confirmed high efficiency of 12% HCl. It dissolves calcite without intensive formation of secondary deposits. Permeability increase confirms effectiveness for this reservoir type. Selective dissolution of carbonate with HCl and organics without destroying silicate framework is also confirmed in recent cases. Absence of permeability decline agrees with data on minimizing fines migration with correct composition.

The selective salt-acid treatment proposed is a technologically simple and economical solution compared to complex HF and HF fracturing, which increase risks of secondary sedimentation (Gao et al., 2025; Qamruzzaman et al., 2021; Zhang et al., 2020).

For fractured terrigenous reservoirs with reverse stress, traditional HF-acid and hydraulic fracturing have limited efficiency due to complex geomechanics and intensive secondary precipitation. Salt-acid treatment is more effective with minimal risk of fracture colmatation.

Conclusions. Reservoir is dense polymict sandstones and siltstones with very low matrix porosity. Main filtration occurs via natural tectonic fractures. Many cracks are partially/completely filled with secondary calcite, which reduces conductivity.

1. Digital models showed promising channels are vertical/subvertical fractures with dip 30°-80°. These form the main migration system. Matrix contribution is negligible.

2. Geomechanical studies: Young's modulus 71.4-80.5 GPa, Poisson ratio 0.240-0.254, UCS 135-157 MPa. Rocks are stiff and mechanically stable.

3. Integration with modeling confirmed reverse stress state $S_v < Sh_{min} < SH_{max}$. Induced fractures develop horizontally, reducing effectiveness of conventional fracturing.

4. Solubility studies showed HF systems dissolve carbonates/silicates but also form secondary insoluble CaF2 and fluosilicates, causing colmatation.

5. SEM-EDS confirmed CaF2 accumulations on crack surfaces after HF exposure. High risk of damage in high-calcite conditions.

6. 12% HCl salt-acid treatment selectively dissolves calcite to highly soluble CaCl2, which is removed without secondary precipitation. Permeability increased >1100x in lab tests and productivity increased in pilot well. The proposed integrated approach allows scientifically based selection of stimulation technology for fractured reservoirs in Western Kazakhstan.

7. Dynamic filtration studies under reservoir conditions confirmed high efficiency of salt-acid impact. During treatment, hydraulic connectivity of natural cracks was restored and filtration resistance decreased. Permeability increased from $0.3\times10{-}3$ to $330\times10{-}3$ µm². That is an increase in conductivity by >1000 times.

8. Pilot field results are consistent with lab data. This confirms the possibility of effective use of salt-acid treatment for hard-to-recover oil reserves in fractured terrigenous reservoirs with calcitic cracks.

Summary

The studies allowed developing criteria for choosing salt-acid treatment as the preferred technology for fractured terrigenous reservoirs of Western Kazakhstan with calcitic cracks and reverse stress.

Scientific significance: Integrated approach based on X-ray CT, geomechanical modeling, SEM-EDS, and filtration tests. This approach makes it possible to increase reliability of stimulation method selection, reduce risk of secondary formation damage, and ensure efficient restoration of reservoir properties of fractured reservoirs.

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