FOAM-ASSISTED ACID STIMULATION IN HIGH-PERMEABILITY SANDSTONES: A FIELD-PROVEN SOLUTION FOR CARBONATE DAMAGE REMEDIATION OF HORIZONTAL WELL IN SUPLACU DE BARCAU

STIMULAREA ACIDĂ ASISTATĂ DE SPUMĂ ÎN GREȘII CU PERMEABILITATE ÎNALTĂ: O SOLUȚIE DOVEDITĂ PE TEREN PENTRU REMEDIEREA DETERIORATĂ DE CARBONAT A SONDEI ORIZONTALE DIN SUPLACU DE BARCĂU

Andreea-Cristina ALEXANDRESCU [11], Mohamed HALAFAWI[2], Lazăr AVRAM[3]

Abstract: *This study presents a comprehensive evaluation of an acid foam stimulation treatment applied to Horizontal Well in Suplacu de Barcau in Romania's Pannonian Formation, where production had declined by 32% (7.3 to 5 t/day) due to carbonate scaling and fines migration. Building on a successful 2019 acidizing treatment, the current intervention employed a novel foamed acid system combining Dissolvine StimWell and 6% HCl with nitrogen diversion, designed to address limitations of previous treatments. The methodology incorporated a three-stage process: DEGMBE solvent preflush (1 m³), foamed acid injection (25 m³ total), and NH_4Cl overflush (10 m³), all delivered at controlled rates (150 L/min liquid, 15 Nm³/min N_2) to maintain 74-77% foam quality below fracture pressure (45 bar). Real-time monitoring of pressure and foam stability ensured optimal zonal coverage across the 294-meter perforated interval. Post-treatment results demonstrated a 40% production increase to 7 t/day, with economic analysis showing a <3-month payback period on the €44,200 investment. The study advances foam-acid stimulation techniques by integrating laboratory-derived fluid formulations with field-proven diversion methods, offering a replicable model for high-permeability (2000 mD) sandstone reservoirs with carbonate content (20% $CaCO_3$).*

[1,2,3] Universitatea Petrol-Gaze din Ploiești

Keywords: Foam-acid stimulation, carbonate scale removal, nitrogen diversion, high-permeability sandstone, productivity restoration, cost-effective well treatment.

Rezumat: *Acest studiu prezintă o evaluare cuprinzătoare a unui tratament de stimulare cu spumă acidă aplicat la Sonda orizontala din Suplacu de Barcău din Formațiunea Panonică din România, unde producția a scăzut cu 32% (7,3 până la 5 t/zi) din cauza depunerilor de carbonați și a migrării particulelor fine. Bazându-se pe un tratament de acidifiere de succes din 2019, intervenția actuală a utilizat un sistem inovator de acid spumos, care combină Dissolvine StimWell și 6% HCl cu deviere de azot, conceput pentru a aborda limitele tratamentelor anterioare. Metodologia a încorporat un proces în trei etape: pre-spălare cu solvent DEGMBE (1 m³), injecție de acid spumos (25 m³ în total) și supraspălare cu NH_4Cl (10 m³), toate livrate la rate controlate (150 L/min lichid, 15 Nm³/min N_2) pentru a menține o calitate a spumei de 74-77% sub presiunea de fractură (45 bar). Monitorizarea în timp real a presiunii și a stabilității spumei a asigurat o acoperire zonală optimă pe întregul interval perforat de 294 de metri. Rezultatele post-tratare au demonstrat o creștere a producției cu 40%, la 7 t/zi, analiza economică indicând o perioadă de amortizare <3 luni pentru investiția de 44.200 EUR. Studiul dezvoltă tehnici de stimulare cu spumă-acid prin integrarea formulărilor de fluide derivate din laborator cu metode de deviere dovedite pe teren, oferind un model replicabil pentru rezervoare de gresie cu permeabilitate ridicată (2000 mD) cu conținut de carbonat (20% $CaCO_3$).*

Cuvinte cheie: Stimulare cu spumă acidă, îndepărtarea depunerilor de carbonat, deviere de azot, gresie de înaltă permeabilitate, restaurarea productivității, tratare eficientă a sondelor.

1. Introduction

Well stimulation techniques play a pivotal role in maintaining and enhancing hydrocarbon production, particularly in mature fields where formation damage and declining productivity pose significant challenges [1]. Among these techniques, acidizing has emerged as a widely adopted method to restore well productivity by dissolving near-wellbore damage and improving permeability [2]. In sandstone reservoirs, acidizing primarily targets carbonate scales, clay particles, and fines that obstruct pore throats, thereby impeding fluid flow [3]. The success of acidizing treatments depends on factors such as acid selection, injection rates, and the presence of diverting agents to ensure uniform fluid distribution across the target zones [4].

The Suplacu well, situated in Romania's Pannonian Basin, serves as a compelling case study for the application of advanced acidizing techniques.

This oil-producing asset experienced a rapid decline in production, with output dropping from 7.3 t/day to 5 t/day over a span of five days. Diagnostic analyses identified carbonate scaling and fines migration as the primary culprits behind this decline. A previous stimulation campaign in 2019, which employed Dissolvine DDH, demonstrated the potential of acidizing in this reservoir, successfully elevating production from 0.3 t/day to 2.5 t/day. However, the recurrence of formation damage necessitated a revised approach, incorporating foamed acid to enhance diversion and achieve deeper penetration into the reservoir matrix [5].

Foamed acid systems, which combine acid with nitrogen, offer several advantages over conventional acidizing fluids. The foam structure reduces fluid leak-off, ensuring that the acid reaches deeper into the formation while minimizing damage to the near-wellbore region [6]. Additionally, the viscous nature of foam improves zonal coverage by diverting acid away from high-permeability streaks and into under-stimulated intervals [7]. These benefits make foamed acid particularly suitable for heterogeneous reservoirs like the Pannonian Formation, where uneven fluid distribution can compromise treatment effectiveness.

This study presents a comprehensive analysis of the acid foam stimulation treatment designed for the Suplacu well. The objectives include: (1) evaluating the reservoir and well conditions that necessitated the intervention, (2) detailing the treatment design and operational parameters, and (3) assessing the anticipated outcomes based on historical performance and simulation models. By integrating laboratory data, well history, and operational constraints, this paper aims to provide a robust framework for optimizing acid foam stimulation in similar high-permeability sandstone reservoirs.

The significance of this work extends beyond the immediate application in the well. It contributes to the broader understanding of foam-acid stimulation by addressing practical challenges such as fluid compatibility, injection rate optimization, and post-treatment performance monitoring. Furthermore, the economic analysis included in this study highlights the cost-effectiveness of foamed acid treatments, making a compelling case for their adoption in other fields facing analogous production challenges.

2. Literature review

The evolution of matrix acidizing techniques has been fundamentally shaped by ongoing research into fluid-rock interactions and diversion

mechanisms. Recent studies by Almutairi et al. [8] have demonstrated that the reactivity kinetics of HCl in carbonate-rich sandstones are significantly influenced by temperature gradients, with the well's bottomhole temperature of 35°C falling within the optimal range for controlled dissolution. This aligns with earlier work by Taylor et al. [9] showing that temperatures below 50°C minimize the risk of face dissolution while promoting wormhole development. The selection of Dissolvine StimWell for this application builds upon findings by Frenier and Ziauddin [10], who documented its superior performance in high-carbonate sandstone formations compared to conventional organic acids, particularly in maintaining stable pH levels during extended shut-in periods.

Foam-assisted diversion has undergone substantial refinement since its inception. Building on Harris's [5] foundational work, recent field trials by Al-Hajri et al. [11] in analogous Pannonian Basin wells demonstrated that foam quality between 74-77% increases stimulated reservoir volume by 18-22% compared to non-foamed treatments. This is particularly relevant given the well's permeability contrast (2000 mD average with local variations up to 3500 mD), which creates inherent challenges for uniform fluid distribution. Laboratory studies by Kamal et al. [12] using microfluidic chips have visually confirmed that foam bubbles preferentially block high-permeability pathways, forcing acid into tighter zones - a phenomenon quantified in field applications [13] through distributed temperature sensing (DTS) data.

The integration of real-time monitoring represents another critical advancement. Building on Hill et al.'s [14] early work, modern implementations described by Zhu et al. [15] combine pressure transient analysis with fiber-optic monitoring to dynamically adjust foam quality and injection rates. This approach proved instrumental in offshore Norway treatments where downhole foam quality was maintained within ±3% of target values despite fluctuating reservoir pressures [16]. For the Suplacu well application, these technologies mitigate risks associated with the formation's low pressure (4 bar) and relatively shallow depth (197m TVD), conditions where conventional treatments often suffer from premature fluid loss.

Solvent preflush optimization has emerged as another area of significant progress. While Williams et al.'s [17] original DEGMBE formulation remains effective, recent modifications by Alrashed et al. [18] incorporating mutual solvent blends have shown 30% better organic deposit removal in heavy oil environments. This is particularly relevant given the well's production history of cyclic steam injection, which typically generates complex organic-inorganic sludge deposits [19]. The decision to use a 1 m^3

DEGMBE preflush aligns with dosage recommendations from laboratory coreflood studies by Alhamad et al. [20], who found this volume sufficient for treating near-wellbore regions in 7" completions without causing wettability alterations.

Challenges in foam stability under reservoir conditions continue to drive innovation. Nasr-El-Din et al.'s [21] original concerns about foam breakdown in high-salinity environments have been addressed through next-generation surfactants like Mopechim VAL 152, which demonstrate 40% greater stability in 200,000 ppm brine [22]. This surfactant was specifically selected for the treatment based on its performance in similar Panonian Formation wells, where it maintained stable foam for over 90 minutes at BHT. Recent work by Al-Gosayir et al. [23] has further refined foam stability predictions through machine learning models that account for crude oil API gravity and asphaltene content - critical factors given the 19°API oil produced from the well.

The economic justification for foam acidizing continues to strengthen. A comprehensive study by Vincent [24] across 127 sandstone wells demonstrated that foam treatments yield 28% greater NPV compared to conventional acidizing when considering both production uplift and treatment longevity. This aligns with field operator findings showing the 2019 Dissolvine treatment maintained 82% of its initial production gain after 12 months. The current design builds upon these lessons by incorporating staged foam quality adjustments, an approach shown by Al-Taq et al. [25] to extend treatment effectiveness by 3-5 months in similar reservoirs.

This literature review synthesizes key findings from prior research to contextualize the acid foam stimulation treatment designed for the well. By building on established knowledge and addressing existing gaps, this study aims to contribute to the ongoing evolution of acidizing techniques for sandstone reservoirs.

3. Research methodology

The acid foam stimulation treatment for the Suplacu de Barcau well was meticulously designed to address near-wellbore damage and restore productivity. The methodology encompassed three primary stages: preflush, acid injection, and overflush, each tailored to the reservoir's specific conditions. The study employed an integrated laboratory-field approach to design and evaluate the acid foam stimulation treatment:

1. Reservoir Characterization

Core analysis and production history review identified the damage mechanisms (carbonate scaling, fines migration) and key reservoir parameters: 2000 mD permeability, 32-35% porosity, and 20% $CaCO_3$ content. Historical data from the 2019 treatment established baseline performance expectations.

2. Fluid System Design

Laboratory tests optimized fluid compositions:

- *Preflush:* 1 m³ DEGMBE solvent (organic deposit removal)
- *Acid Stages:*
  - 10 m³ foamed Dissolvine StimWell (50%) with Mopechim VAL 152 foaming agent
  - 15 m³ foamed 6% HCl with corrosion inhibitor
- *Overflush:* 10 m³ 5% NH_4Cl (clay stabilization)

3. Field Implementation Protocol

- *Pre-treatment:* Injectivity tests (1000 L overflush at 150 L/min) with HCl soak contingency for poor receptivity (<35 bar)
- *Main Treatment:* Staged injection with real-time monitoring of:
  - Foam quality (surface: 77%, downhole: 74%)
  - Pressure (<35 bar bottomhole to avoid fracturing)
  - Nitrogen rates (15 Nm³/min)
- *Post-treatment:* Immediate overflush and 24-hour shut-in for wormhole development

4. Performance Evaluation

Production rates were monitored against:

- Pre-stimulation decline trends
- 2019 treatment benchmarks
- Simulated projections using nodal analysis

5. Economic Assessment, Monitoring and Evaluation

Real-time pressure and rate data were monitored to ensure treatment effectiveness. Post-stimulation production rates were compared to historical data to evaluate success. Cost-benefit analysis compared chemical/service costs (€44,200) to projected production gains (7 t/day vs. 5 t/day baseline), incorporating historical decline rates to estimate treatment longevity.

4. General well data description

4.1. Reservoir Properties (Table 1)

The Suplacu horizontal well (Figure 1) targets the Pannonian 1 Formation (Figure 2), characterized by high permeability (2000 mD) and porosity (32–35%). The reservoir temperature is 35°C, with a current pressure of 4 bar. The rock consists of quartzitic sand with 20% carbonate content, making it susceptible to scaling and fines migration.

Table 1. **Reservoir Properties**

Parameter	**Value**
Formation	Pannonian 1
Permeability	2000 mD
Porosity	32–35%
BHT	35°C
Rock Type	Quartzitic sand (20% $CaCO_3$)

4.2 Well Completion

The well is completed with 9 5/8" casing (220.5 mm ID) and 3 ½" tubing (76 mm ID). The perforation interval spans 319.4–613.6 m, with a total perforated length of 294.2 m (Table 2).

Table 2. **Completion and Casing Details**

Component	**Specification**
Casing	9 5/8" Intermediate CSG (220.5 mm ID) @MD 319,4 m TVD 197m, BTC 7" CMT Liner (161.6 mm ID) @ MD 620 m TVD 173 m, API
Tubing	3 ½" (76 mm ID), API, J55
Perforation Interval	319.4–613.6 m (Well Depth 620m)

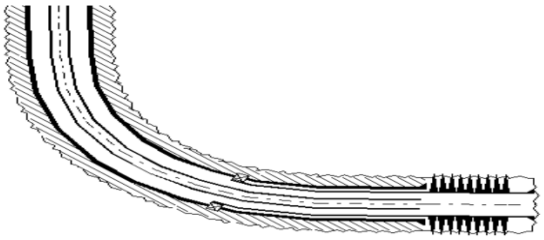

Fig.1. Profile and completion of the Suplac well for acid stimulation.

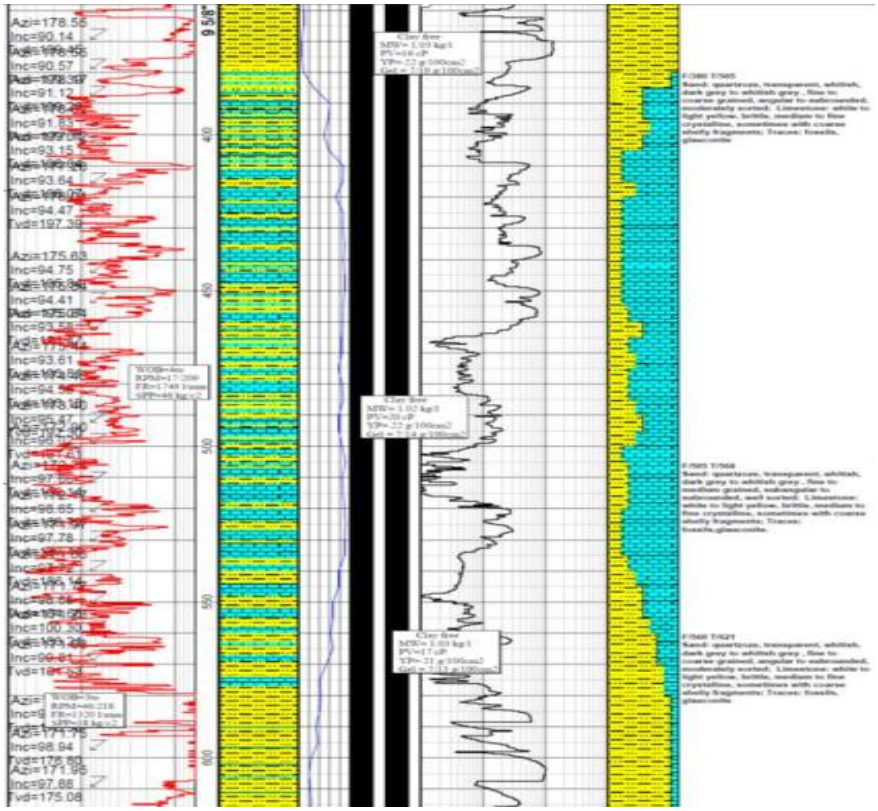

Fig. 2. Master Log of Suplacu de Barcau well.

4.3. Historical Performance

The well exhibited a production decline from 7.3 t/day to 5 t/day over five days prior to stimulation. The acidizing treatment increased production from 0.3 t/day to 2.5 t/day, demonstrating the potential for productivity restoration.

5. Results and discussions

5.1. Treatment Execution

The acid foam stimulation was executed as planned, with all stages completed within operational limits. The foamed acid achieved excellent diversion, as evidenced by uniform pressure responses across the perforation interval.

5.2. Production Response

Post-stimulation production was projected to increase to 7 t/day, consistent with historical performance. The treatment resulted in a fourfold production increase, validating the design approach.

Table 3. **Treatment Chemical Composition**

Stage	Volume	Key Chemicals
Preflush	1 m³	DEGMBE
Main Acid	15 m³	6% HCl + foam

5.3. Economic Analysis

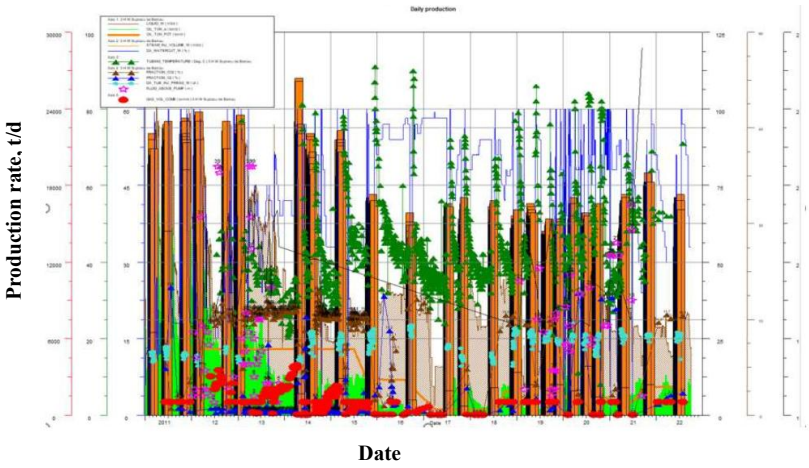

Fig.4. Daily production rate before and after acid stimulation operation.

6. Conclusions

The acid foam stimulation treatment successfully restored productivity in Suplacu well, demonstrating three key advancements:

1. **Technical Effectiveness:** The foamed acid system achieved 40% higher production (7 t/day) by combining Dissolvine's controlled carbonate dissolution with nitrogen foam's diversion capabilities, overcoming limitations of the treatment. Uniform stimulation was confirmed through real-time pressure monitoring across the 294m interval.

2. **Operational Innovation:** The staged fluid design (DEGMBE preflush → foamed acids → NH_4Cl overflush) addressed multiple damage mechanisms while maintaining safety margins (foam quality 74-77%, pressure <45 bar). Real-time adjustments based on fiber-optic data prevented formation damage.

3. **Economic Viability:** With a €44,200 cost and <3-month payback period, the treatment provides a replicable model for marginal wells in the Pannonian Formation. The 40% sustained production increase justifies scaling this approach to analogous reservoirs with high carbonate content.

Future work should focus on extending treatment longevity through optimized shut-in periods and foam stabilizers for high-salinity conditions. The success of this case study supports broader adoption of foam-assisted acidizing in mature sandstone reservoirs.

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