

Influence of erosive fluidization on the morphology of fluid flow and escape structures

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Key Points:

- We model the formation of fluid escape structures (FES) like pipes, chimneys and pockmarks.
- Model predicts pulsed gas flow and morphological features like conical pipe/chimney, annular gas channel, and W-, U-, ring-shaped pockmarks.
- Morphology of FES depends on sediment-fluid interactions (e.g. erodibility, anisotropy), not on intrinsic properties (e.g. permeability).

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Abstract

Mechanisms of fluid flow localization and pockmark formation remain an open question. Many conceptual models have been proposed, but very few predictive models exist. We propose a model based on erosive fluidization where seepage induced erosion, fluidization, and transport of granular material leads the formation of fluid escape structures (FES) like pipes, chimneys and pockmarks. The model predicts: 1) formation of conical focused flow conduits with brecciated core and annular gas channels encased within a halo of low permeability sediment, 2) pockmarks of diverse shapes and sizes, including W-, U-, and ring-shapes, and 3) pulsed gas release. Results show that the morphology of FES depends on properties related to sediment-fluid interactions (like erodibility and flow anisotropy), not on intrinsic sediment properties (like permeability). Although the study is theoretical, we show that our predicted FES have many real world analogs, highlighting the broad scope of the predictive capability of our model.

Plain Language Summary

Pockmarks are seafloor manifestations of subsurface fluid flow, typically found on top of focused flow conduits (pipes and chimneys), suggesting that the formation of pipes, chimneys, and pockmarks are inherently interlinked. Pockmarks are found worldwide and exhibit wide variability in shapes, sizes, and structure, making their characterization hard and quantitative analysis harder. Many conceptual models have been proposed to explain the observed pockmarks, seismic pipes and chimneys, but surprisingly few predictive models exist. Here, we propose a mathematical model based on the mechanism of erosive fluidization, where seepage of fluids erodes the sediment, and the eroded sediment particles are fluidized, transported, and redeposited. This redistribution of the sediment mass leads to localization of fluid flow, evolution of pipes and chimneys, and formation of pockmarks. Through numerical studies of idealized scenarios, we show that this model can not only simulate the formation of focused flow conduits and pockmarks of different shapes and sizes, but also makes important predictions regarding the role of intrinsic sediment characteristics (like permeability) vis-a-vis characteristics of sediment-fluid interactions (like sediment erodibility and flow anisotropy). Although this study is theoretical, we show that the results are widely applicable with many real world analogs based in diverse geological settings.

1 Introduction

Pockmarks are bathymetric depressions on the seafloor formed due to venting of subsurface fluids, which is accompanied by erosion and removal of sediment (Judd & Hovland, 2007). They are found worldwide on the floors of active or relict oceans and lakes (Sultan et al., 2014; Reusch et al., 2015; Böttner et al., 2019; Callow et al., 2021), and exhibit wide variability in their shapes and sizes (Gafeira et al., 2018). Pockmarks typically form on top of focused fluid conduits, which appear in seismic data as pipes or chimneys (K. J. Andresen, 2012; Karstens & Berndt, 2015; Cartwright & Santamarina, 2015), generally attributed to localized release of overpressure in the subsurface through hydraulic connection of deeper sediment layers with the seafloor (Cathles et al., 2010). These conduits are efficient pathways for fluid migration from deeper sediments to the seafloor and atmosphere, and are therefore, critical for constraining global carbon emissions (Berndt, 2005). Due to active fluid and hydrocarbon emissions, they are important ecological hotspots (Berndt, 2005), indicators of hydrocarbon reservoirs (Judd & Hovland, 2007; Strozyk et al., 2018), and potential geohazard for offshore operations (Vanneste et al., 2014; Roelofse et al., 2020).

Most field observations of pockmarks and seismic pipes/chimneys have been qualitatively explained using conceptual models based on mechanisms like capillary invasion, hydraulic fracturing, erosive fluidization, and local volume loss (e.g., due to carbonate dissolution or hydrate melting, etc.) (e.g., (K. Andresen et al., 2021; Cartwright & Santamarina, 2015) and references therein). However, surprisingly few predictive models can actually simulate the initiation and propagation of focused flow, and even fewer can resolve the evolution of pockmarks. Currently, two prominent models deal with the formation of pipes/chimneys: 1) based on *hydraulic fracturing* hypothesis where overpressured gas in the source rock induces fractures in the overburden, and a network of hydraulic fractures propagates towards the surface as high-permeability conduits (Wangen, 2020), and 2) based on the concept of *solitary porosity waves* where self-propagating high-porosity, high-permeability channels emerge spontaneously due to complex nonlinear coupling between fluid buoyancy, asymmetric compaction-decompaction of pores, and viscoplastic deformations of sediment matrix (e.g., (Räss et al., 2019; Yarushina et al., 2021)). Although not explicitly resolved, pockmarks appear in these models as a consequence of localized mechanical deformations within focused flow conduits. While these models are highly sophisticated and capture interesting dynamics related to flow localization,

77 they completely ignore aspects of erosive fluidization and sediment transport. Fluidiza-
 78 tion is ubiquitous in geological subsurface (McCallum, 1985). Pockmarks and pipes/chimneys
 79 are primarily considered to be erosive structures (Judd & Hovland, 2007), and there is
 80 evidence of mud slurry transport (Roberts et al., 2010) and complete or partial loss of
 81 stratigraphy within focused flow conduits due to fluidization and brecciation (Huuse et
 82 al., 2005).

83 To the best of our knowledge, no predictive models have considered focused fluid
 84 flow and pockmark formation through erosive fluidization. To address this gap, we pro-
 85 pose a mathematical framework that can resolve flow localization through internal ero-
 86 sion and fluidization, and simulate the evolution of seafloor and subsurface morphology
 87 through sediment redistribution. Using numerical simulations of an idealized pockmark
 88 formation scenario, we analyze the influence of sediment-fluid interactions on the mor-
 89 phology of fluid flow and escape structures.

90 **2 Methodology**

91 **2.1 Mathematical Model**

92 To model the physics of erosive fluidization, we conceptualize the subsurface sed-
 93 iment as an additive decomposition of two distinct physical states (or phases): 1) Intact
 94 sediment, where the porous structure is preserved, and 2) fluidized sediment, where the
 95 porous fabric is destroyed and granular material is suspended in water in a muddy-slurry.
 96 Phase transitions between intact and fluidized sediment states are controlled by erosion
 97 due to fluid seepage, and deposition due to limited carrying capacity of pore-fluids. Fluid
 98 flow drives phase transitions and leads to conservative redistribution of the granular ma-
 99 terial, affecting surface and subsurface morphology.

100 This conceptual model is formalized through a generalized mathematical frame-
 101 work where coupled fluid flow, sediment-fluid interactions, and conservative sediment trans-
 102 port are described within the macroscopic theory of porous media, and the changing seafloor
 103 morphology is resolved as a manifestation of the redistribution of aggregate sediment mass.

104 Domain of interest $\Omega \subset \mathbb{R}^d$ with $d = \{1, 2, 3\}$, is partitioned into two non-overlapping
 105 sub-domains: Free-flow domain $\Omega_w \subset \Omega$ and porous domain $\Omega_p \subset \Omega$, s.t., $\Omega_w \cup \Omega_p =$
 106 Ω and $\Omega_w \cap \Omega_p = \emptyset$. Inner boundary between these sub-domains, $\Gamma_{wp} \subset \mathbb{R}^{d-1}$, is in-
 107 stationary, evolving over time due to continuous sediment redistribution. The domain

108 and the associated homogenized representative elementary volume (REV) are described
 109 in Fig.1).

110 Three distinct phases are considered: 1) water, denoted by subscript ‘w’, 2) an ‘in-
 111 vading’ phase (e.g. gas, light hydrocarbons, etc.) by ‘n’, and 3) continuum sediment phase
 112 by ‘s’. Furthermore, within the scope of this study, the invading phase is assumed to be
 113 gaseous (much lighter than water). Therefore, eroded sediment particles, denoted by ‘f’,
 114 are fluidized only within w-phase. There is continuous exchange of mass between intact
 115 and fluidized sediment through erosion (by seepage of invading phase) and deposition
 116 (of particles suspended in water phase). The main governing equations, which include
 117 mass conservation statements for w-, n-, and s- phases and f-component, are as follows:

$$118 \quad \partial_t \phi \rho_w S_w + \nabla \cdot \rho_w \mathbf{v}_w = 0 \quad (1)$$

$$119 \quad \partial_t \phi \rho_n (1 - S_w) + \nabla \cdot \rho_n \mathbf{v}_n = 0 \quad (2)$$

$$120 \quad \partial_t (1 - \phi) \rho_s = -\epsilon_n + \delta_w \quad (3)$$

$$121 \quad \partial_t \phi \rho_w S_w \Theta_f + \nabla \cdot \rho_w \mathbf{v}_w \Theta_f = \epsilon_n - \delta_w \quad (4)$$

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 123 with, local porosity ϕ , wetting phase saturation S_w , mass fraction of the sediment sus-
 124 pended in water Θ_f , phase densities $\rho_{(\cdot)}$ s.t., $\frac{\rho_n}{\rho_w} \ll 1$, phase velocities $\mathbf{v}_{(\cdot)}$, and erosion
 125 and deposition rates ϵ_n and δ_w .

126 Sub-surface fluid seepage is characterized by low Reynolds numbers and can be mod-
 127 elled using Darcy’s law (Helmig, 1997). In the surface domain, families of Darcy-Brinkmann-
 128 Stokes models are considered more accurate when surface water run-off is dominant com-
 129 pared to sub-surface fluid seepage. However, in this study we ignore bottom water cur-
 130 rents, and therefore, assume that Darcy model is sufficient to resolve phase velocities in
 131 both sub-domains, such that,

$$132 \quad \text{for each } \alpha = \{w, n\}, \quad \mathbf{v}_\alpha = -\mathbf{K} \frac{k_{r\alpha}}{\mu_\alpha} (\nabla P_\alpha + \rho_\alpha \mathbf{g}) \quad (5)$$

$$133 \quad \text{where,} \quad K_i = K_{0,i} \exp \left[a_{0,i} \left(\frac{\phi - \phi_0}{1 - \phi_0} \right) \right] \quad \text{for each } i \in d \quad (6)$$

$$134 \quad \text{and,} \quad k_{rw} = S_w^{(2/\lambda+3)}$$

$$135 \quad k_{rn} = (1 - S_w)^2 \left(1 - S_w^{(2/\lambda+1)} \right) \quad (7)$$

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 137 where, \mathbf{K} is the intrinsic permeability (defined as a d -dimensional diagonal matrix), $K_{0,i}$
 138 and ϕ_0 are ‘reference’ permeability and porosity of the intact sediment, and $a_{0,i}$ is a model
 139 parameter which controls the range of permeability variation w.r.t. porosity (Hommel et

140 al., 2018). Note, when $\phi = \phi_0$, $K_i = K_{i,0}$, and when $\phi = 1$, $K_i := K_{i,max} = K_{0,i} \exp(a_{0,i})$.
 141 Finally, $\mu_{(\cdot)}$ are phase viscosities and $k_{r(\cdot)}$ the relative permeabilities (Helmig, 1997) with
 142 material parameter λ related to the particle size distribution.

143 Phase pressures $P_{(\cdot)}$ are related through a pressure jump, called capillary pressure,
 144 across the fluid-fluid phase boundaries, s.t.,

$$145 \quad P_n - P_w := p_c(\phi, S_w) \quad (8)$$

147 where, p_c can be modelled using empirical or analytical parameterizations (Helmig, 1997).
 148 Our general model implicitly resolves capillary pressure, but within this study, capillary
 149 effects are ignored (i.e., $p_c := 0$) to highlight the role of erosive fluidization in flow lo-
 150 calization, as opposed to the capillary hypothesis (Cathles et al., 2010).

151 Finally, erosion and deposition rates are modelled as (see (Rahmati et al., 2013)
 152 and references therein),

$$153 \quad \epsilon_n = e_0 (1 - \phi)^m \left| \frac{\mathbf{v}_n}{v_c} \right|^n \quad (9)$$

$$154 \quad \delta_w = ds_0 \left(\frac{\Theta_f}{\phi S_w} \right)^\gamma \quad (10)$$

156 with, internal erosion and deposition rate constants e_0 and ds_0 , characteristic seepage
 157 v_c , and empirical parameters m, n and γ .

158 2.2 Numerical Scheme

159 Governing equations (1)-(4) were discretized using fully-upwinded cell-centered fi-
 160 nite volume scheme, with P_w , S_w , ϕ , and Θ_f as primary variables. To evaluate erosion
 161 rates, fluid velocity fields were reconstructed using an $L2$ -projection of the phase pres-
 162 sures from their native $P0$ -space to a higher $Q1$ -space. The discrete model was par-
 163 titioned into three sub-modules: 1) two-phase flow module composed of the governing
 164 equations (1),(2) with primary variables $\mathcal{P}_1 = [P_w, S_w]^T$, 2) $L2$ -projection module with
 165 projected phase pressures as ‘intermediate’ primary variables $\mathcal{P}_2 = [\bar{P}_w, \bar{P}_n]^T$, and 3)
 166 sediment transport module composed of governing equations (3),(4) with primary vari-
 167 ables $\mathcal{P}_3 = [\phi, \Theta_f]^T$. The solution of the coupled problem was obtained by solving the
 168 sub-modules iteratively at each time-step using a blocked Gauss-Seidel method (Gupta
 169 et al., 2015). The numerical scheme was implemented in C++ based DUNE-PDELab
 170 (Sander, 2020), and used in-built matrix assembler and solvers (Newton and parallel Al-
 171 gebraic Multi-Grid).

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2.3 Computational Setting

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An idealized geological test setting (see Fig. 1) is considered where a light hydrocarbon (e.g. methane gas) is trapped under high pressure in a source rock layer sealed by a capillary barrier. The overlying sediment is assumed to be stratigraphically homogeneous, fully water saturated, and continuously connected to the seafloor. At $t = 0$, a fracture spontaneously punctures the capillary barrier and allows the escape of overpressured gas. We identify a 2D computational domain Ω as a region around the fracture, located just above the capillary barrier. Computational domain encompasses the overburden Ω_p as well as the water column Ω_w , and implicitly resolves the seafloor Γ_{wp} . Numerical parameters and material properties are summarized in Fig. 1. Reference permeabilities are chosen such that a broad range of continental shelf sediments are represented (Dutkiewicz et al., 2015).

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Here, we only focus on flow localization within Ω_p and evolution of Γ_{wp} due to sediment redistribution. We do not resolve the source of free gas in the source rock and the cause of the fracture. Moreover, to isolate the effects of internal erosion, we also ignore bottom water currents in Ω_w in the vicinity of Γ_{wp} .

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3 Results and discussion

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Simulations demonstrate the mechanism of erosive fluidization, where seepage of overpressured gas causes erosion of the sediment and subsequent fluidization, transport, and deposition of eroded soil particles. Distinct focused flow conduits open up in the subsurface and pockmarks appear at the seafloor. Figs. 2 and 3 show selected results from scenarios with $K_{0,1} = 10^{-13} \text{m}^2$, with an extended selection included in the Supplementary Material. Effects of erosive fluidization are analyzed in terms of $r_0 := \frac{\epsilon_0}{ds_0}$ (erosion vs deposition rate constants) and $K_F := \frac{K_{0,0}}{K_{0,1}}$ (lateral vs vertical permeability), where r_0 compares relative erodibility of granular material and K_F measures sediment anisotropy and stratigraphic layering. Results show that even for the same geological setting, gas source, and sediment hydraulic characteristics (i.e., permeability, porosity, etc.), the morphological manifestations of fluid-flow may not be unique. Rather, variability in sediment-fluid interactions can result in large differences in flow localization, gas fluxes, and pockmarks. Based on the numerical results, our key findings are:

- 202 1. Erosive fluidization leads to characteristic morphological features like conical
 203 focused-flow pathway with annular gas flow that may be interpreted as gas pipe/chimney,
 204 encased in a halo of low permeability sediment that acts as a seal against lateral
 205 gas transport. Figs. 2-A and 3-A show the focused-flow pathway and sediment halo,
 206 while Figs. 2-B and 3-B highlight the annular gas channels. The sediment within
 207 the focused flow pathways undergoes intense seepage driven mixing, resulting in
 208 partial or total loss of stratigraphic structure and brecciation. These features bear
 209 striking similarities with the sand-box experiments analyzing formation of pierce-
 210 ment structures through controlled fluidization (McCallum, 1985; Nermoen et al.,
 211 2010).
- 212 2. Erosion and deposition are competing processes with complex feedbacks. Higher
 213 relative erosion vs deposition (r_0) leads to more prominent cylindrical focused-flow
 214 pathway with a ‘tight’ halo; whereas, higher sediment anisotropy (K_F) leads to wider
 215 focused-flow pathway with wide and more diffuse sediment halo.
 216 In literature, the terms ‘chimney’ and ‘pipe’ are often used interchangeably for fo-
 217 cused flow pathways, although some authors (e.g., (K. Andresen et al., 2021; Karstens
 218 & Berndt, 2015)) consider a stricter nomenclature where pipe refers to cylindri-
 219 cal flow conduits with sharp boundary between focused flow zone and host sed-
 220 iment, and chimney refers to conduits with chaotic transition. Based on this nomen-
 221 clature, our results suggest that high r_0 leads to pipes and high K_F leads to chim-
 222 neys, although transition between the two structures is continuous.
 223 On the seafloor, higher r_0 leads to narrower pockmarks with sharp depressions,
 224 whereas variations of K_F show more complex trends: If r_0 is high and K_F is low,
 225 sediment collects on the rim of the pockmark, forming a raised ring-shaped en-
 226 casing. As K_F increases, more and more lateral transport occurs leading to ‘flat-
 227 tening’ of the ring, formation of secondary rings, and eventually, large lateral ex-
 228 tension of the pockmarks. On the other hand, as r_0 decreases, smaller sediment
 229 mass reaches the surface and ringed pockmarks do not form. For small enough r_0 ,
 230 deposition exceeds erosion, which leads to reversal of the effect of increasing sed-
 231 iment anisotropy on lateral extension, leading to narrower and shallower pockmarks.
- 232 3. Differences in sediment-fluid interactions lead to diversity in pockmark shapes
 233 and sizes. Within the constraints of this test setting, two interesting pockmark
 234 geometries emerge, W-shaped and ring-shaped.

- 235 • W-shaped pockmarks are widespread in nature (e.g., (Watson et al., 2020; Gafeira
 236 et al., 2018)), and are associated with active fluid escape (Lazar et al., 2019;
 237 Schattner et al., 2012). In plan-view, such pockmarks are reported as either ra-
 238 radially symmetric (e.g., Fig.4-A4) or as pockmark-pairs (e.g., Fig.4-A2,3,5). Our
 239 results suggest that the depression of the annular gas channel follows radial sym-
 240 metry. However, as the depressions become sharper, pockmarks can deviate from
 241 their radial symmetry and localize to form pockmark-pairs. An example in lit-
 242 erature where our results apply is a ~ 60 m across and ~ 10 m deep, radially sym-
 243 metric, W-shaped pockmark reported offshore northern Israel (Schattner et al.,
 244 2012) (see Fig.4-A4)). This geological setting has many similarities with our ide-
 245 alized scenario like, the pockmark is linked to active venting of methane gas,
 246 is located on seabed in shallow water depth (< 100 m), and sits directly above
 247 a chimney originating just above the LGM (last glacial maxima) unconformity
 248 at depths between 100 and 200 m. Another example is a pockmark-pair reported
 249 in the Scanner region (Callow et al., 2021) (Fig.4-A3), also linked with active
 250 venting of methane-rich gas. More strikingly, gas escape from this pockmark
 251 exhibits an episodic character.
- 252 • While the inverted-dome in the center of the pockmarks is an intrinsic feature
 253 of active-fluid escape, our model suggests that for high K_F and low r_0 , this dome
 254 becomes flatter such that the W-shape transitions to a U-shape with a wide
 255 and shallow base. Fig. 4-C1 shows an example of a shallow U-shaped pockmark
 256 reported in Sea of Galilee (Lazar et al., 2019). Such shallow U-shaped pockmarks
 257 are linked to active fluid escape, and are therefore, different from the inactive
 258 V-shaped pockmarks that transition to U-shape through surface erosion from
 259 bottom water currents.
- 260 • Our results show that erosive fluidization can lead to ring-shaped pockmarks,
 261 and predict that these can emerge in sediments with a combination of high erodi-
 262 bility and low anisotropy. Occurrence of such pockmarks is relatively rare, with
 263 Hudson Bay being a rather prominent example (Fig.4-B1), where these pock-
 264 marks likely formed in post glacial times due to movement of icebergs that may
 265 have breached capillary seals, allowing escape of unknown hydrocarbon fluids
 266 from source rocks possibly located at depths of ~ 80 – 200 m (Roger et al., 2011).
 267 In Hudson Bay, the Holocene sediments (surficial deposits of 6–20m and bank

268 and barrier deposits of 200m thickness) are made of unconsolidated layers of
 269 fine sandy to silty clays that are highly susceptible to erosion. Moreover, the
 270 surficial deposits are acoustically transparent, suggesting little to no stratigraphic
 271 layering. Both these sediment characteristics are qualitatively congruent with
 272 our prediction.

273 4. Gas release occurs in pulses (Figs. 2-D, 3-D). A combination of low r_0 and high
 274 K_F lead to higher amplitude (black curves), while high r_0 and high K_F lead to
 275 higher frequency of gas pulses. In nature, periodicity of high frequency gas pulses
 276 is likely masked by the bottom water currents. However, our results suggest that
 277 the pulsed release of gas is an intrinsic feature of the physics of flow localization
 278 through erosive fluidization. Interestingly, this pulsed gas release was also reported
 279 in the experiments by Nermoen et al., (2010), and the simulated localization of
 280 gas in the subsurface closely resembles the air ascent imaged in these experiments
 281 (Fig. 4-D1).

282 5. Finally, our results show that intrinsic permeability $K_{0,1}$ does not impact the
 283 shape and size of fluid escape structures (Fig.5-A). It only affects the time-scale
 284 of flow localization. Furthermore, the morphology of pockmarks and pipes/chimneys
 285 is controlled by the ratio of e_0 and ds_0 (i.e., r_0) and not by their individual mag-
 286 nitudes. This strongly suggests that the morphology of the fluid escape structures
 287 depends on the properties controlling sediment-fluid interactions, like erodability
 288 and flow anisotropy, rather than the intrinsic sediment properties like permeabil-
 289 ity. Interestingly, differences do appear in the gas flow behaviour (Fig.5-B), with
 290 lower $K_{0,1}$ leading to higher frequency and lower e_0 (or conversely higher ds_0) lead-
 291 ing to higher amplitude gas pulses.

292 4 Conclusions

293 We presented a mathematical model for simulating flow localization and pockmarks
 294 formation through erosive fluidization and sediment redistribution. Numerical simula-
 295 tions of an idealized scenario of gas escape from over-pressured source rock showed 1)
 296 formation of conical focused flow conduits with brecciated core and annular gas chan-
 297 nels encased within a halo of low permeability sediment; 2) pockmarks of diverse shapes
 298 and sizes on the seafloor, including W-, U-, and ring-shapes; and 3) a pulsed release of
 299 gas. Results highlight the dominant role of sediment-fluid interactions. In particular, they

300 suggest that evolution of surface and subsurface morphologies depends on flow anisotropy
 301 but not on intrinsic permeability. Although theoretical, our results have striking real-
 302 world analogs in nature as well as controlled experiments.

303 **Open Research**

304 Version 2.8 of the C++ based ‘DUNE-PDElab’ toolbox was used for the implemen-
 305 tation of the numerical scheme described in Sec. 2.2. This version is preserved at [https://](https://gitlab.dune-project.org/pdelab/dune-pdelab)
 306 gitlab.dune-project.org/pdelab/dune-pdelab and developed openly at [https://](https://www.dune-project.org/)
 307 www.dune-project.org/. The archiving of the source code for the model and test sce-
 308 narios presented in this manuscript is underway in the following public repository: [https://](https://git.geomar.de/shubhangi-gupta/erosivefluidizationmodel.git)
 309 git.geomar.de/shubhangi-gupta/erosivefluidizationmodel.git.

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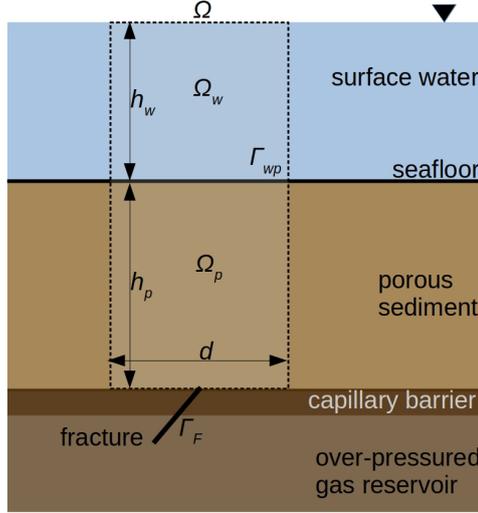
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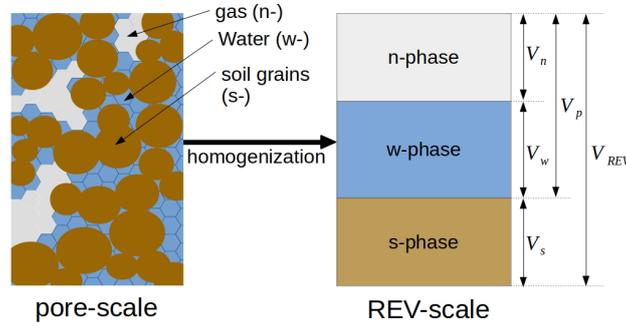
A Test-setting and computational domain.

A

Ω denotes the 2D computational domain, composed of non-overlapping surface (free-flow) and sub-surface (porous) sub-domains Ω_w and Ω_p such that $\Omega_w \cup \Omega_p = \Omega$ and the evolving 1D sea floor Γ_{wp} .

Fracture Γ_F (not part of Ω) transports over-pressured gas from reservoir to the overburden porous sediment (i.e. Ω_p)

Values of h_w , h_p , and d are specified in part (C) below.



B Representative elementary volume (REV).

B

On REV scale, following homogenized variables are defined:

- Porosity $\phi(\mathbf{x}, t) = \frac{V_p}{V_{REV}}$ such that $0 < \phi < 1$ in Ω_p and $\phi = 1$ in Ω_w .
- Saturations for mobile (i.e. w- and n-) phases, $S_w(\mathbf{x}, t) = \frac{V_w}{V_p}$ and $S_n(\mathbf{x}, t) = \frac{V_n}{V_p}$ such that $S_w + S_n = 1$

parameter	symbol	unit	value
computational domain			
height of water column	h_w	m	100
height of sediment column	h_p	m	200
domain width	d	m	500
domain discretization	$\Delta x, \Delta y$	m, m	2.5, 1
time steps	Δt	s	adaptive $1 \leq \Delta t \leq 3600$
excess gas pressure	$\Delta P_n _{\Gamma_F}$	MPa	2
material properties and parameters			
reference porosity	ϕ_0	-	0.2
reference permeability *	$K_{0,1}$	m^2	10^{-13}
	$K_{0,0} := K_F K_{0,1}$	m^2	$K_F = \{1, 10, 100\}$
permeability model parameters	$a_{0,1}$	-	3
	$a_{0,0} := a_F a_{0,1}$	-	$a_F = 1$
	λ	-	1.2
erosion model parameters **	e_0	$kg/m^3 \cdot s$	1
	m	-	1/2
	n	-	1
	v_c	m/s	10^{-6}
sedimentation model parameters	ds_0	$kg/m^3 \cdot s$	{0.01, 0.02, 0.04}
	\mathcal{J}	-	1
gas density	ρ_n	kg/m^3	10
water density	ρ_w	kg/m^3	1027

C Material properties and test parameters.

C

* Reference permeability $K_{0,1} = 10^{-13}$ is a reference case. Other permeability values, $K_{0,1} = \{10^{-11}, 10^{-15}\}$, were also tested.

** Reference permeability $K_{0,1}$ and characteristic seepage v_c are related. For $K_{0,1} = 10^{-11}$, $v_c = 10^{-4}$ and for $K_{0,1} = 10^{-15}$, $v_c = 10^{-8}$

Figure 1. REV, test setting, and parameters.

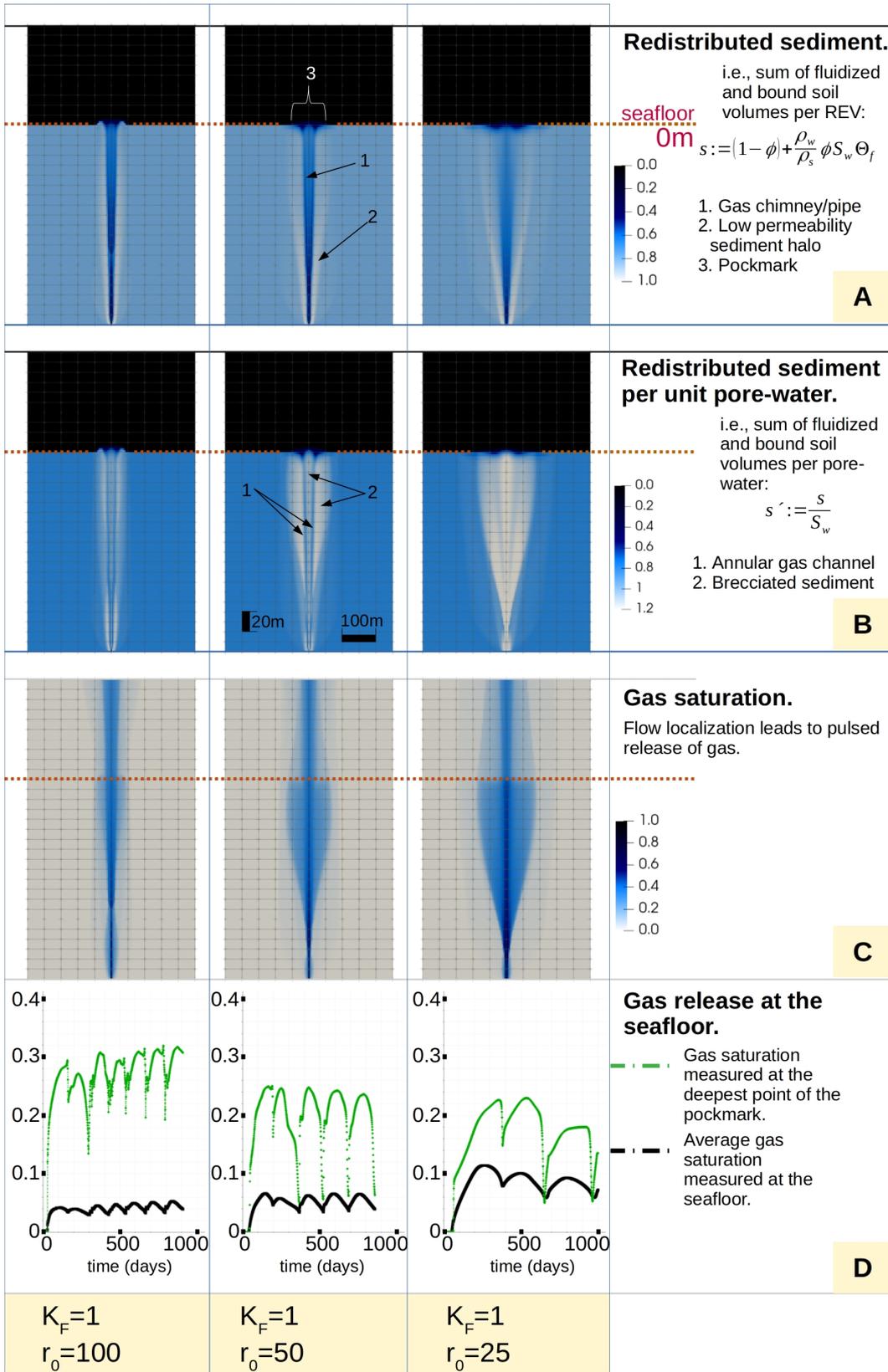


Figure 2. Impacts of relative erodibility r_0 on sediment redistribution, gas flow, and morphology of pockmark and pipe/chimney.

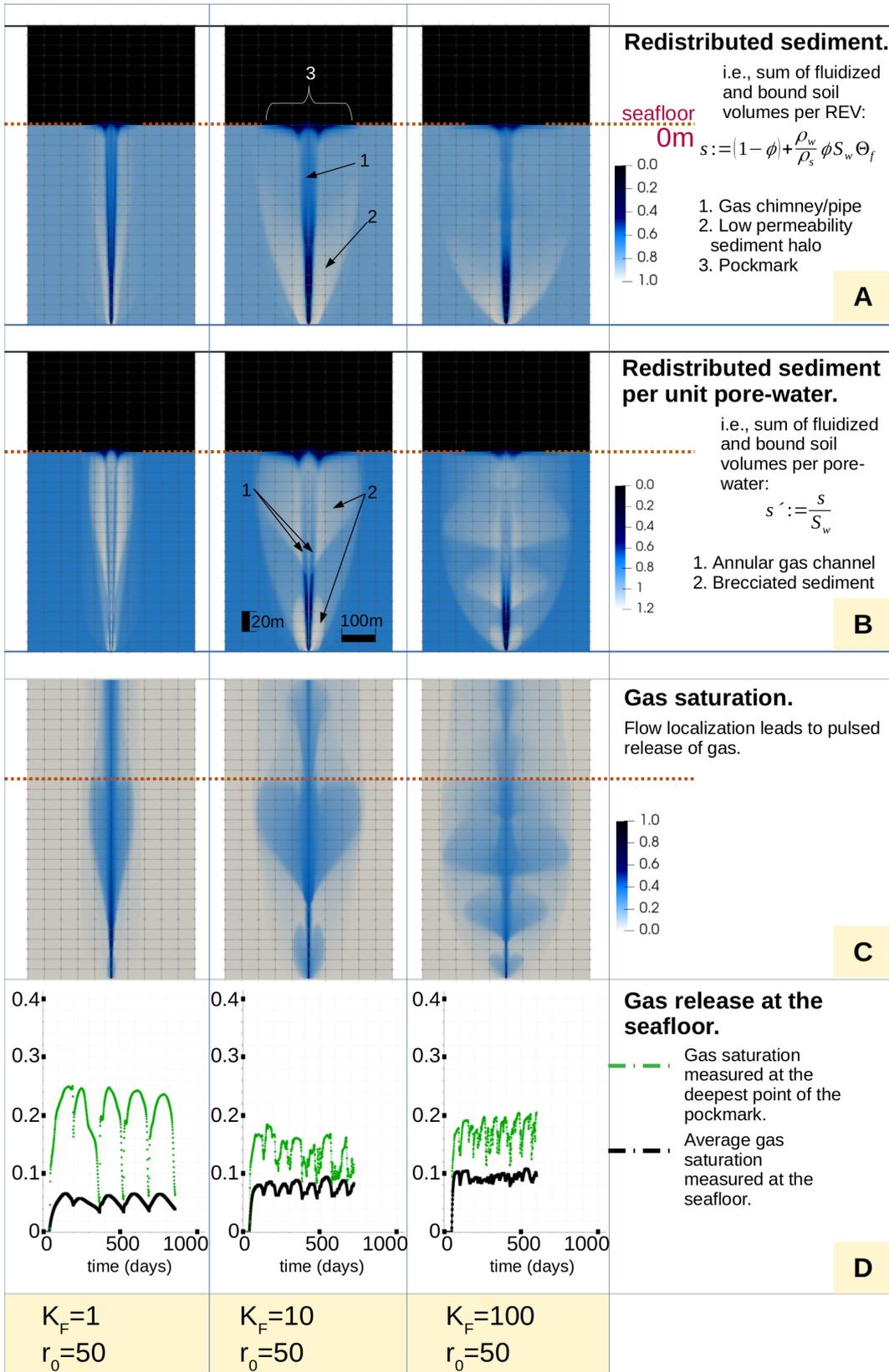


Figure 3. Impacts of sediment anisotropy K_F on sediment redistribution, gas flow, and morphology of pockmark and pipe/chimney.

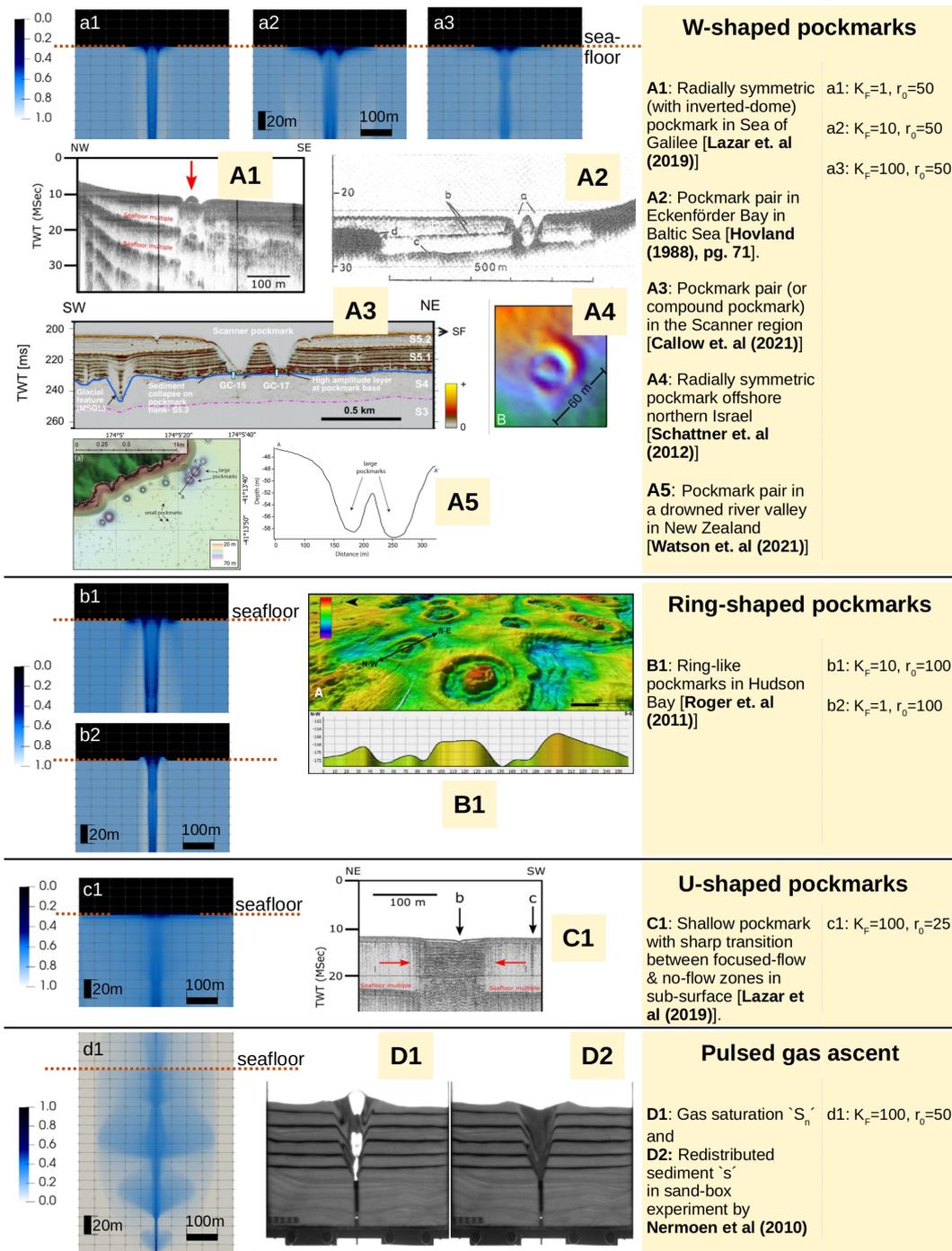


Figure 4. Qualitative similarities between simulated pockmarks (a1-3, b1-2, c1, d1-2) and those reported in literature (A1-5, B1, C1, D1-2). Pockmarks are compared on the basis of shapes, i.e. (A1-5;a1-3) W-, (B1;b1,2) ring-, and (C1;c1) U-shapes. Also shown are (D1,2) sand-box experiment results, and its similarity with (d1) simulated gas ascent behaviour.

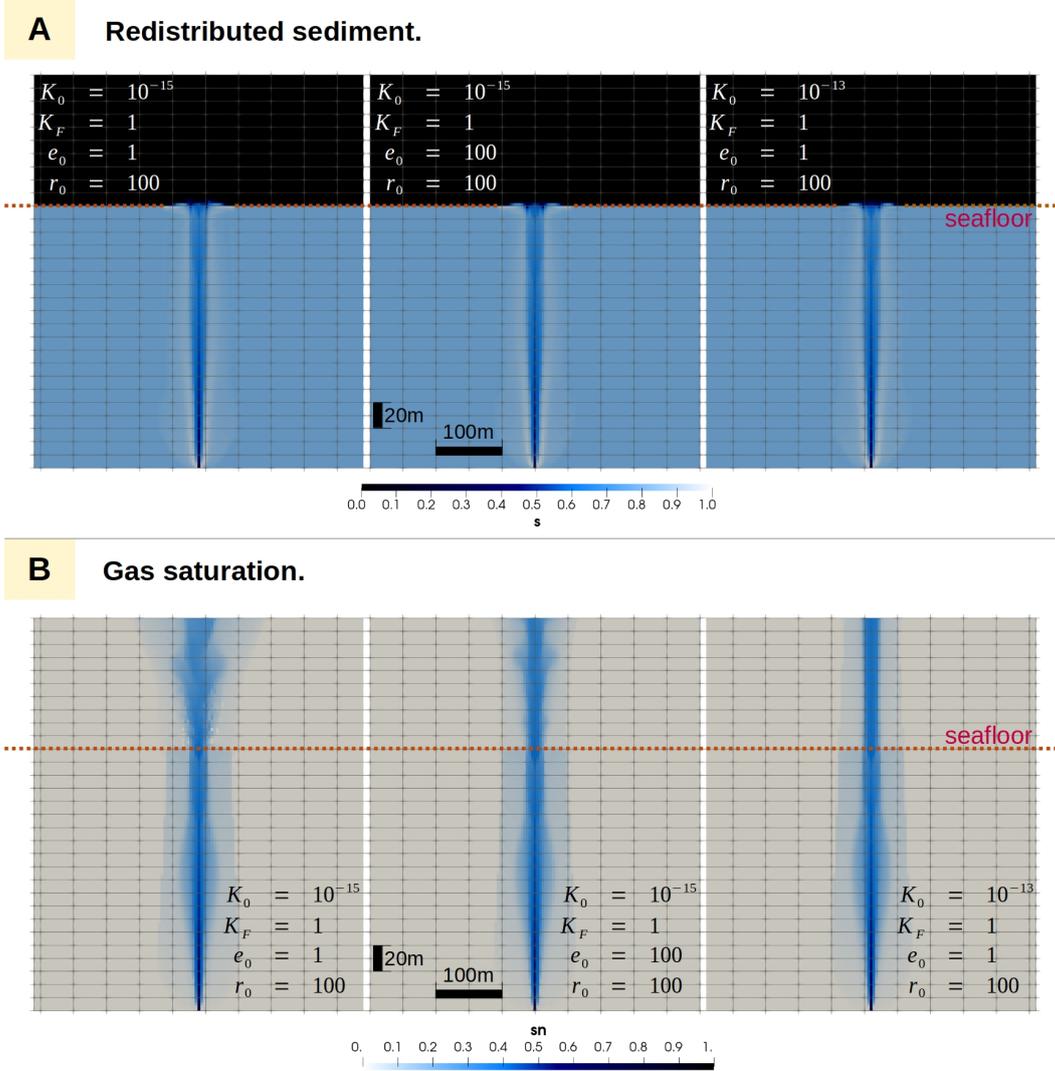


Figure 5. Impacts of intrinsic permeability $K_{0,1}$ and erosion rate constants e_0 on the evolution of surface and subsurface morphological features as well as the gas flow behaviour. Snapshots for scenarios with $K_{0,1} = 10^{-15}m^2$ correspond to time $t = 100$ years, while those with $K_{0,1} = 10^{-13}m^2$ correspond to $t = 1$ year.