NUMERICAL MODELING OF FLUID FLOW IN GAS HYDRATE BEARING SEDIMENTS IN BLACK SEA

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SCAN FOR ABSTRACT

What is the motivation in this research ?

As global energy demand surges, searching for innovative energy sources intensifies. In this dynamic perspective, the exploration of gas hydrates emerges as a pivotal pursuit, given their remarkable energy potential—housing 164 cubic meters of natural gas within just one cubic meter of space. Among regions of strategic interest, the Black Sea stands out for its substantial gas hydrate reserves. Seismic reflection sections serve as indispensable tools for mapping gas hydrates, while numerical modeling stands as the sole reliable method for comprehending their dynamic behavior over time, encompassing phenomena such as migration and dissolution within marine sediments. Understanding the principal factors influencing their stability is paramount, especially for predicting potential gas hydrate reservoirs and ensuring their stability during production. In this context, the proposed project titled "Numerical Modeling of Fluid Flow in Gas Hydrate Bearing Sediments in Black Sea" marks a pioneering attempt in the field. Its innovative approach not only enhances the significance and value of this study but also promises to yield invaluable insights into the complex dynamics of gas hydrate reservoirs, thereby advancing our understanding of this critical energy resource.

GAS HYDRATE

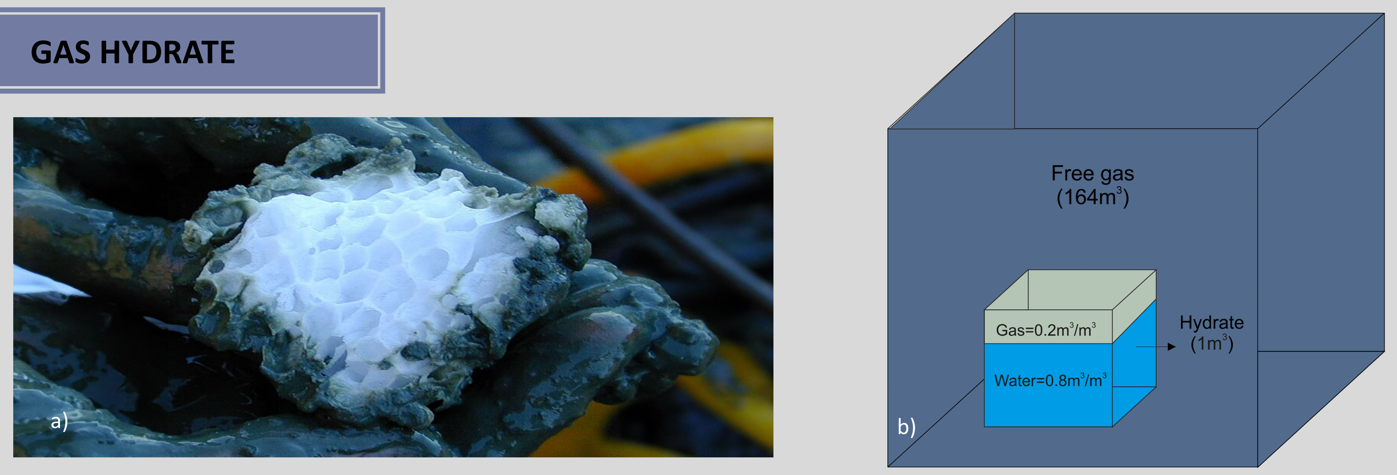

Fig.1. (a) Extracted gas hydrate sample. Retrieved from https://en.wikipedia.org/wiki/Clathrate_hydrate
(b) Methane hydrate composition.

- Gas hydrates are crystalline compounds formed when water (or ice) comes into contact with small molecules under specific temperature and pressure conditions.
- Gas hydrate deposits are found in active and passive continental margins as well as in permafrost areas where stable conditions of low temperature and sufficient gas saturation exist.
- It is known that at least 95% of natural gas hydrates are located in ocean sediments, with the remaining being associated with permafrost structures (Kvenvolden, 1993; Dillon, 2002).

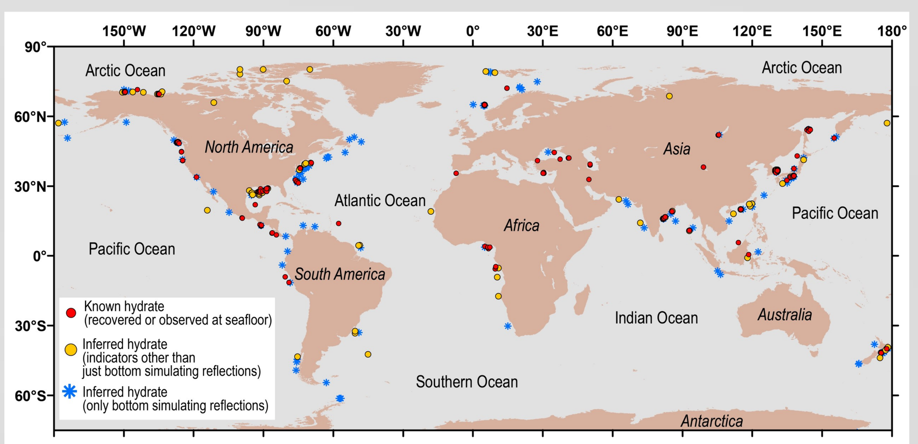

Fig.2. Map of identified gas hydrate regions and detection methods worldwild (USGS,2020).

STUDY AREA

The Black Sea, spanning an impressive 432,000 km², is a semi-closed basin renowned for its unique characteristics. Notably, it holds the distinction of being the world's largest anoxic (oxygen-free) basin, maintaining connections to the global oceans via the Bosphorus and the Dardanelles.

The Danube Deep Sea Fan, the main study area, is one of the most advanced deep sea sediment deposition systems in Europe, fed by the Danube River. Over time, sediment deposition has played a pivotal role in shaping the geological structure, transforming the northwestern Black Sea shelf from its coastal origins to the depths of its basin. Notably, this transformation is marked by the presence of extensive deep-sea fan complexes, with the Danube Deep Sea Fan standing as a prominent example. Renowned for its fine-grained turbidite system, as elucidated by Popescu et al. (2001), the Danube Deep Sea Fan represents a fascinating and intricate geological phenomenon within the Black Sea's dynamic ecosystem.

NUMERICAL MODELING

Gas hydrate modeling entails the meticulous consideration of numerous factors, ranging from regional geology to temperature and pressure conditions, as well as the intricate interplay of fluid dynamics within sediments and biogeochemical processes impacting hydrate formation and dissociation. Given the directional dependency inherent in subsurface structures and the complexity of model geometries, numerical modeling becomes indispensable. Therefore, the computational fluid dynamics (CFD) program ANSYS FLUENT emerges as the most fitting method for conducting comprehensive fluid and temperature analyses. Leveraging its advanced capabilities, ANSYS FLUENT enables precise simulations that account for the intricacies of gas hydrate systems, thereby facilitating a deeper understanding of their behavior in diverse geological settings.

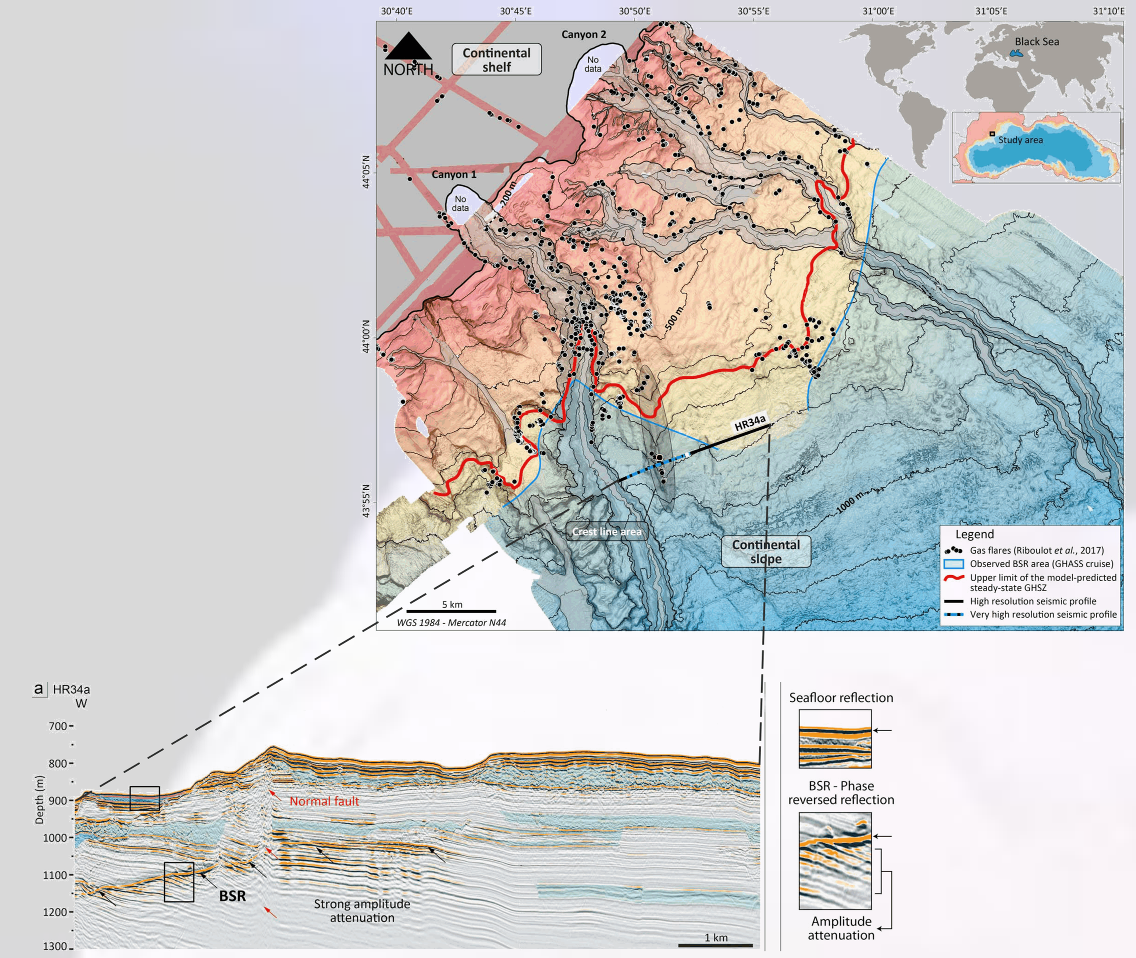

Fig.3. Location of the study area and digitalized seismic section image (modified from Ker et al.,2019).

The seismic section published by Ker et al. (2019) is selected for numerical modeling. This section contains the BSR (Bottom Simulating Reflector) level, which represents the bottom of the gas hydrate zone with a strong reflection. Additionally, the section encompasses the fault, providing an opportunity to investigate the fault's impact on the model.

CONSTRUCTING MESH

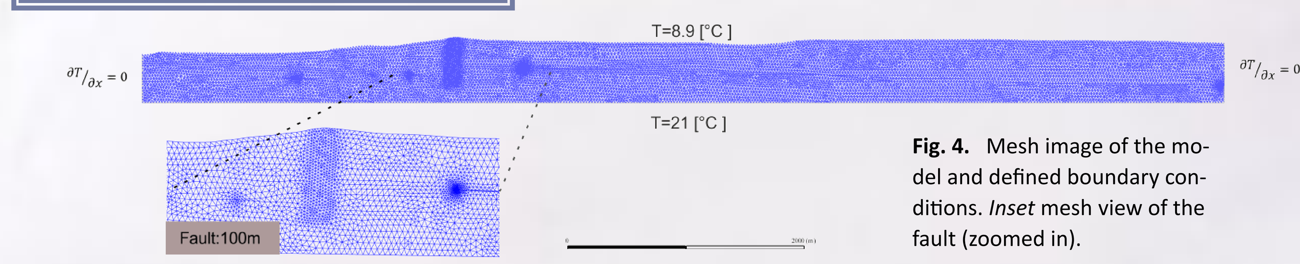

Fig. 4. Mesh image of the model and defined boundary conditions. *Inset* mesh view of the fault (zoomed in).

- In this section, the exact cross-sectional image of the HR34A seismic section shared in Figure 3 was digitized,.
- The model has a width of 9155.72 m and a depth of 553.5 m. The thickness of the fault interpreted as a normal fault is assigned as 100 m.
- The heat flux conditions on the left and right walls was set to "0" due to the adiabatic consideration of the system implementations.
- Riboulot et al. (2017) reported a sea floor temperature of 8.9°C. A bottom wall temperature of 21°C is appointed using a thermal gradient value of 24.5°C/km for the investigation area.
- The triangular mesh geometry was discretized using smaller mesh element sizes (12.0 m) for the fault and its immediate surroundings (Fig.4.). As one moves away from the fault zone, the mesh element size increases to 24.0 m.
- The model consists of 19314 triangular elements, 10064 notes.
- The density of seawater was taken as 1025 kg/m³ (Zander et al., 2017) and the gravitational acceleration was included in the model as 9.81 m/s².

Fig.5. Structures defined in the seismic section.

- Constructed model consists of 19 units and the solid material of the whole model is basaltic bedrock.
- The fault is assigned with lower permeability and lower porosity compared to the surrounding sediments.

Table 1. Physical parameters of each sediment.

Unit	Fault	s1_1	s1_2	s2_1	s2_2	s3_1	s3_2	s4_1	s4_2	s5	s6	s7	s8_1	s8_2	s9	s10	s11	s12	bsr_ bottom
Permeability (m^2)	1e+14	1e+15	1e+15	1e+15	1e+15	1e+15	1e+15	1e+15	1e+15	1e+15	1e+15	1e+15	1e+15	1e+15	1e+15	1e+15	1e+15	1e+15	1e+15
Porosity	0.20	0.36	0.37	0.36	0.36	0.35	0.35	0.35	0.35	0.34	0.34	0.34	0.34	0.34	0.33	0.33	0.33	0.32	0.35
Reaction												✓							✓

CHEMICAL REACTION

The most important step in the setup section is to initiate a chemical reaction within the system. The primary purpose of this implementation is to simulate chemical interactions of those hydrate related free gases (methane) which take place in free gas sediment.

$$CH_4(g) \; 2H_2O(\ell) \longrightarrow CO_2(g)$$

Underneath the methane sediment there lies the free gas sediment which will host the chemical interactions of methane with groundwater. Methane, also known as free gas emitted from solid gas hydrate, reacts with groundwater to produce CO_2(g) and H_2(g). In Table 2, all materials' physical properties are defined.

Table2. Physical parameters of each materials.

Parameters	Hydrogen (H_2)	Carbon-dioxide (CO_2)	Methane (CH_4)	Water-liquid (H_2O)	Basaltic-bedrock (Solid)
Density [kg/m^3]	0.08189	1.7878	0.6679	998.2	3300
Cp (Specific Heat) J/(kg K)	(UDF	(UDF)	(UDF)	4182	871
Thermal Conductivity [W/(m K)]	0.1672	0.0145	0.0332	0.6	2.5
Viscosity [kg/(m s)]	0.008411	1.37e-05	1.087e-05	0.001003	
Molecular Weight [kg/kmol]	2.01594	44.00995	16.04303	18.0152	
Standard State Enthalpy [J/kgmol]	0	-3.935e+08	-7.49e+07	-2.858e+08	
Standard State Entropy [J/(kgmol K)]	130579.1	213720.2	186040.1	69902.21	

CALCULATION PARAMETERS

In this marine sediment system, it was assumed that a certain amount of methane exists with a mass fraction of 0.36; this implies that methane occupies 36% of the free gas sediment. By applying chemical reactions to the free gas sediment, the behavior of methane in this chemical reaction as a reactant and its products were observed over time. Therefore, calculations were initiated with a certain amount of methane, and since there is no methane input, it is known that there is no infinite methane source to be consumed at a certain point. As a result, our models were run over a specific time frame 1 minute, 3 minutes, 5 minutes, 20 minutes and 60 minutes, respectively.

RESULTS

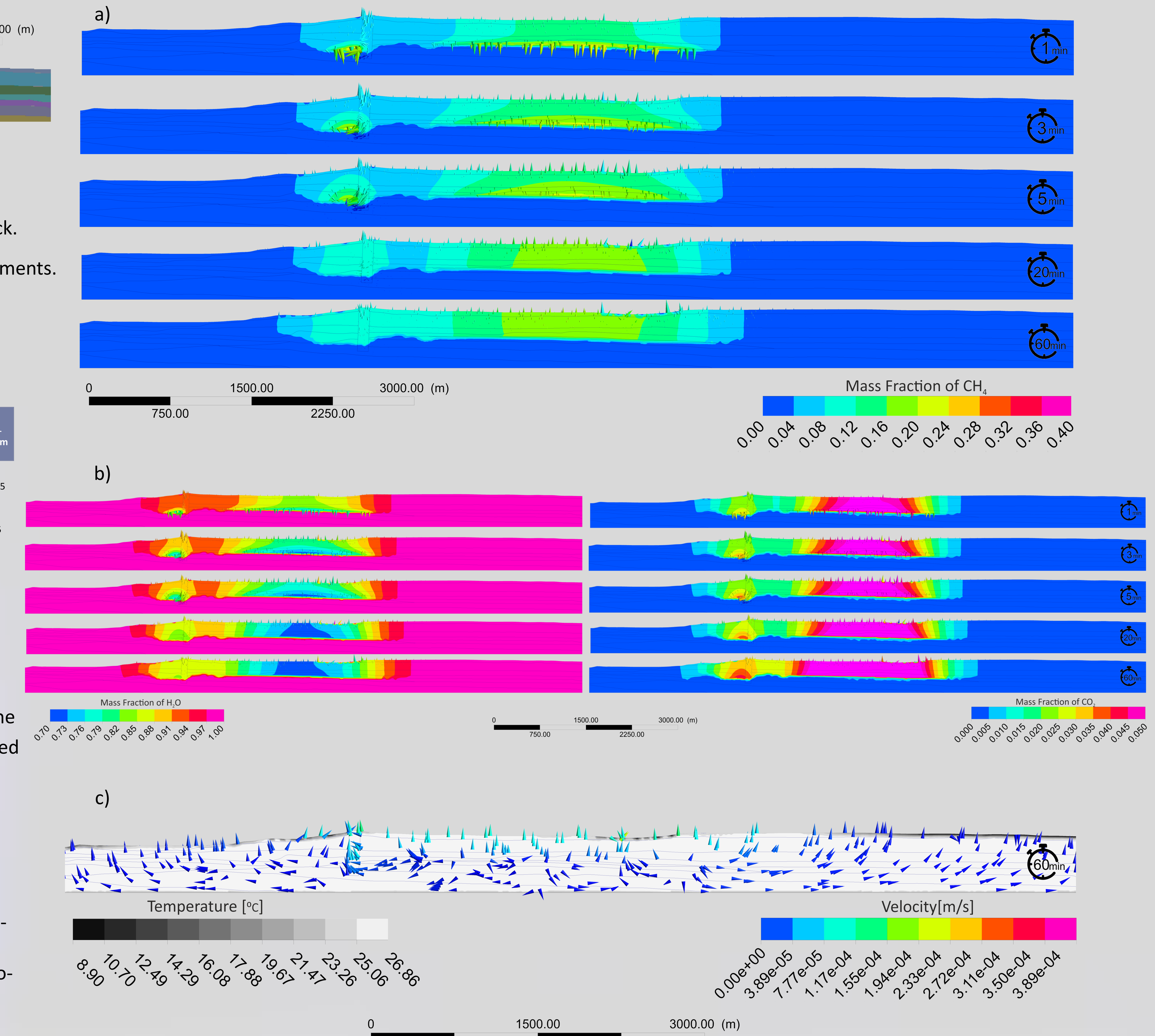

Fig.7. a) Mass fractions of CH_4 at 1 min, 3 mins, 5 mins, 20 mins and 60 mins, respectively. **b)** Mass fractions of H_2O and mass fractions of CO_2 at 1 min, 3 mins, 5 mins, 20 mins and 60 mins, respectively. **c)** Calculated fluid flow and heat flow for 60 mins.

CONCLUSIONS

- Dissolved CH_4 exhibits a propensity to disperse from its initial sedimentary reservoirs (s7 and bsr_bottom) into the surrounding sediments right from the onset.
- As anticipated, the CH_4 dissolution reaction prompts CO_2 production within the models, manifesting as a diffusion through sediments and a consequent decrease in the H_2O mass ratio. Notably, these reactions exhibit localized intensity in regions where they occur.
- Faults serve as pivotal conduits for the transportation of all materials, facilitating their movement with notable efficacy.
- Fluid flow velocities exhibit noticeable increases in proximity to and within fault zones.
- The fault establishes a pathway for fluid migration, characterized by heating at and subsequent density reduction. Consequently, areas surrounding the fault register lower temperatures compared to adjacent regions.

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