Numerical Modeling of Fluid and Heat Flow in the Southern North Sea

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QR code of the abstract:

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Motivation

- Understanding **fluid flow and temperature distribution** in geothermal potential fields is crucial, providing valuable insights into the governing mechanisms.
- **Faults and salt structures** significantly influence fluid and heat flow, making exploration of **geothermal potential** in the subsurface imperative. Numerous studies have investigated this aspect (Ward et al., 2016; Daniilidis & Herber, 2017; Üner et al., 2019; Alves et al., 2022; Başokur et al., 2022; Zhang & Alves, 2024).
- **The objective** of this research is to develop a two-dimensional real earth model using high-resolution seismic reflection data from the Broad Fourteens Basin in the Southern North Sea. This model aims to accurately observe heat and fluid flow dynamics and temporal changes within the basin.

How do geological features like salt structures and faults in the region impact the subsurface system?

Mathematical Model

- The model box, considered a mathematical model, has a width of 20 km and a length of 2193 m. Fault thicknesses within the model were taken as 100 m.
- The vertical boundaries of the model are insulated walls that do not allow mass and heat transfer (impermeable and adiabatic). Horizontal layers are in an isothermal. Based on well data from the region (K15-09 well), the temperature value of the upper wall is fixed at 55°C, and the temperature value of the lower wall is fixed at 117°C (Alves et al., 2022).
- The pressure boundary condition applied to the upper wall was defined as 3.14486e7 Pa by including the depth at which the seismic section starts and the water column pressure in the calculation.
- The models were solved in a time-dependent approach. In the software used (ANSYS FLUENT), Darcy's law (Equation 1) is valid and solves the equations of mass, energy, and momentum conservation, simultaneously (Energy conservation in Equation 4). The calculated Darcy velocities satisfy the continuity equation shown in Equation (2). Moreover, inertial effects are neglected and the density of the fluid (ρ_w) is assumed to vary with temperature according to the Boussinesq equation (Equation 3).

$$u = -\frac{K}{\mu}(\nabla P - \rho_w g) \quad (1)$$

$$\nabla \cdot (\rho_w u) = 0 \quad (2)$$

- u is the flow velocity (m/s), K is the permeability of the medium (m^2), μ is the dynamic viscosity of the fluid (kg/ms), P is the pressure in the medium (Pa), ρ_w is the density of the fluid (kg/m^3), g is the acceleration of gravity (m/s^2), ∇ is the Laplace operator.

Parameter	Value	Unit
Density of fluid (ρ_f)	998.2	kg/m^3
Specific Heat of fluid (Cp)	4182	J/kgK
Thermal Conductivity of fluid (k)	0.6	W/mK
Viscosity of fluid (μ_f)	0.001003	kg/ms
Density of sediment (ρs)	3300	kg/m^3
Specific Heat of sediment (Cp)	871	J/kgK
Thermal Conductivity of sediment (k)	2.5	W/mK
Density of salt (ρ_f)	2170	kg/m^3
Specific Heat of salt (Cp)	880	J/kgK
Thermal Conductivity of salt (k)	5.4	W/mK

Table 1. The fluid and heat flow calculations' parameters were taken from previous research (Daniilidis & Herber, 2017; Alves et al., 2022).

$$\rho_w = \rho_0[1 - \beta(T - T_0)] \quad (3)$$

- ρ_0 is the density of the fluid at time T_0 (kg/m^3), and β is the coefficient of thermal expansion (1/K).

$$\rho c_p \frac{\partial T}{\partial t} + \nabla \cdot (u \rho_w c_p T) = \nabla \cdot (\lambda \nabla T) \quad (4)$$

- c_p is the heat capacity of the porous medium (J/kgK), λ is the thermal conductivity coefficient of the saturated porous medium (W/mK) (McKibbin, 1986; Nield & Bejan, 1999).

Geological Unit	Permeability (kx/kz) (m^2)	Porosity (φ) (1)
Fault	1e-14	0.2
Sediment	1e-15	0.1
Faulted Bedrock Layer	1e-18	0.2
Salt	1e-25	0.01

Table 2. The medium parameters were determined in an approach consistent with previous modeling research (McKenna & Blackwell, 2004; Daniilidis & Herber, 2017; Düşünür Doğan ve Üner, 2019).

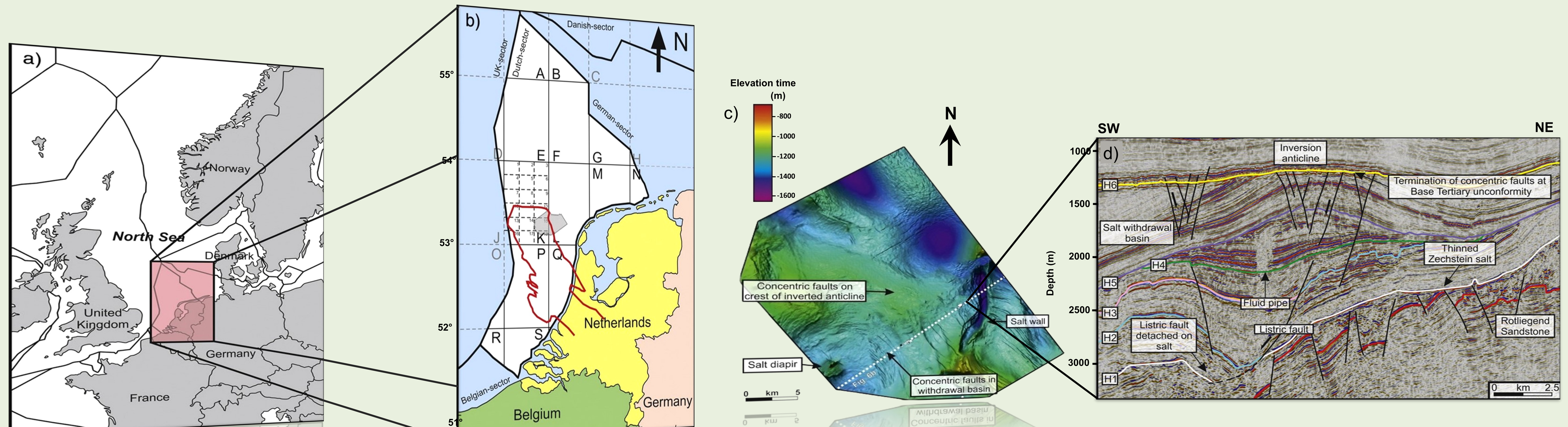

Figure 1. Location map of the study area derived from (Ward et al., 2016). a) Map of Western Europe. b) Enlarged location map of the Southern North Sea. The seismic line used in the models is shaded in a gray box. c) Interpreted Horizon Base Tertiary displaying features and seismic line modeled in this study. d) Seismic section used in modeling showing fluid escape pipes,faults, and Zechstein salt.

Numerical Model

- To investigate the influence of fault and salt structures on fluid and heat flow, a numerical modeling study was conducted using **ANSYS FLUENT**, a finite volume-based Computational Fluid Dynamics (CFD) software. The two-dimensional model incorporated the geometry of the studied field derived from the seismic section, along with the physical and hydraulic properties of the medium. The results generated as the simulation proceeded over time include the patterns of fluid flow and temperature distribution in the subsurface, as well as the factors governing them.
- It is anticipated that fluid movement will be notably enhanced within the fault zone, consequently leading to a dominant heat transfer phenomenon within and around the fault region. Thus, the mesh geometry was discretized using smaller mesh elements (25 m) within the immediate vicinity of the fault, gradually transitioning to larger mesh elements (50 m) as the simulation moved away from the fault zone. A total of **92923 nodes** and **45992 mesh elements** are used.

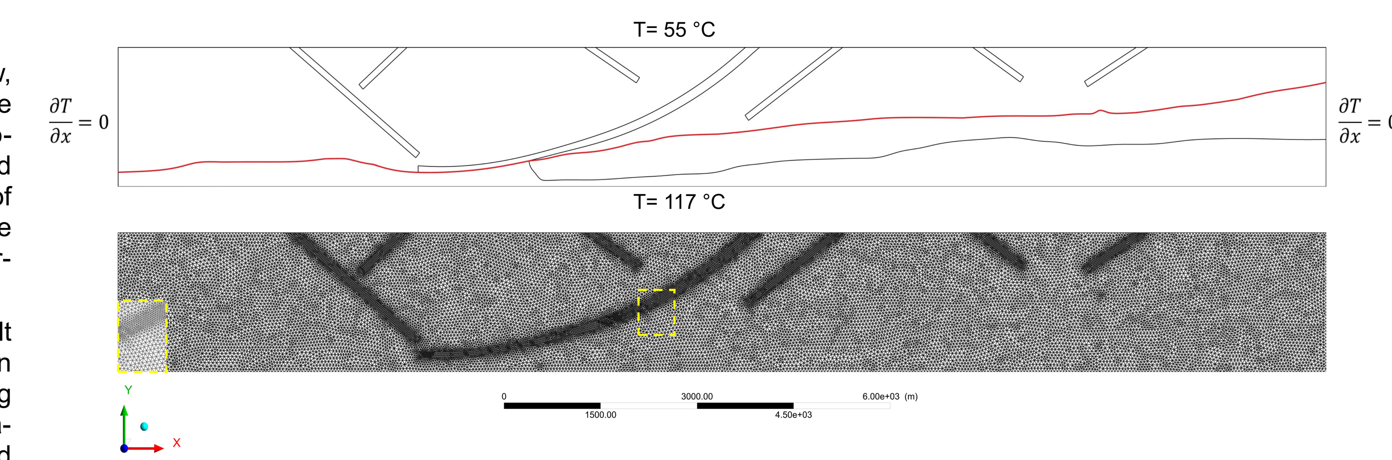

Figure 2. Model geometry for the numerical modeling (top) and triangular mesh structure (bottom). The inset figure shows the zoomed mesh elements.

Results

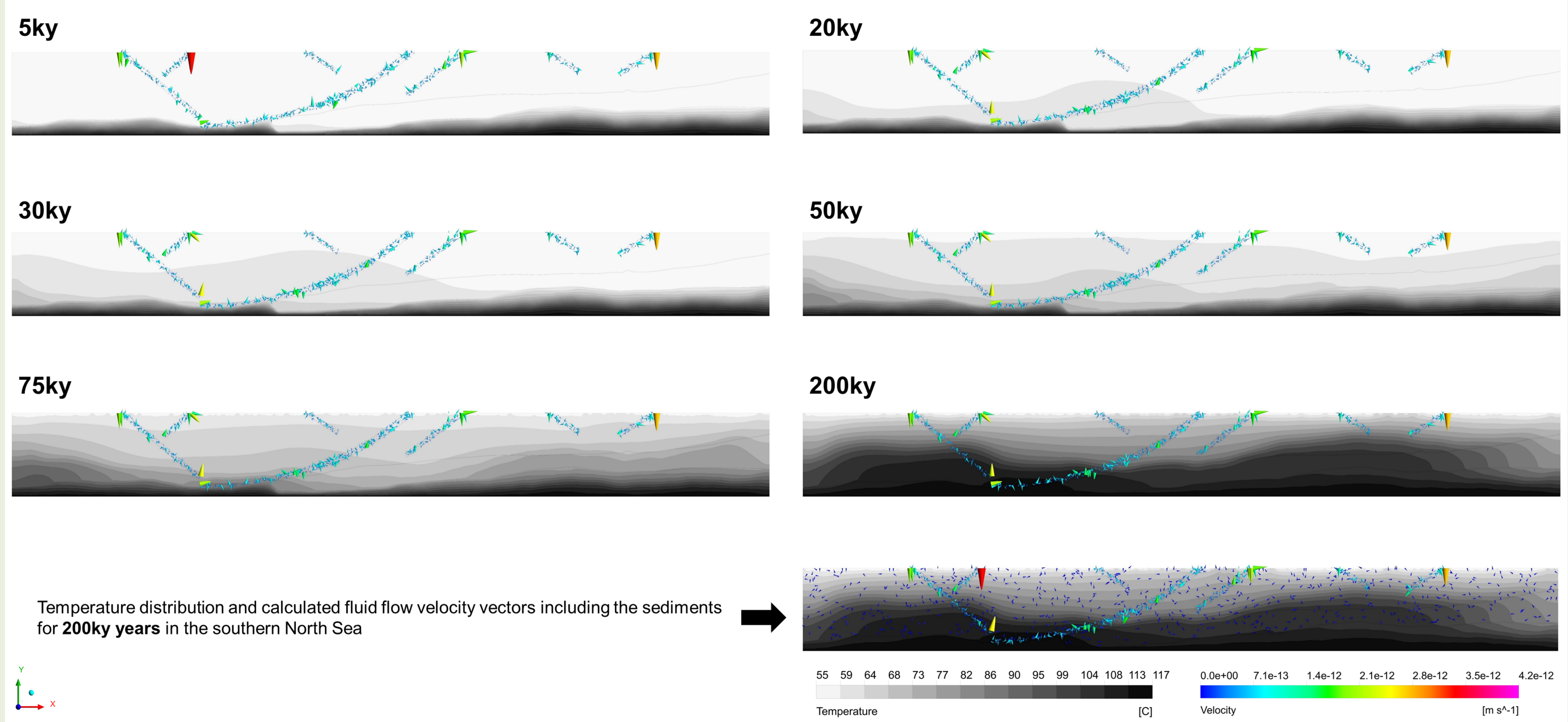

Figure 3. Temperature distribution and calculated fluid flow velocity vectors in the southern North Sea for 5ky, 20ky, 30ky, 50ky, 75ky, 200ky, and 200ky with sediment velocity vectors, respectively.

Conclusions

⇒ The influence of **salt structures** on temperature distribution is notable, primarily attributed to their **high thermal conductivity** characteristics.

⇒ **Faults** within the subsurface exert a profound impact on **fluid flow** dynamics, consequently affecting temperature distribution. Certain faults facilitate the transport of relatively colder fluid from shallow to deeper depths, thus modulating temperature contours. Conversely, some faults facilitate the movement of warmer fluid from deeper to shallower depths, thereby altering the overall **temperature distribution** and circulation patterns within the region. Faults, distinguished by their **higher permeability** values, serve as conduits for fluid and heat transport.

⇒ **Velocity vectors** within the sediment exhibit minimal values, with the highest velocities predominantly observed within faults due to their elevated **permeability and porosity** attributes. Thus, faults and salt structures emerge as the principal factors governing fluid and heat flow within the region.

⇒ Moreover, the **bathymetric characteristics** of the area impose a pressure gradient on the offshore model, accounting for depth-related variations and considering the pressure exerted by the water column. This pressure gradient constitutes another significant factor influencing **fluid and heat flow dynamics.**

Future Work

➡ Determining particular locations along fault lines where fluids escape and comparing them to established models will be an engaging direction for future research.

➡ Moreover, as interest in the potential application of geothermal systems in the region increases, an opportunity arises for a comprehensive study of the areas where faults intersect the seabed. These areas require meticulous examination to assess their suitability for geothermal installations and offer prospects for identifying the most suitable areas for harnessing geothermal energy.

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