

Numerical Investigation of Hydrocarbon Transport by Solitary Waves in the Eugene Island Field, Gulf of Mexico Basin*

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Abstract

Hydrocarbons hosted by shallow Plio-Pleistocene sand reservoirs in the Eugene Island field in the northern Gulf of Mexico basin are thought to have ascended distances of 1.5 to four kilometers from overpressured Tertiary source sediments at rates as high as 100's of m/yr. Most of the hydrocarbon transport appears to have occurred episodically along the Red growth fault despite its relatively low permeability. Solitary waves are a plausible mechanism for hydrocarbon transport in a geologic setting like Eugene Island in that they have the potential to travel at rates much greater than the rates of flow through porous media predicted from Darcy's law. The present study has sought to quantify the behavior of solitary waves for the geologic conditions found at Eugene Island.

The initial focus of the research was on solitary wave transport of oil. This research showed that solitary waves could arise in sediments undergoing steady pore pressure increase due to compaction disequilibrium and hydrocarbon generation, provided that permeability was a sensitive function of effective stress and overall was very low (10^{-25} to 10^{-24} m²), and that pore fluid pressures reached levels equal to 91-93% of lithostatic pressure. The solitary waves were found to reach maximum velocities on the order of 10^{-3} m/yr and could ascend 1-2 km before dissipating into the background. Although solitary waves could transport oil much more quickly than possible through the prevailing background flow regime, they seem unlikely to have been able to travel the vertical distances and at the velocities observed at Eugene Island, though they could have been important oil transport agents in other fields where source rocks and reservoirs are closer together.

Current research is focused on methane transport by solitary waves. The scenario investigated thus far is for an instantaneous increase in pore fluid pressure in the source rock and one-dimensional transport in a methane-saturated porous medium. Methane saturated solitary waves could travel further than oil saturated waves at rates on the order of tens of meters per year or more. Methane saturated solitary waves could also form under higher and much less restrictive permeability of up to about 10^{-18} m². The results suggest that solitary waves may be much more effective agents of methane transport than oil transport.

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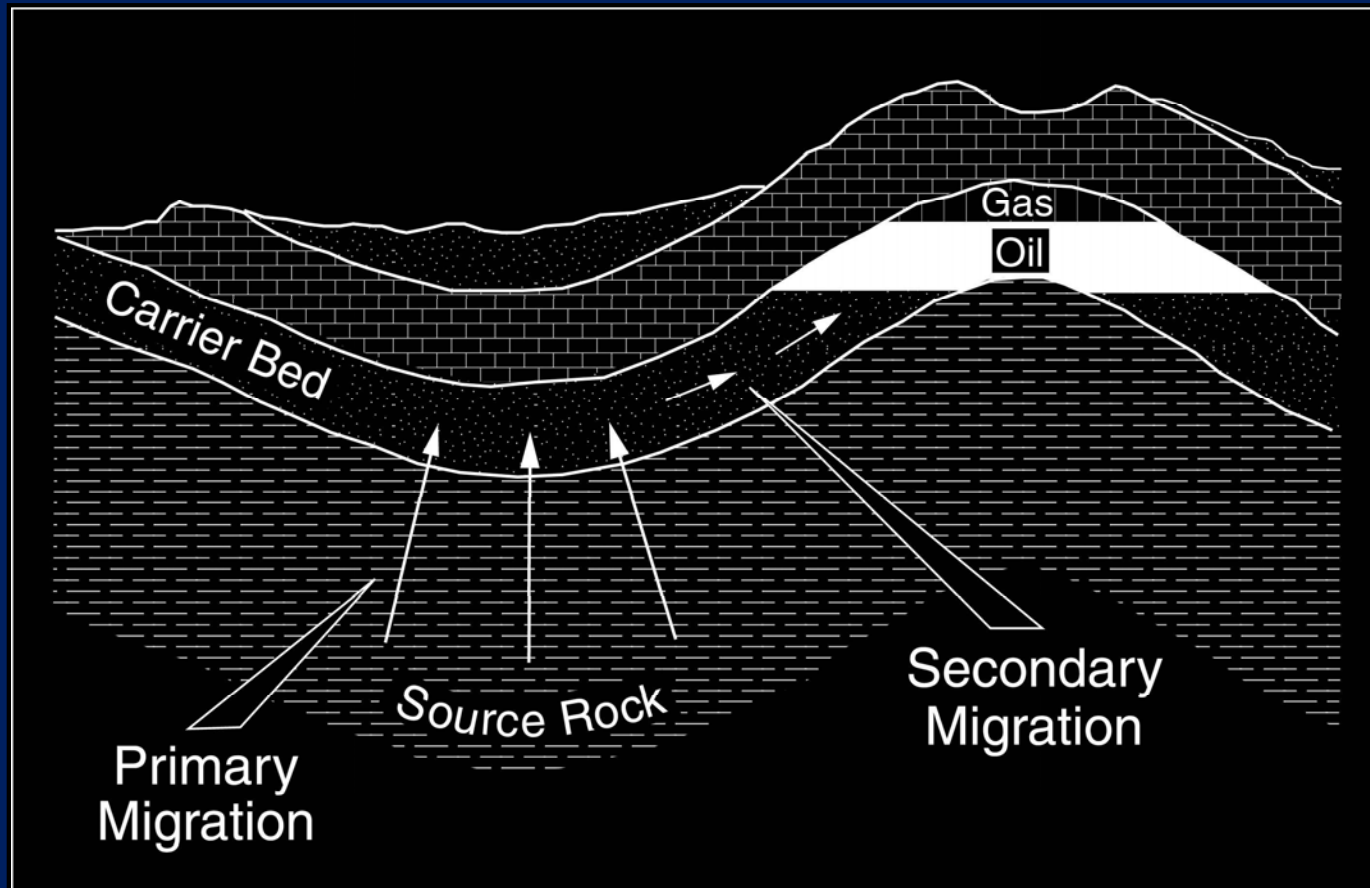
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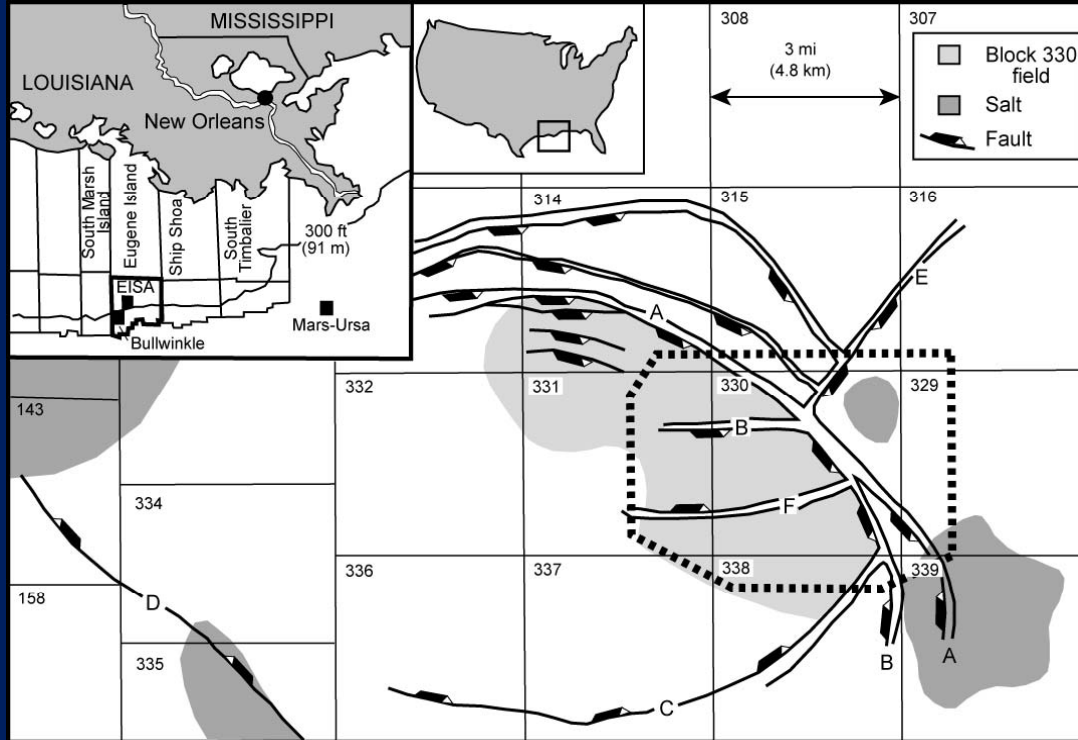


Research Motivation

- How are hydrocarbons able to traverse thick sections of low permeability geologic media between their source and reservoir in relatively short periods of time?

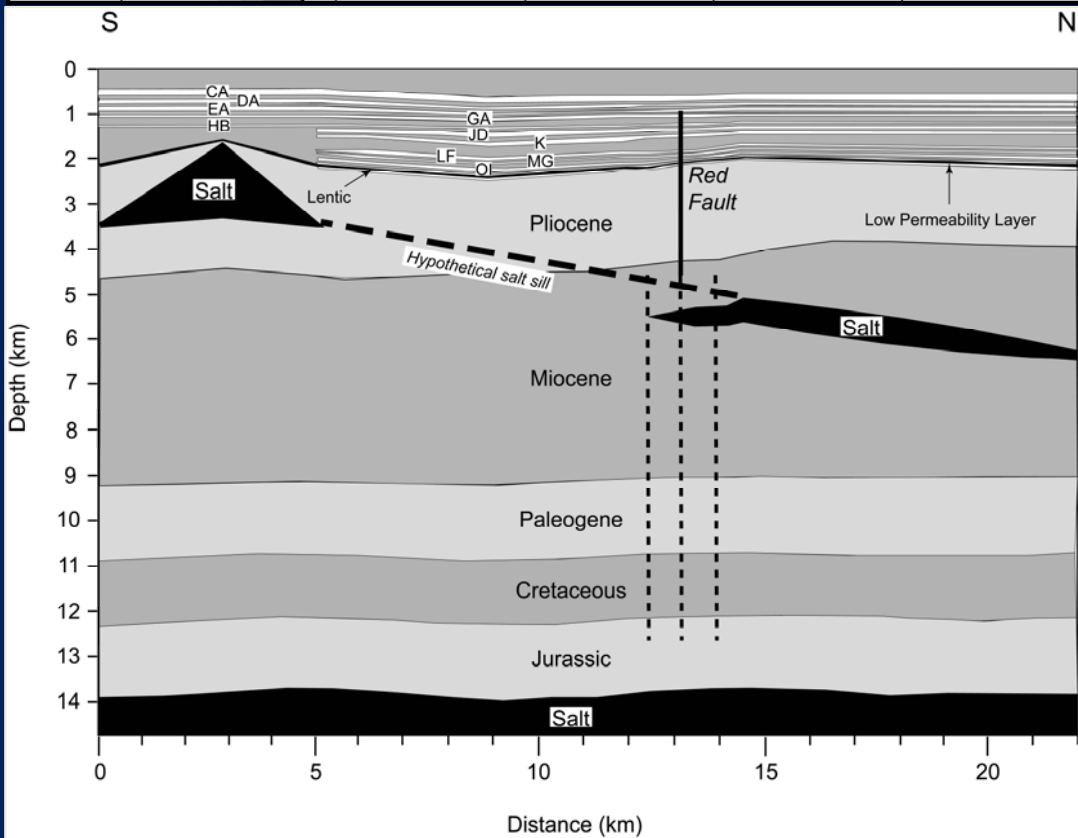


England et al (1987)



Eugene Island field, Gulf of Mexico basin

- Oil and gas sourced from ~4.5 km depth
- Ascended into Plio-Pleistocene reservoirs at rates of at least mm/yr to as high as 100's of m/yr

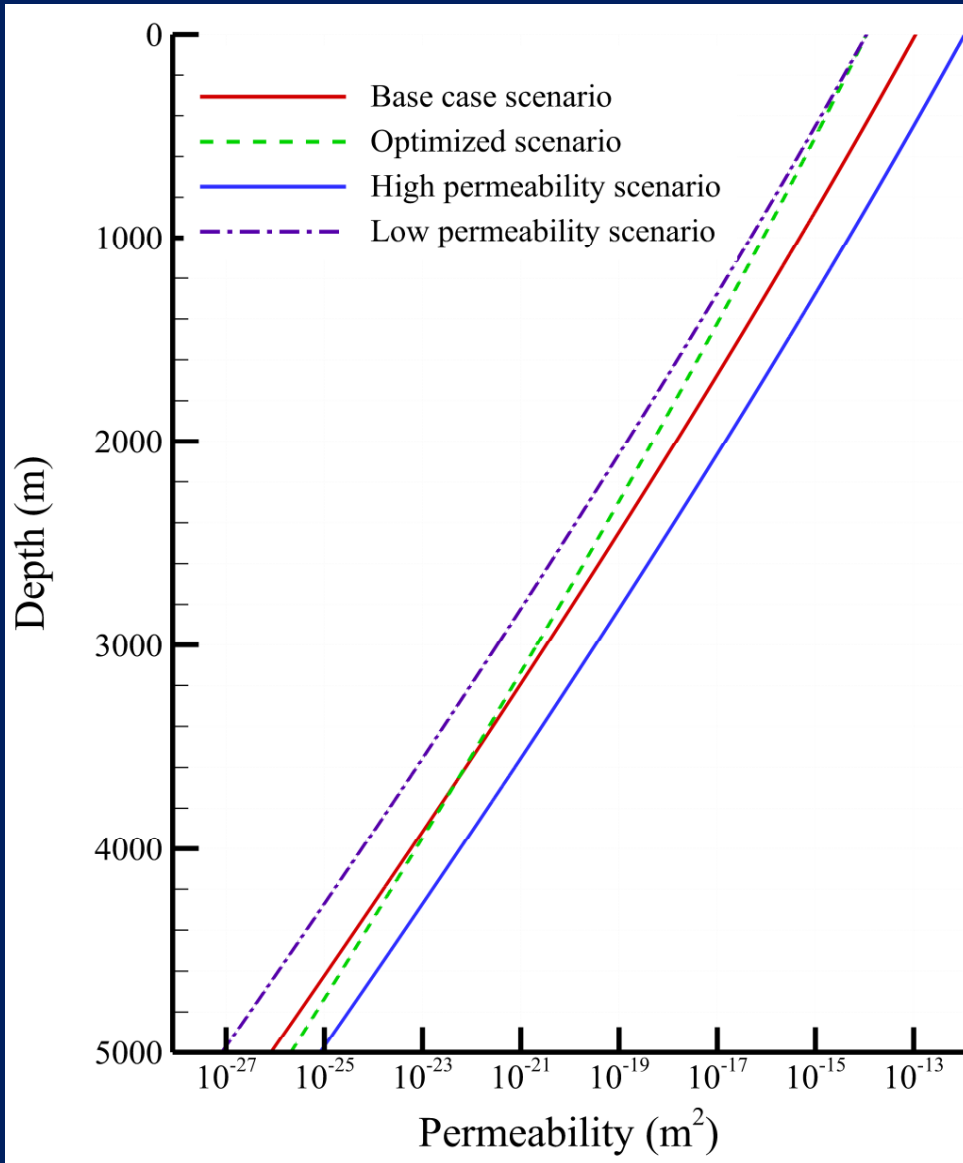


- Temporal changes in hydrocarbon composition
- 4D seismic surveys
- Thermal anomalies centered on Red fault

Alexander & Handschy (1998); Roberts et al. (1996); McBride (1998)

Permeability-depth profiles for the Red fault

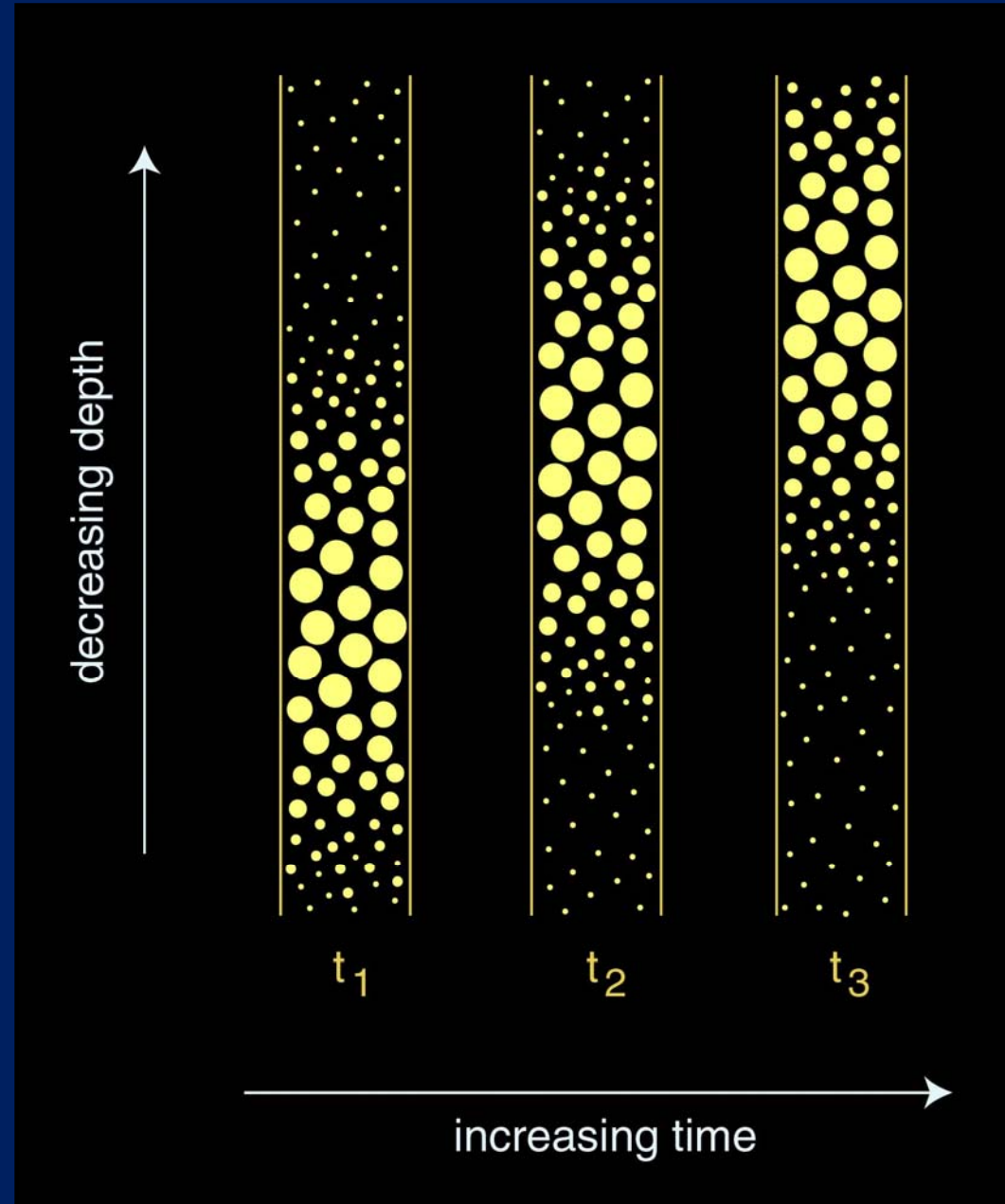
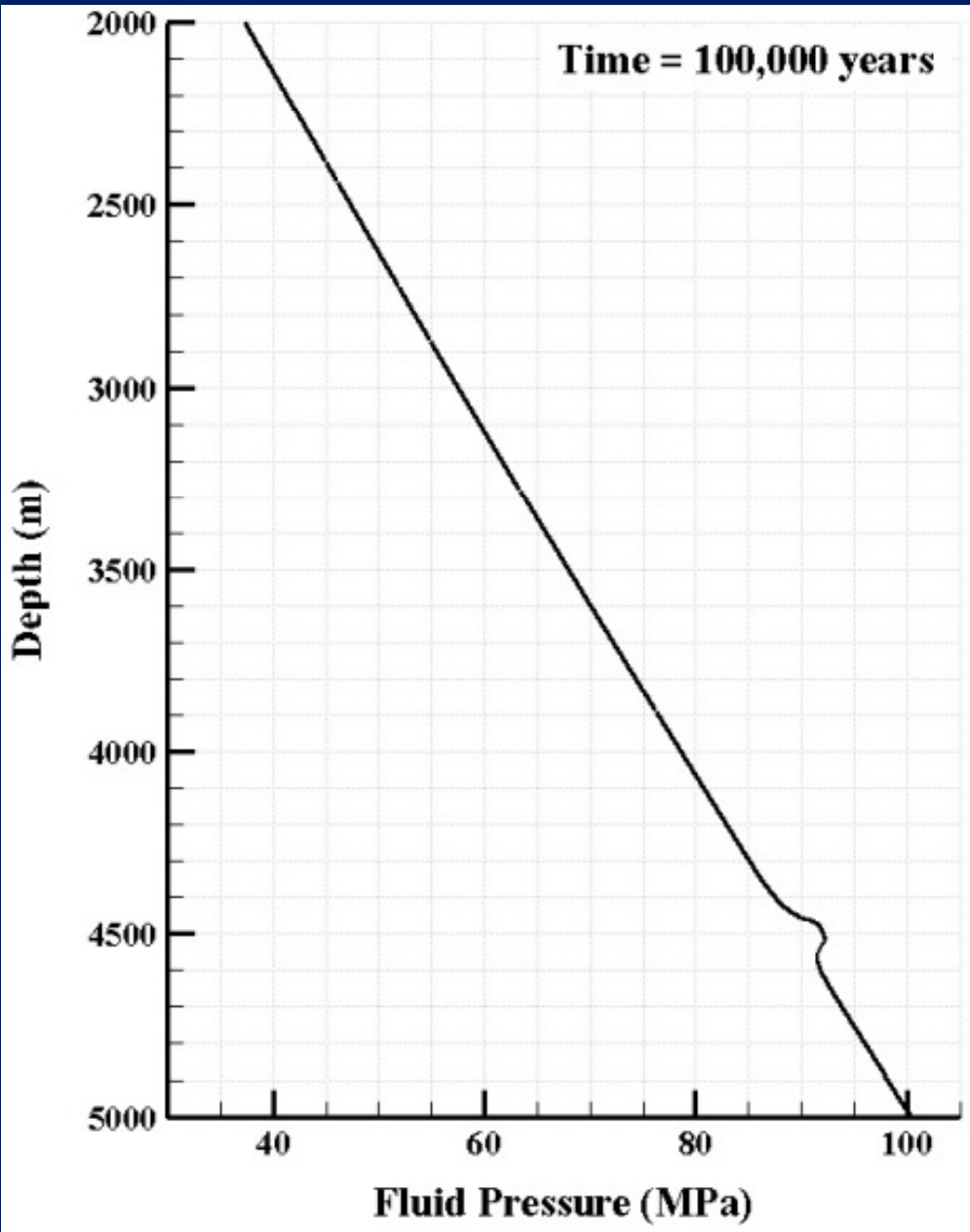
- Permeability at source region depth (4.5 km) is very low



- How could fluids have moved out of such low permeability sediments within the 3.6 m.y. year history of the Eugene Island minibasin?

Base case curve extrapolated from Revil and Cathles (2002)

Hypothesis: Solitary waves could be responsible for rapid hydrocarbon transport at Eugene Island



Solitary waves are predicted from solution of fluid mass conservation equations for elastic porous media if (Rice, 1992)

- Permeability is a sensitive function of effective stress

$$k = k_o \exp(-\sigma_e / \sigma^*)$$

- Pressure generation rate is high enough
- Effective stress is low enough (fluid pressure high enough)

Potential mass transport advantages of solitary waves relative to prevailing Darcian flow regime

- Higher velocity
- Higher porosity

Questions to test solitary wave hypothesis:

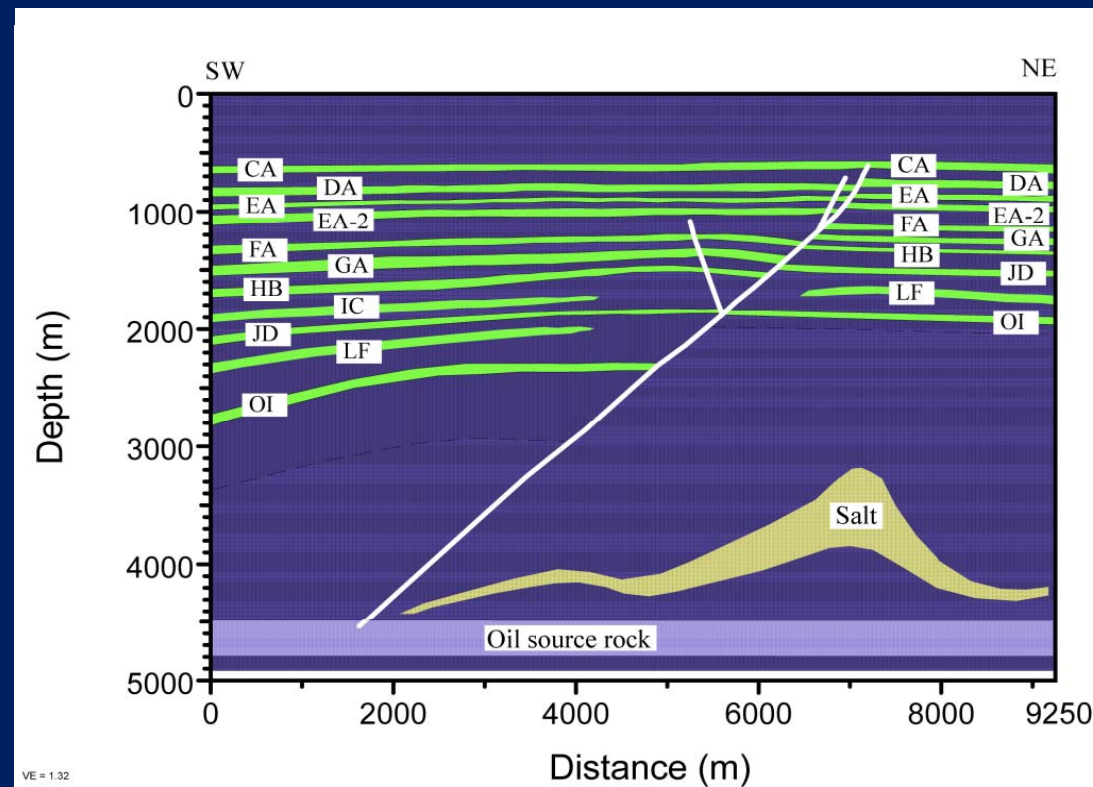
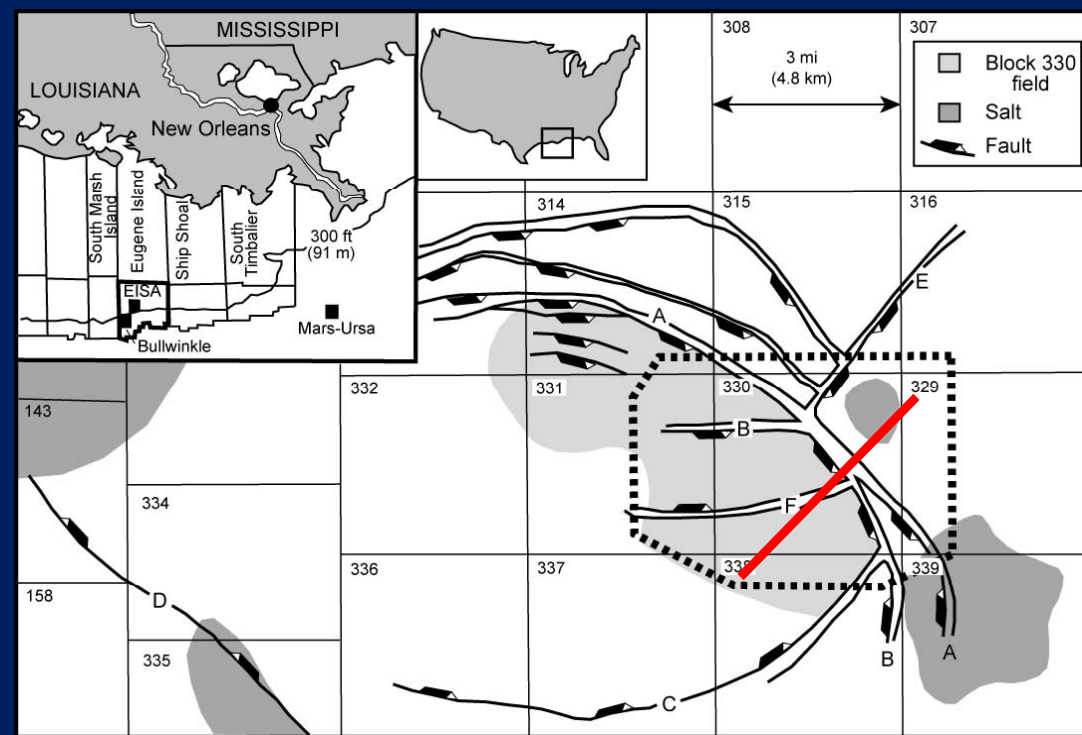
- How frequently do the waves form?
- How fast do they move?
- How far can they travel?
- How big do they get?
- How much oil can they transport?

How rapidly would fluid pressure have increased in the source rocks at Eugene Island?

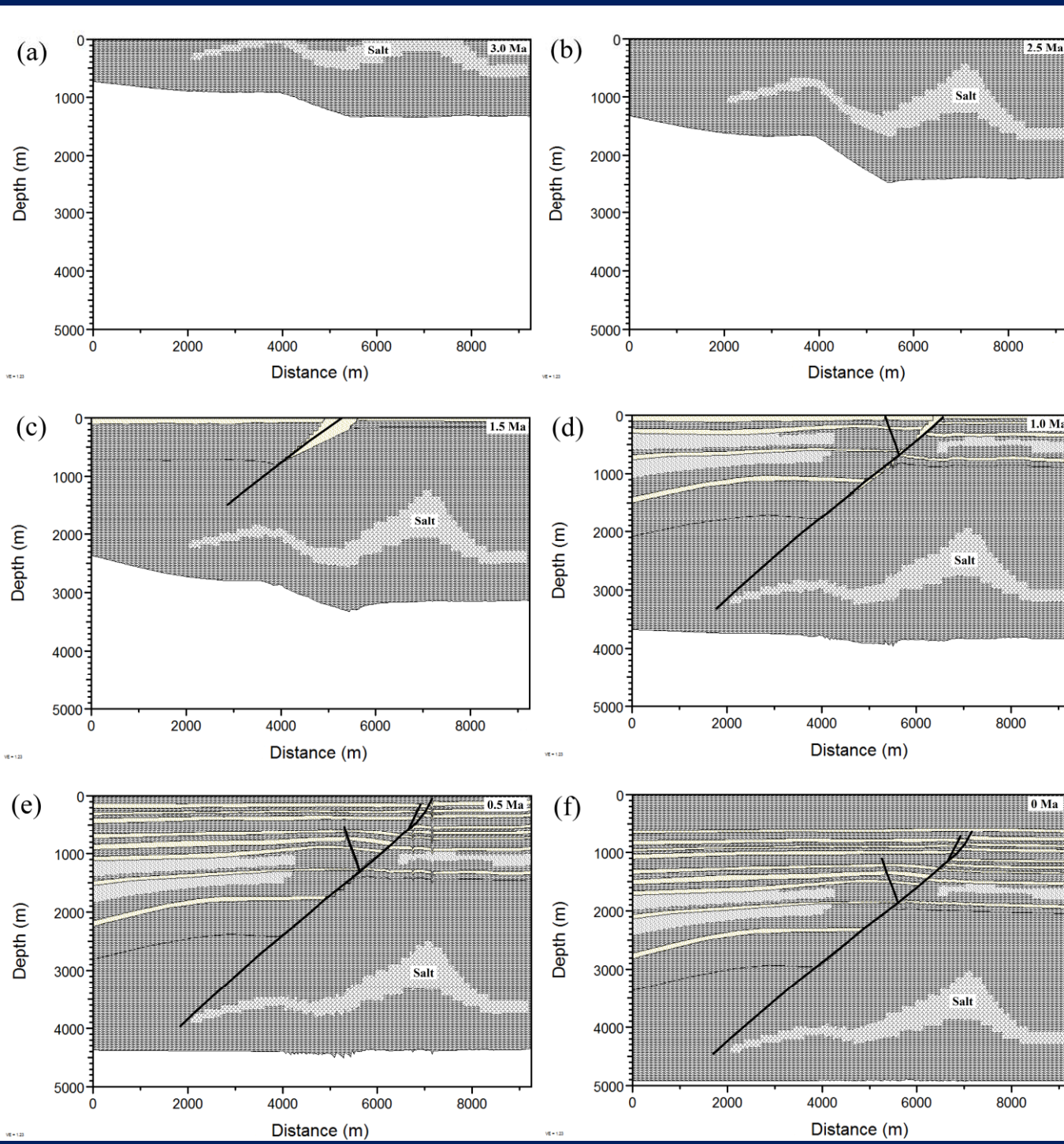
Created a model of the formation of the Eugene Island minibasin, including:

- Deposition of sediments
- Compaction of sediments
- Hydrocarbon generation
- Fluid pressure evolution
- Multi-phase fluid flow
- Heat transport

Calculations performed using BasinMod2D™ software

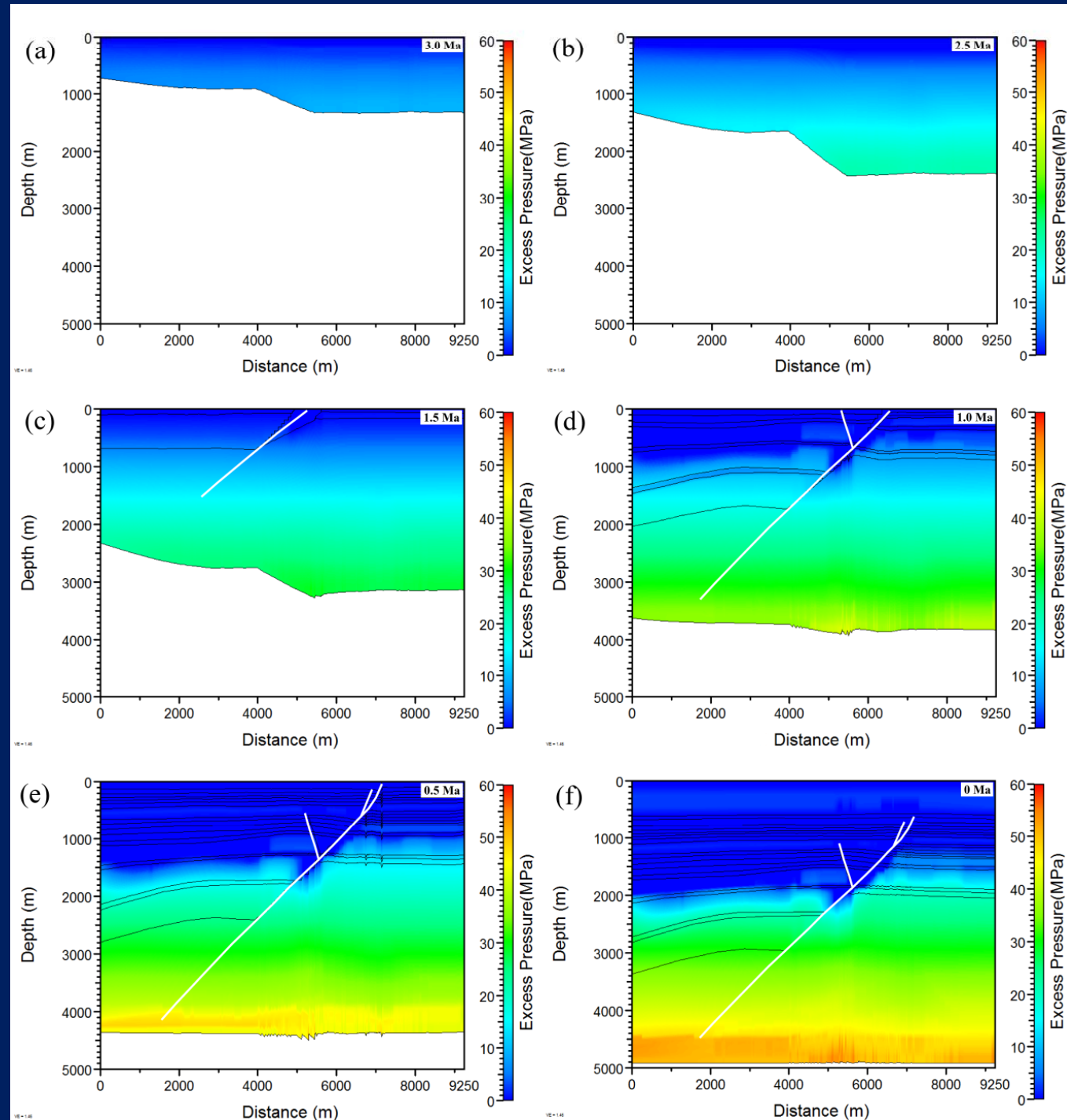


Model stratigraphic evolution



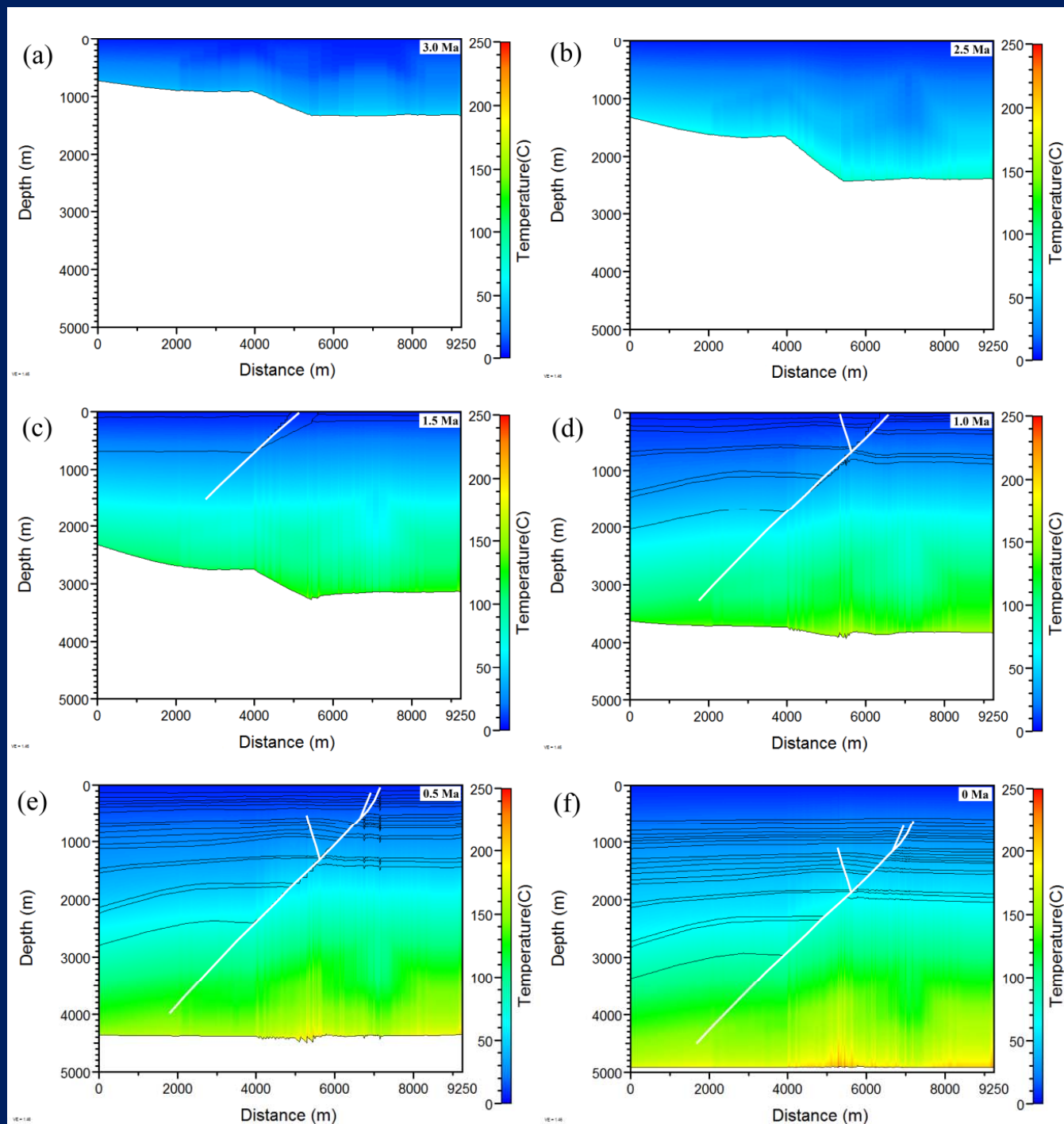
Evolution of excess fluid pressure (overpressure)

- Less overpressure development in shallow sand layers (less compressible)
- Overpressure leakage along Red fault
- Overpressure displacement along Red fault
- Flow rates on order of 10^{-6} m/Myr



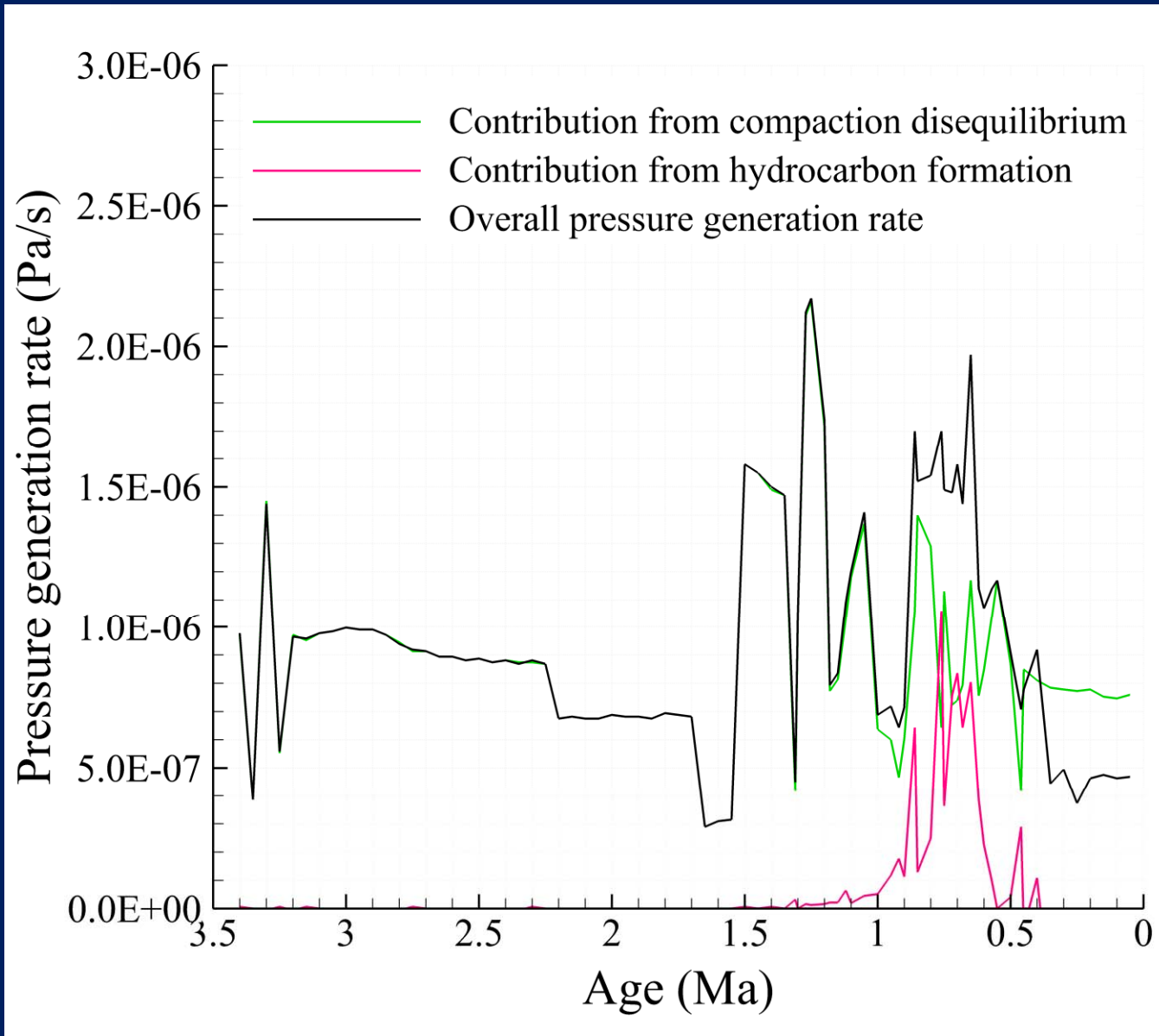
Evolution of temperature

- Heat transport primarily by conduction
- Displacement of temperature along Red fault
- No anomalous temperature elevation along Red fault
- Shales interbedded with sand reservoirs too cool to generate oil & gas



Fluid pressure generation rate at the base of the Red fault

- Excess fluid pressure (overpressure) generated mainly by compaction disequilibrium
- Overpressure contribution from hydrocarbon generation limited to ~1 to 0.5 Ma



Solitary wave model governing equations

- Pore pressure diffusion in porous media

$$\frac{d}{dz} \left(\frac{k}{\mu} \left(\frac{dp}{dz} - \rho_f \cdot g \right) \right) = \frac{s_s}{g} \cdot \frac{dp}{dt}$$

- Permeability as a function of effective stress (Rice, 1992)

$$k = k_0 e^{-\sigma_e / \sigma^*}$$

- Porosity as a function of effective stress

$$\varphi = \varphi_0 e^{-\beta \cdot \sigma_e}$$

- Oil viscosity as a function of temperature

$$\mu = (1.663 * 10^6) T^{-3.368}$$

- Oil flow velocity

$$q = -\frac{k}{\mu} \left(\frac{dP}{dz} - \rho_f g \right)$$

Four model scenarios tested

1) Base case

- Most likely parameter values

2) Optimized

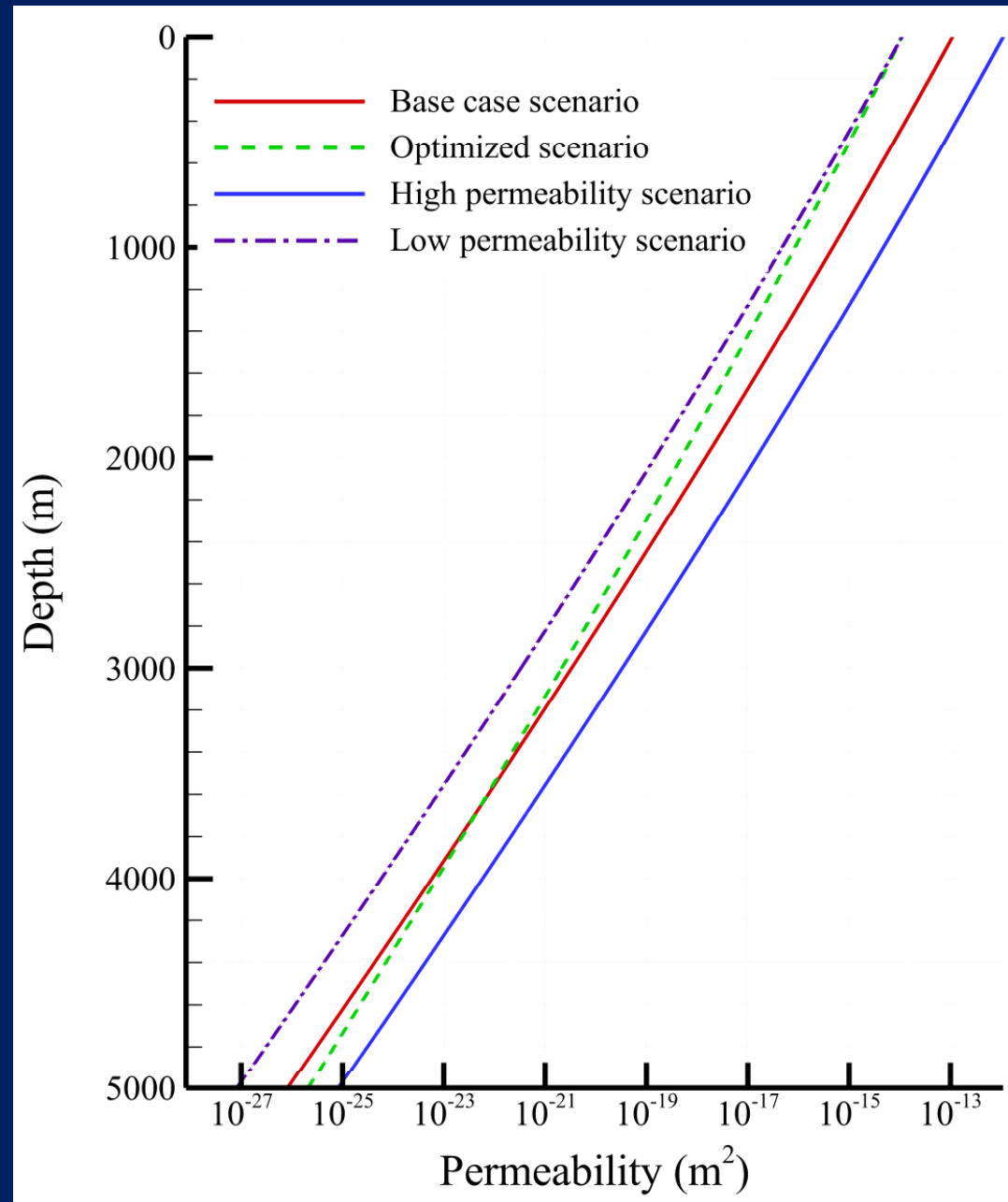
- Model parameters that optimized solitary wave formation & migration

3) High permeability

- Increased by factor of 10 from base case

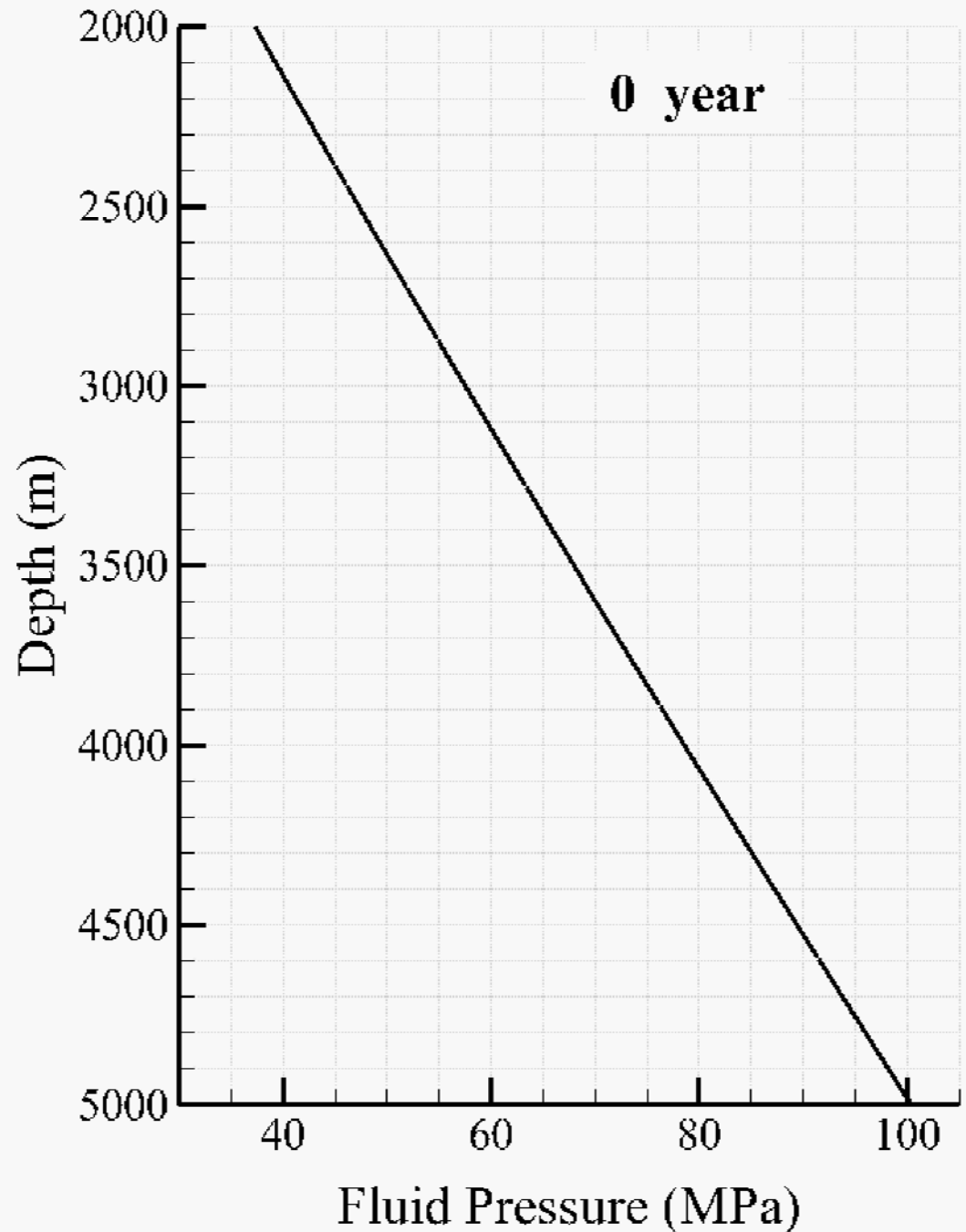
4) Low permeability

- Decreased by factor of 10 from base case

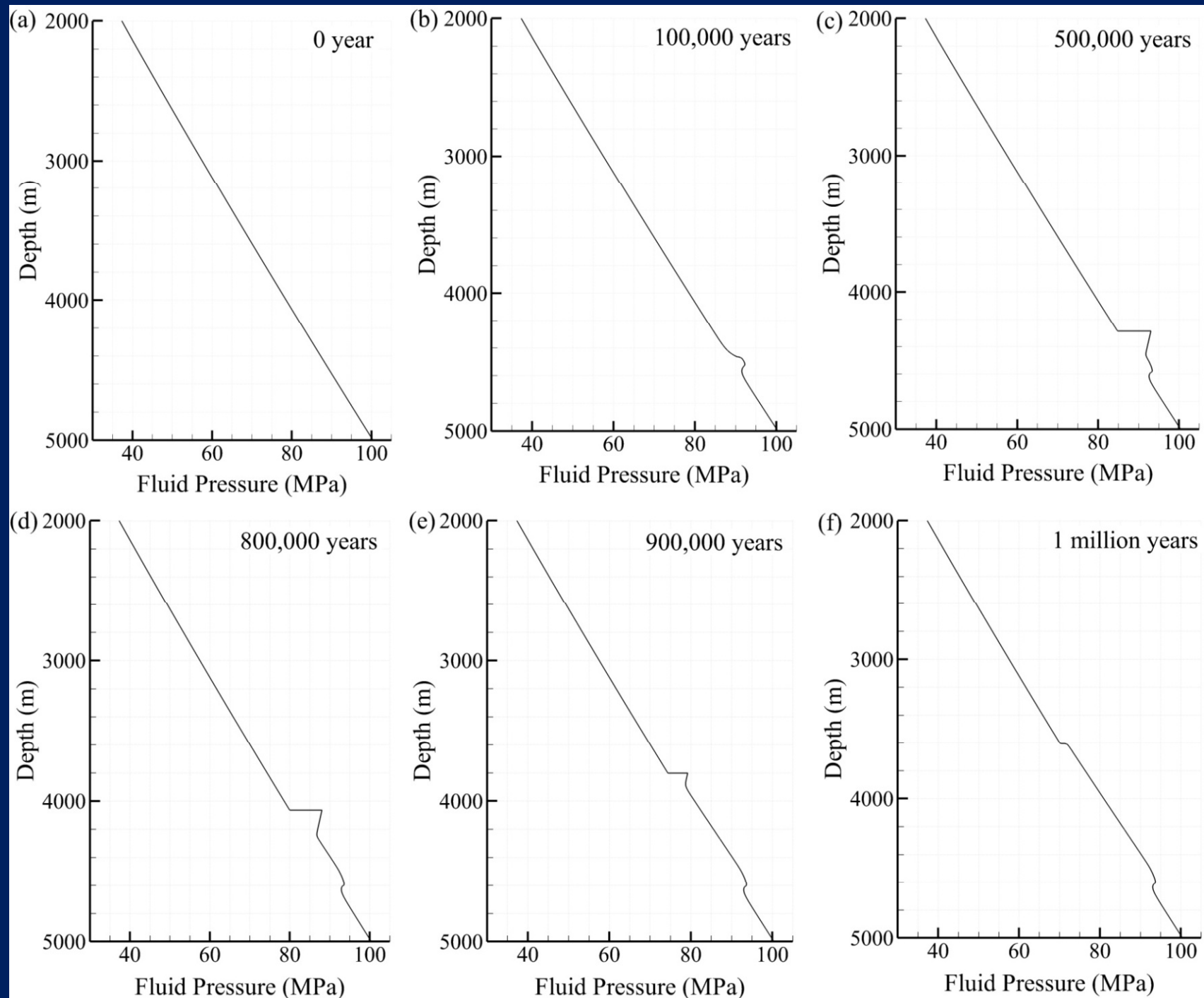


Base case scenario

- Solitary wave accelerates as it ascends but diminishes in amplitude
- Solitary wave leaves behind a wake of elevated fluid pressure
- Solitary wave disappears after ascending ~ 1 km, after ~ 1 million years
- No further solitary waves form after the first wave
Why?



Solitary wave migration for base case scenario



For solitary waves to form and migrate, pressure generation rate must exceed pressure diffusion rate

Pressure diffusion rate is governed by the hydraulic diffusivity

$$D = \frac{K}{S_s}$$

K = hydraulic conductivity

S_s = specific storage

Wake of elevated fluid pressure behind solitary wave elevates permeability

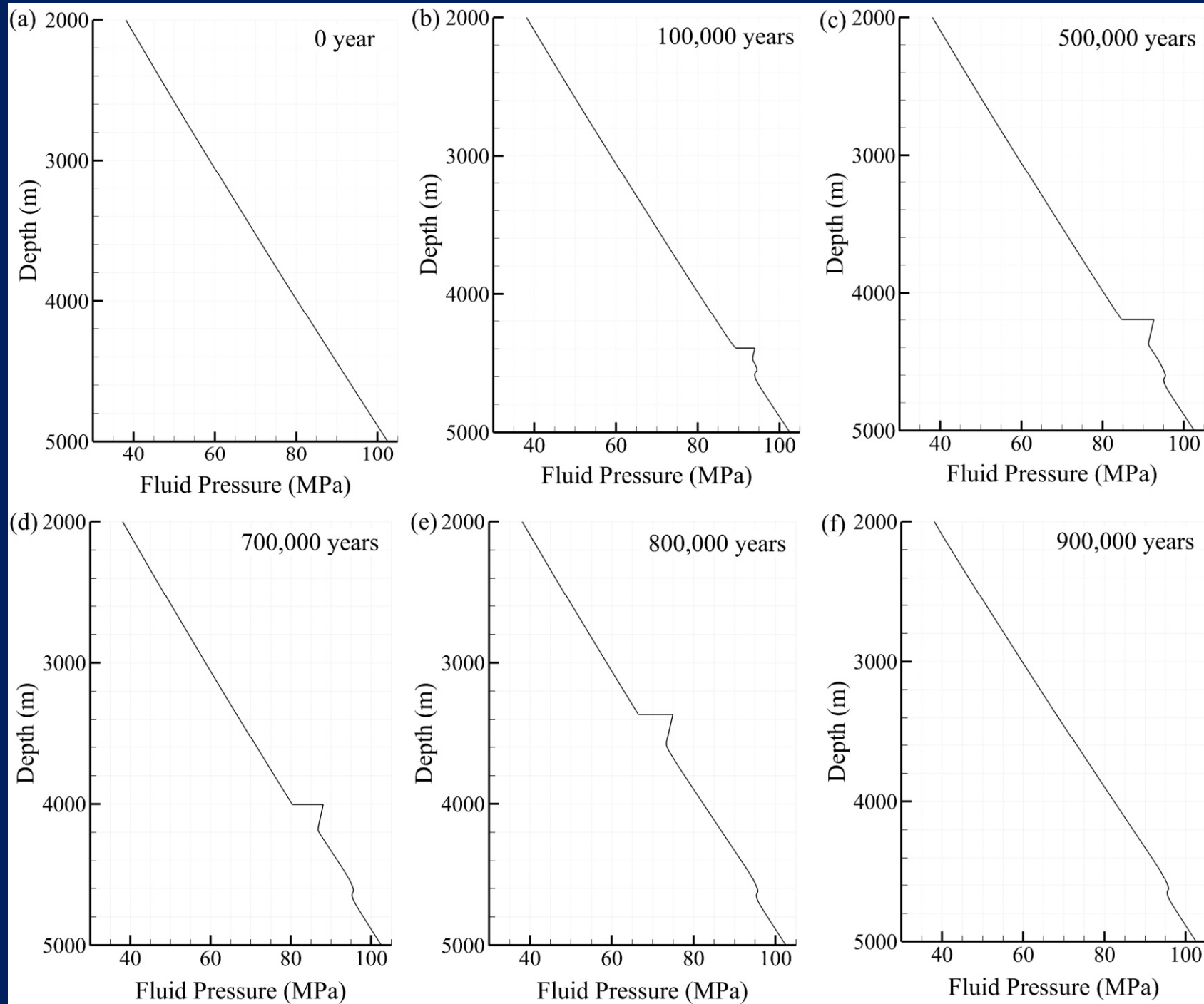
- Elevated permeability raises hydraulic diffusivity enough to allow further pressure increases to dissipate before consolidating into discrete solitary wave

Optimized scenario

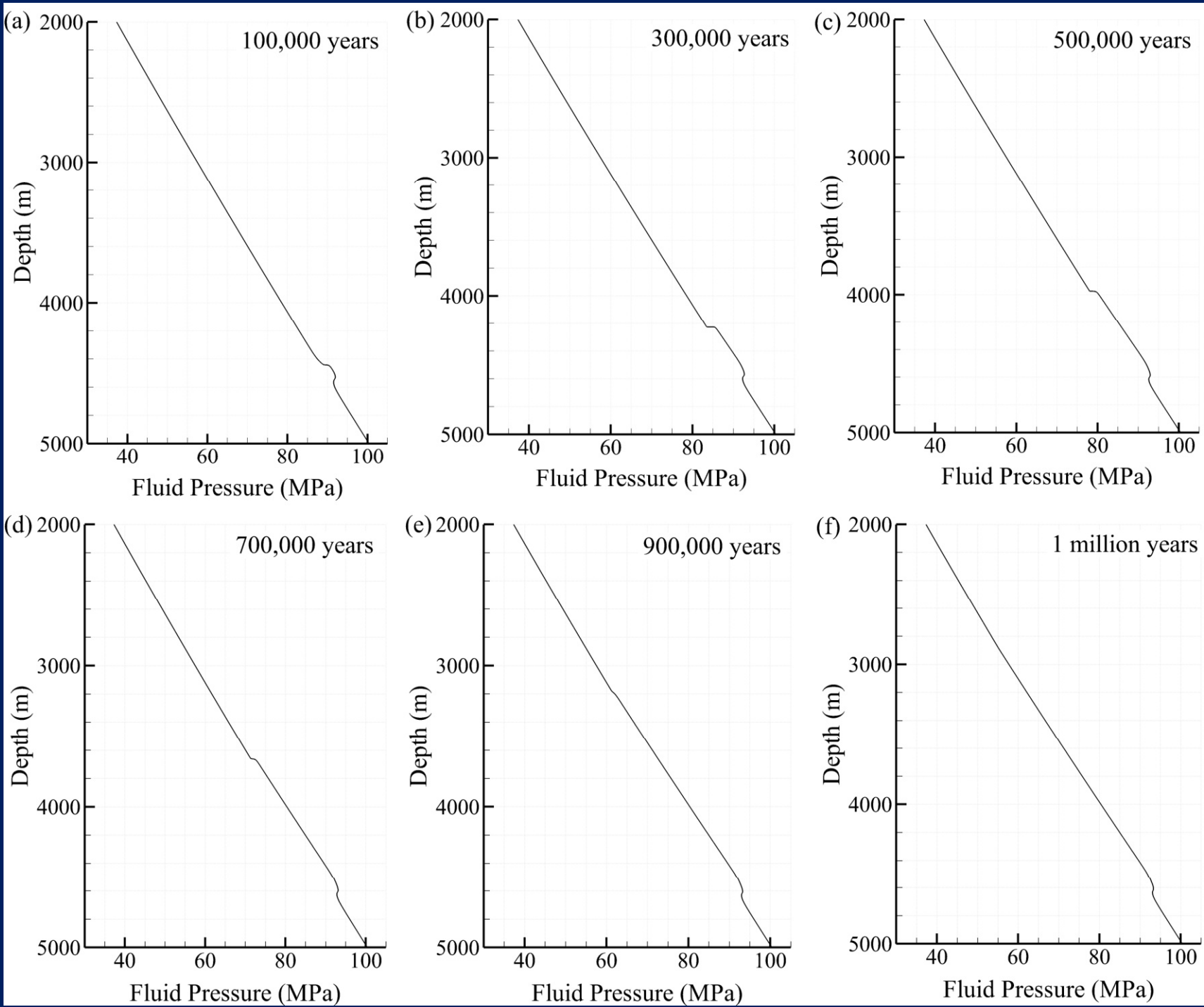
Compared to base case scenario,

- Pressure generation rate doubled
- Sediment bulk compressibility doubled
- Surface temperature doubled
- Permeability changes less strongly with depth
- Compaction factor (σ^*) lowered from 0.25 to 0.2 MPa
- Background fluid pressure raised from 93 to 95% of lithostatic

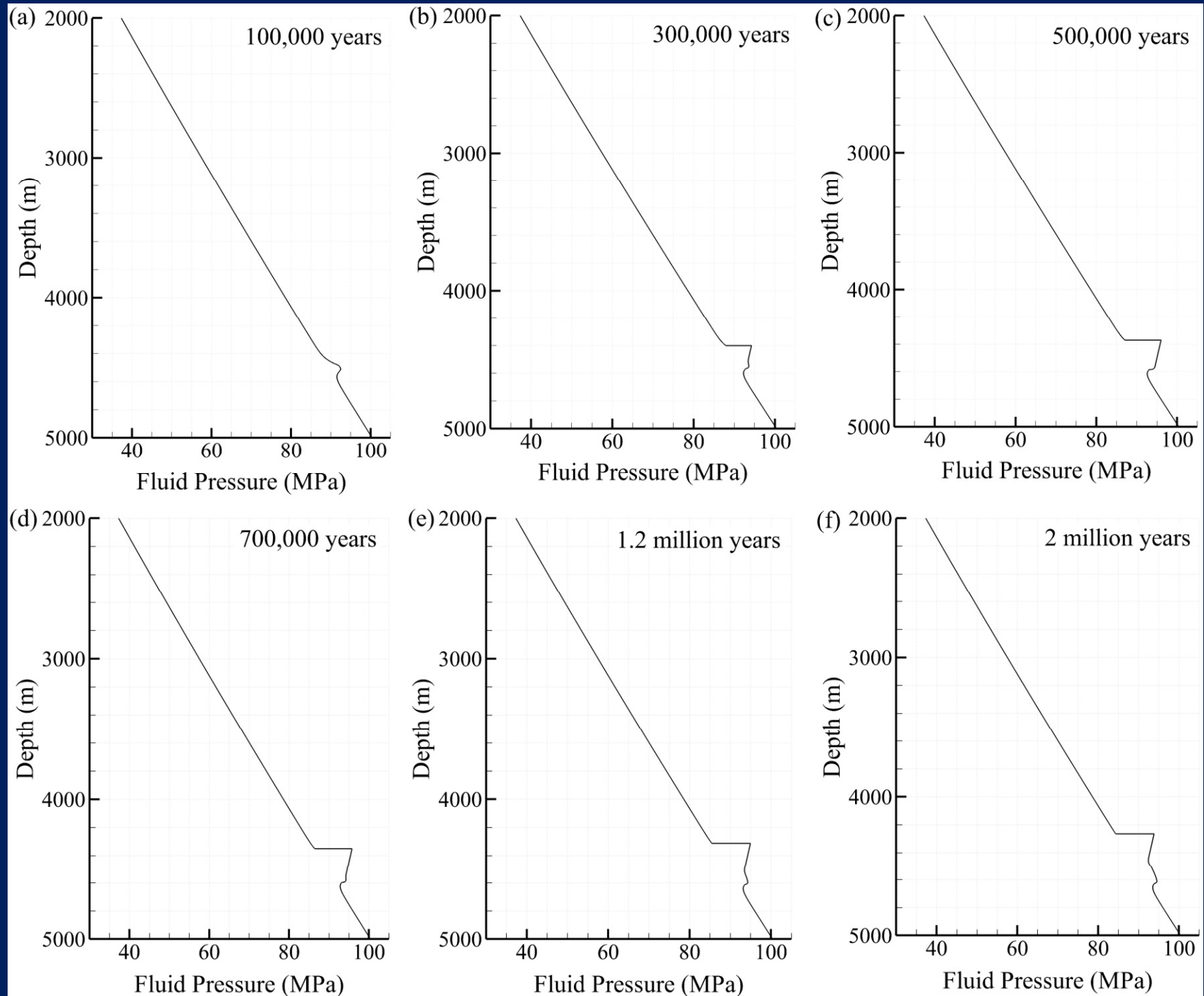
Solitary wave migration for the optimized scenario



High permeability scenario: no wave formation—diffusion too fast

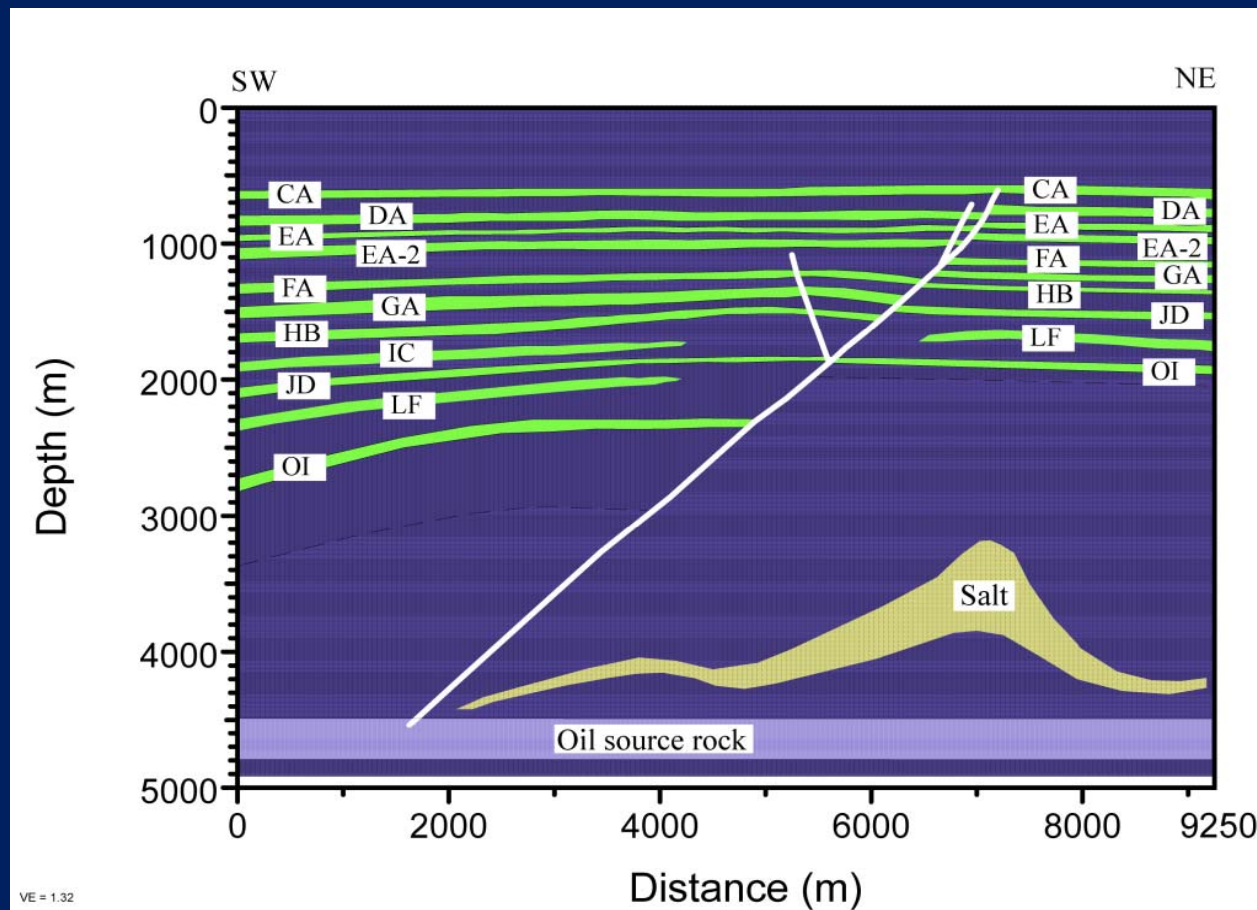


Low permeability scenario: No wave migration—perm. too low



Could solitary waves have charged the reservoirs at Eugene Island?

- For base case scenario, solitary wave would ascend only 1 km and not reach any of the reservoirs
- For optimized scenario, solitary waves would ascend 2 km and reach only the deepest reservoirs



If solitary waves had been able to reach the reservoirs, would they have been able to deliver the amount of oil observed (645 million barrels = 100 million m³)?

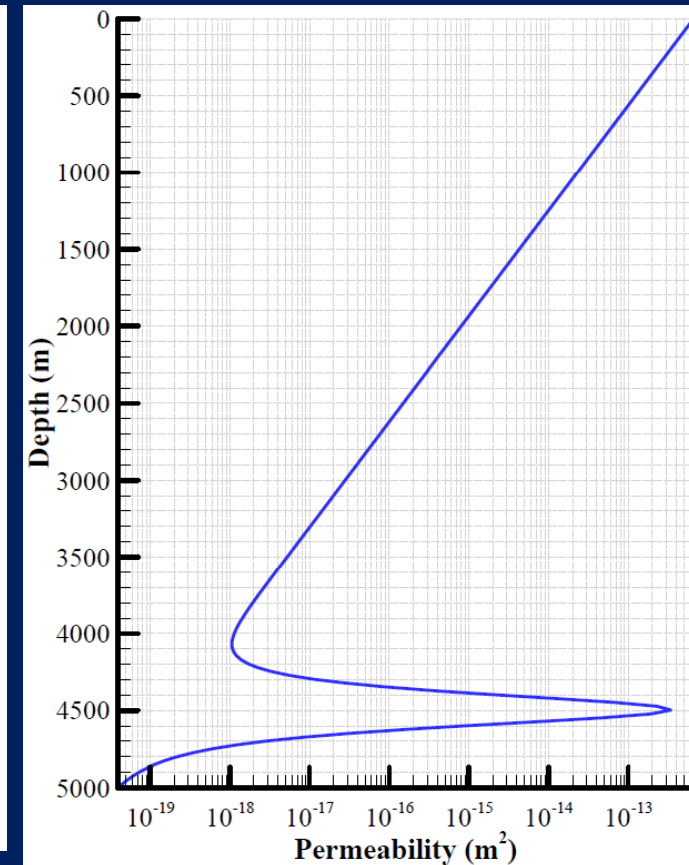
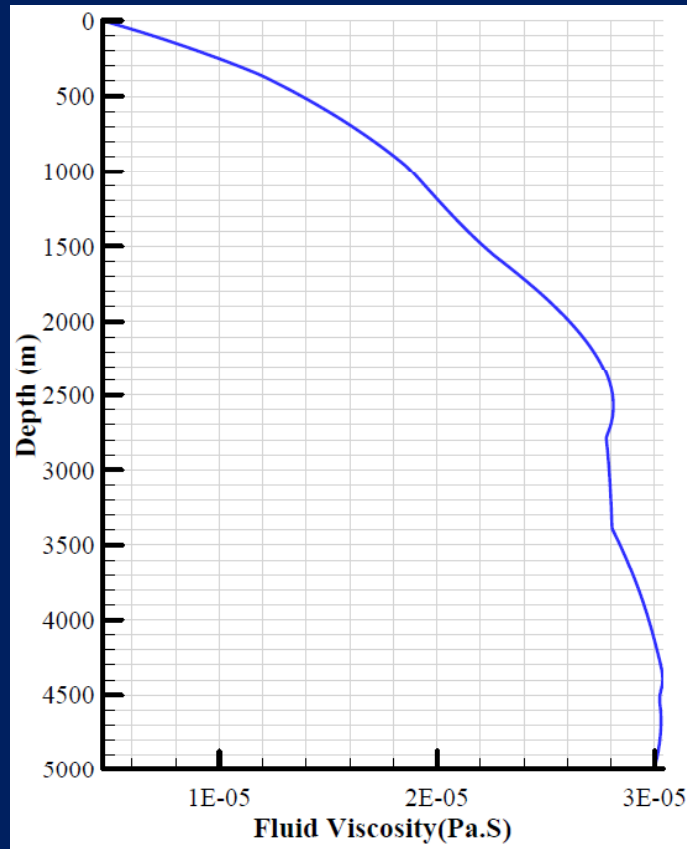
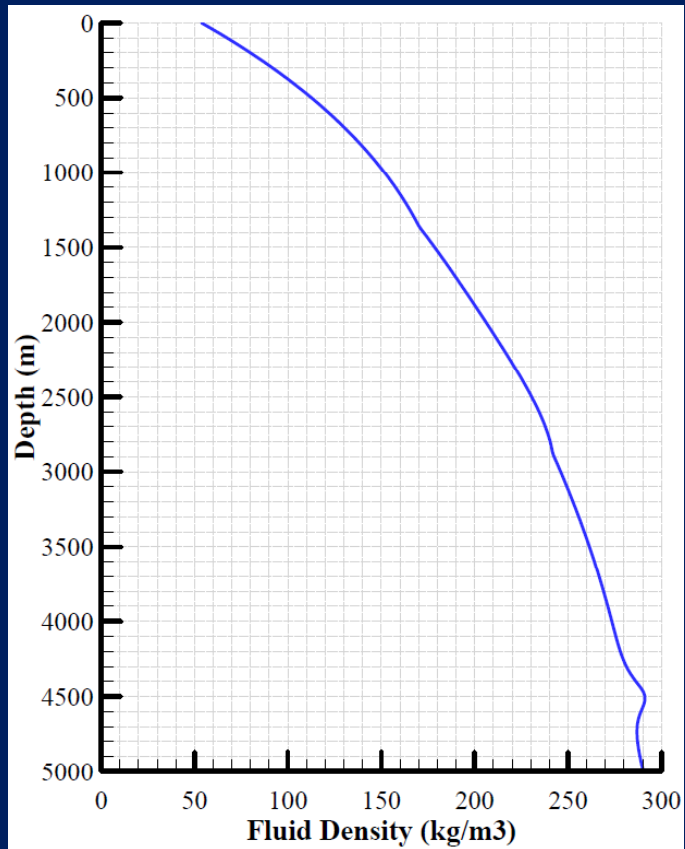
- Predicted volumetric flow rates of 10's of m³/yr
- Solitary waves migrate over time scales of 100's of thousands of years
- Thus, hundreds of solitary waves would have been needed to charge Eugene Island reservoirs

Solitary waves not predicted to occur with this frequency in the models

Conclusions

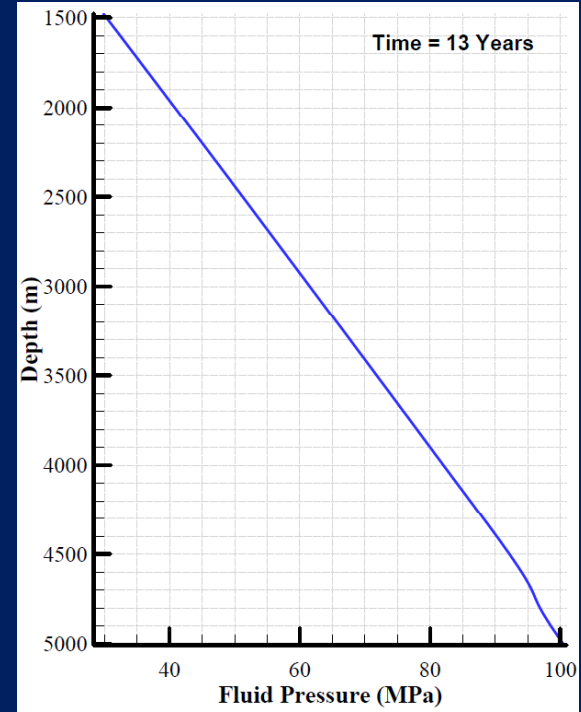
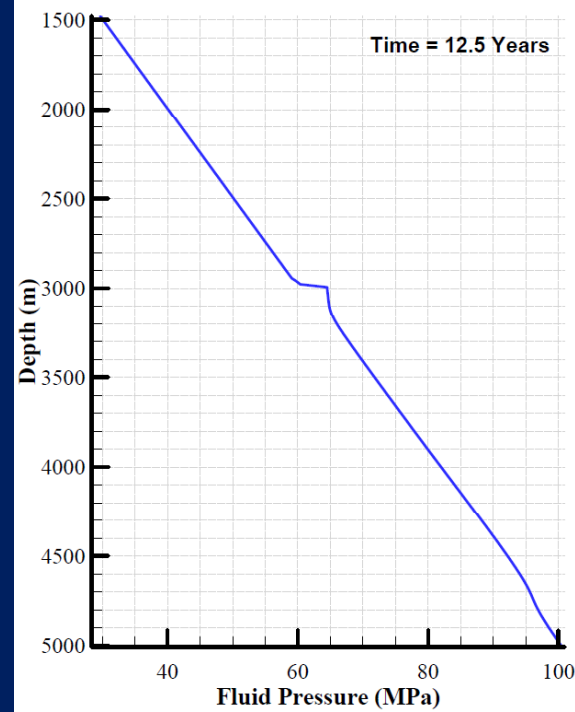
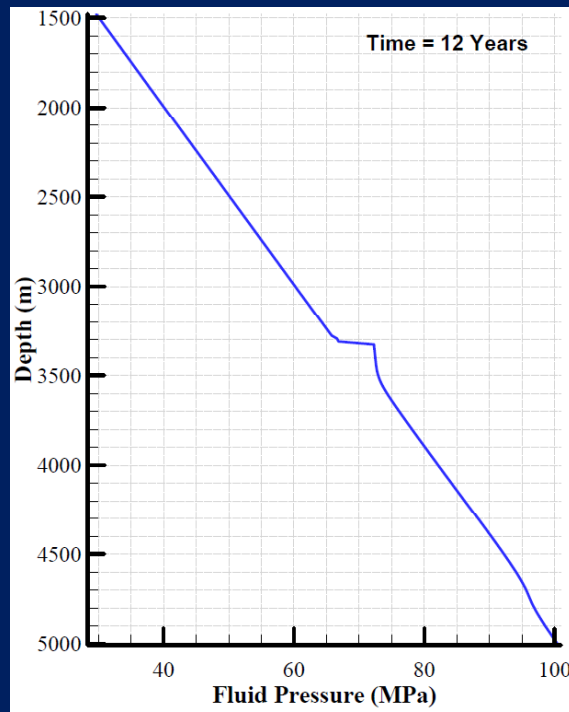
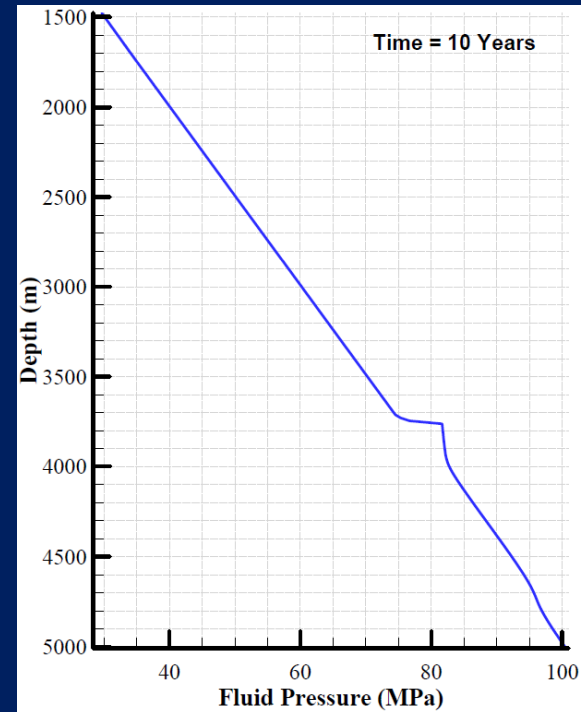
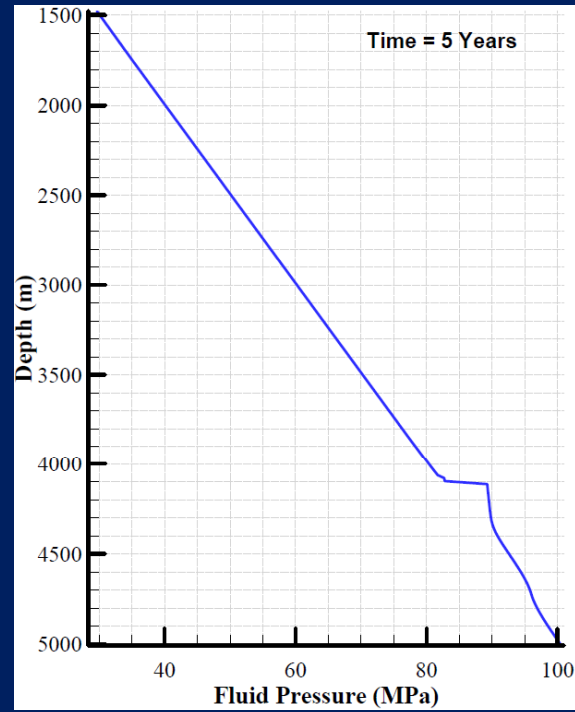
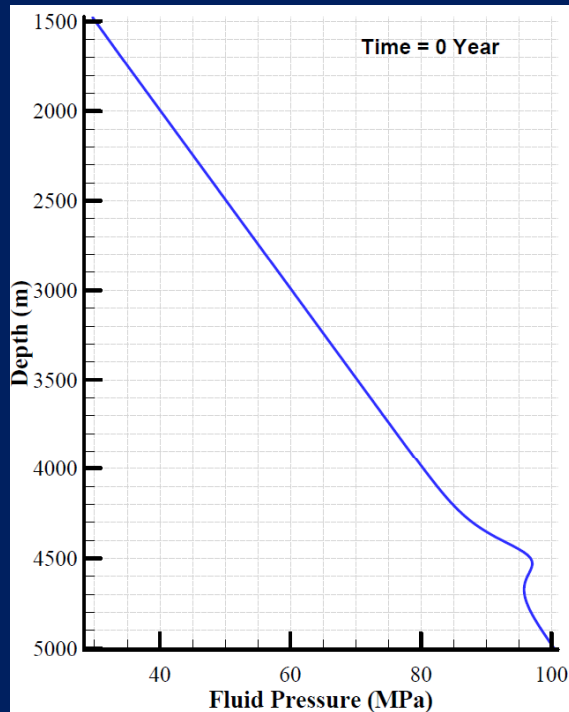
- Solitary waves could only form under narrow range of low permeabilities between 10^{-24} and 10^{-25} m²
- Solitary waves could only ascend 1-2 km before dissipating into the background
- Wake of elevated fluid pressures prevented further solitary waves from forming, despite ongoing pressure generation
- Solitary waves traveled at velocities of mm/yr, much faster than background flow regime
- Solitary waves could not have delivered enough oil to account for amount observed at Eugene Island
- Solitary waves could perhaps be important oil transport mechanism in other fields where reservoirs and source rocks are closer to one another

Current Investigation of Methane Saturated Solitary Waves



Density and viscosity data are from Francesconi et al, 1981 and Atilhan et al, 2010

Solitary waves may be much more effective at transporting methane



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