Solitary Waves in Low Permeability Sediments: A Possible Mechanism for Rapid Methane Transport in the Eugene Island Field, Gulf of Mexico Basin*

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Abstract

Hydrocarbons in the Eugene Island Field, offshore Louisiana appear to have migrated through 2-4 km of low permeability muds and shales at surprisingly high rates as high as 100's of meters per year (m/yr) to reach their present day shallow Plio-Pleistocene reservoirs. Recent seismic and thermal data suggest that hydrocarbons may have traveled in part as discrete and episodic fluid pressure pulses along the Red growth fault. Initial calculations in the present study were aimed at evaluating the ability of solitary waves to transport oil. These calculations showed solitary wave formation to be limited to a narrow range of source sediment permeabilities between 10^{-24} and 10^{-25} m and for the waves to travel at a maximum rate of order 10^{-3} m/yr for distances of 1-2 kilometers. The flux of oil transported by the solitary waves was found to be too low to account for the amount of oil present in the Eugene Island reservoirs. Solitary waves however could be much more effective at transporting methane because of the lower density and viscosity of methane compared to oil. This hypothesis was tested by modeling the Red fault as a one-dimensional vertical profile saturated with methane, with a maximum of about 5.12 MPa of overpressure emplaced instantaneously at a depth of 4.5 km. Though work is ongoing to improve the accuracy and stability of the numerical solution, the results obtained thus far show that methane-saturated solitary waves can migrate vertical distances of more than a kilometer at rates of at least 100's of m/yr. In contrast to oil-saturated solitary waves, methane-saturated solitary waves in the models do not leave behind a wake of elevated fluid pressure that inhibits repetitive solitary wave formation. However, in order for solitary waves to form, pressure generation rates significantly greater than the 30 Pa/year predicted from compaction disequilibrium and hydrocarbon generation would be needed to overcome the high diffusivity of methane at a fault permeability between 10^{-18} and 10^{-19} m. Thus, provided a geologic mechanism exists for rapid fluid pressure generation, solitary waves would be capable of very rapid methane transport in low permeability sediments.

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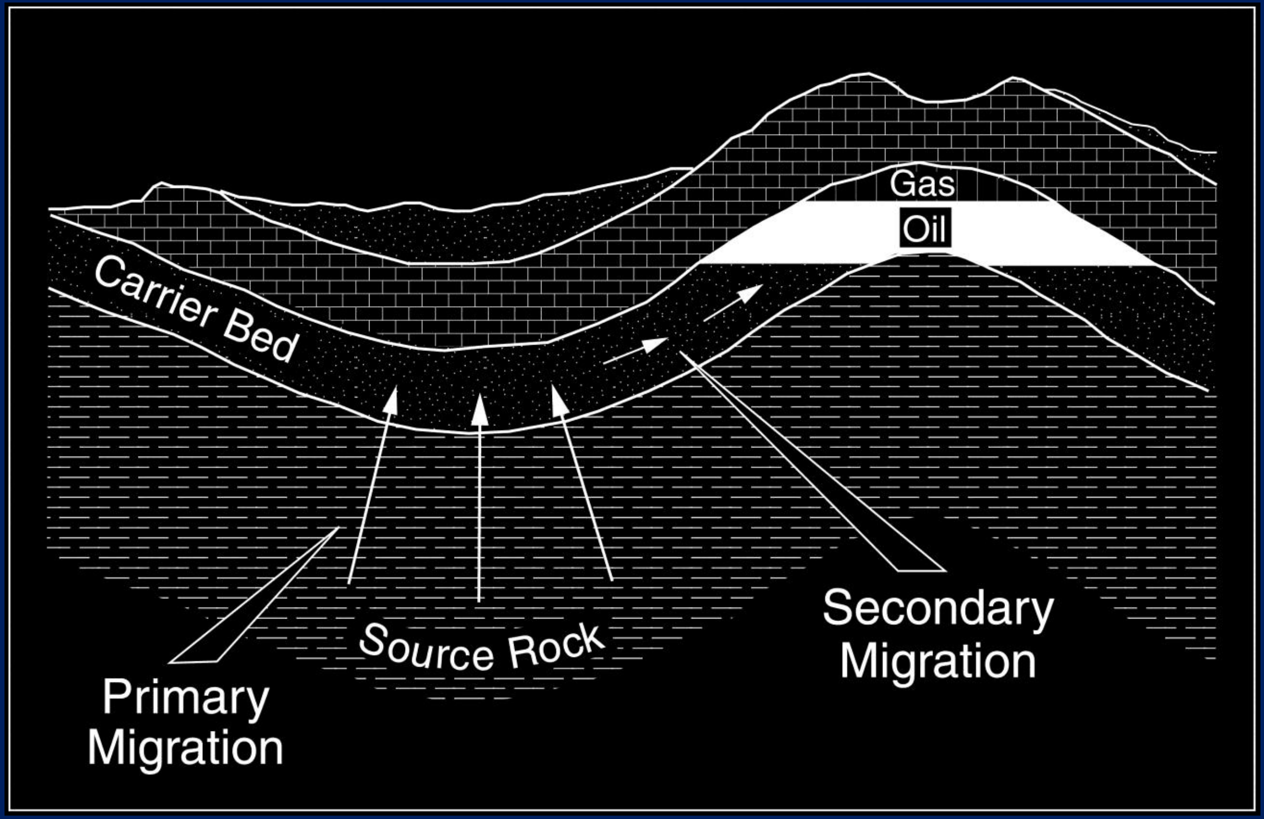
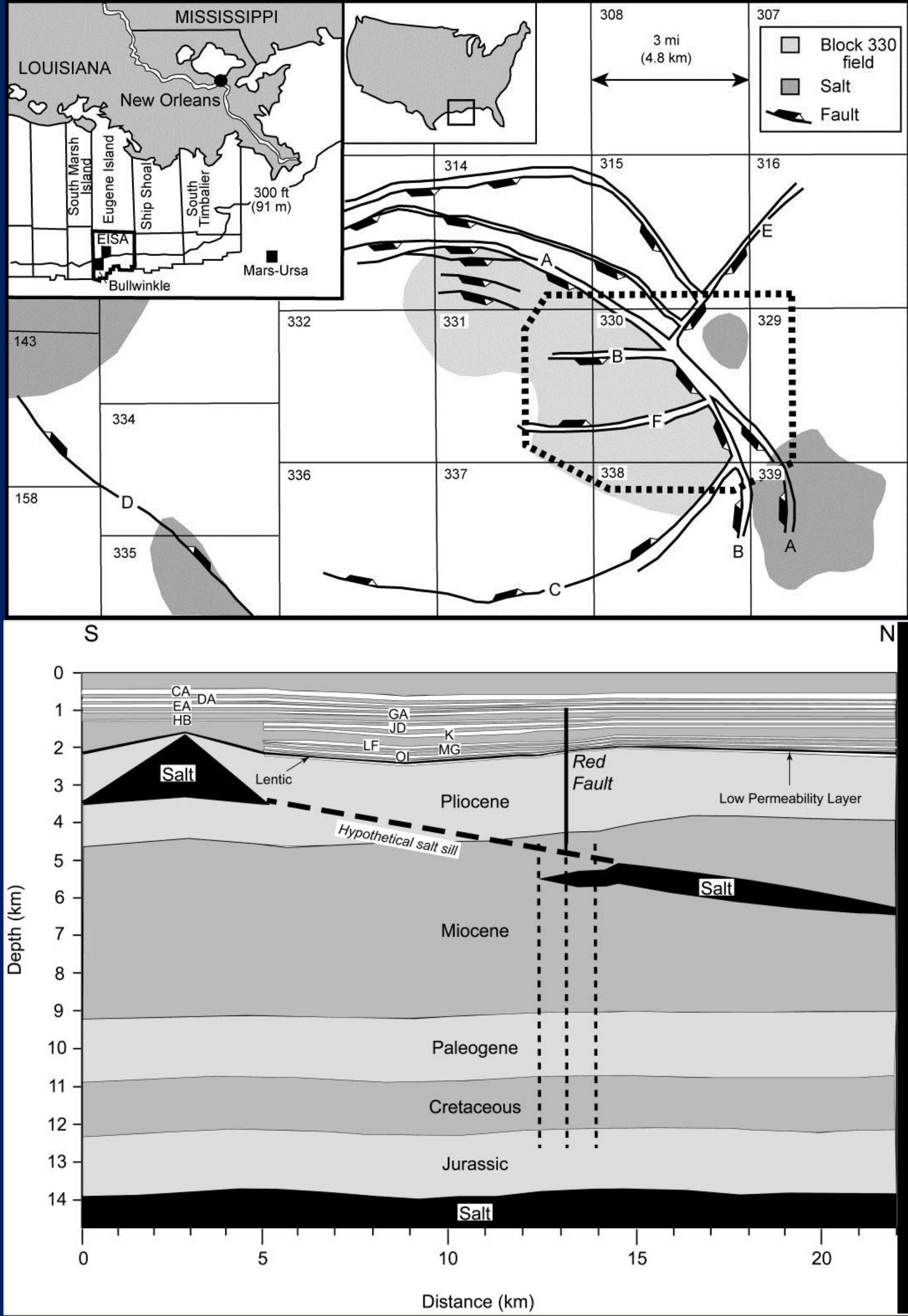
Research Motivation

- 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)

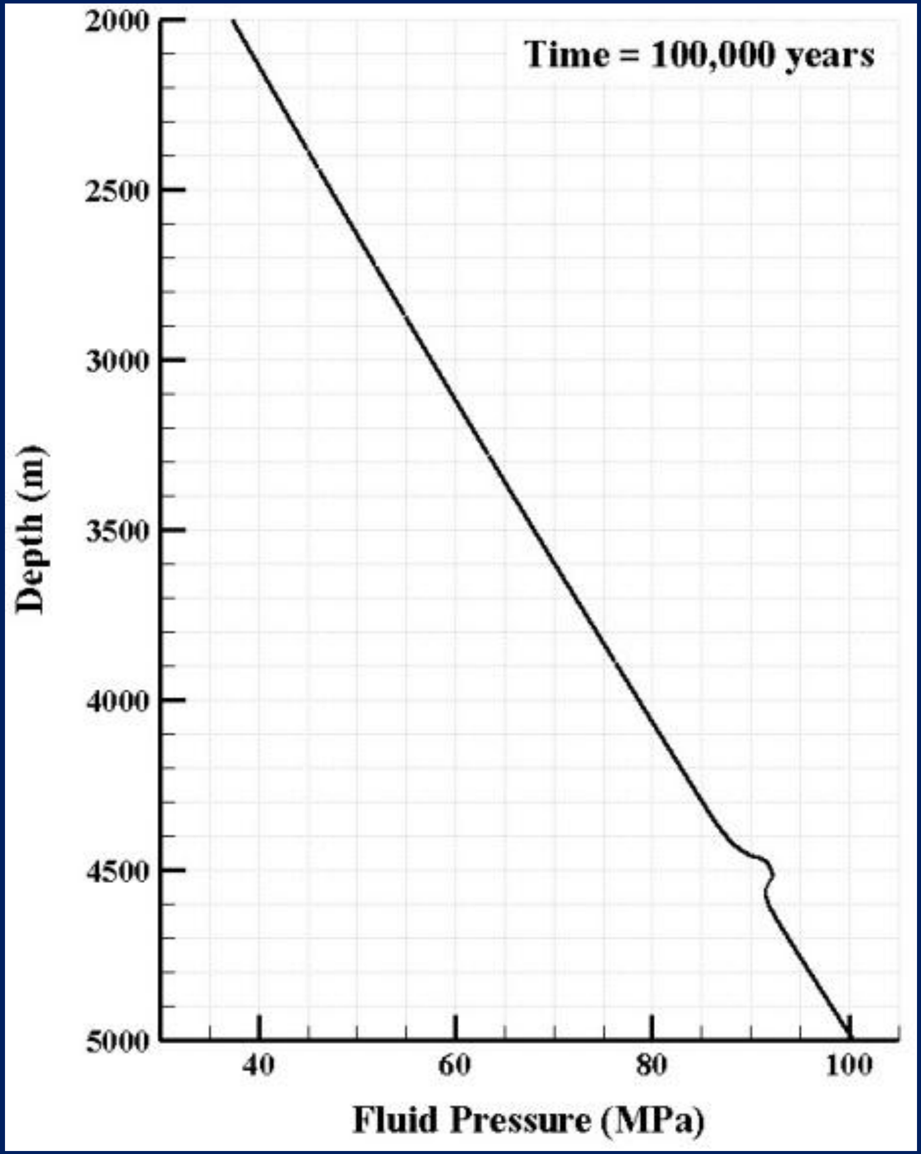


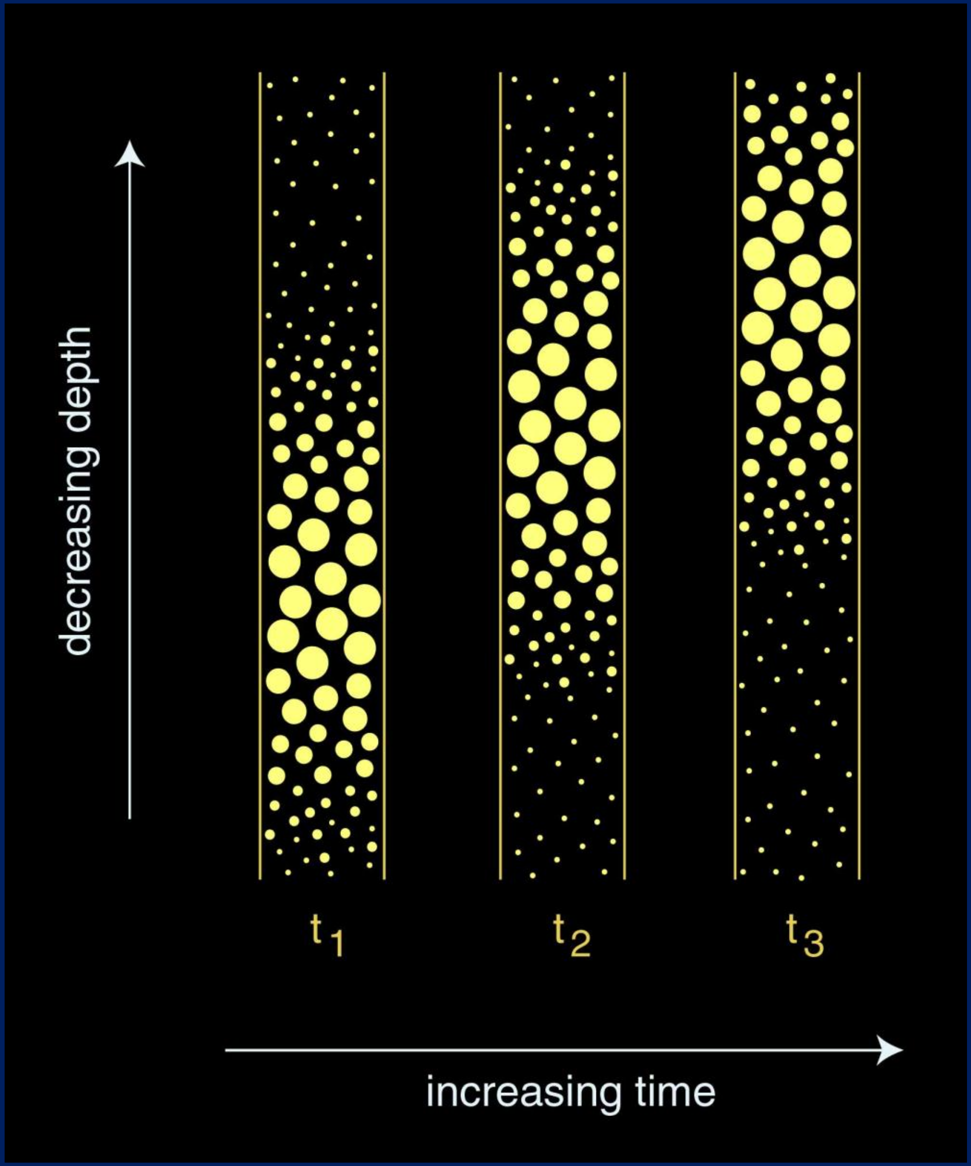
Eugene Island field, Gulf of Mexico basin

- 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)

Hypothesis 1: Solitary waves could be responsible for rapid hydrocarbon transport at Eugene Island





Two scenarios were modeled to test this hypothesis:

- One-dimensional oil-saturated model
- One-dimensional methane-saturated model

Solitary waves are predicted using mass conservation equations for elastic porous media if (Rice, 1992)

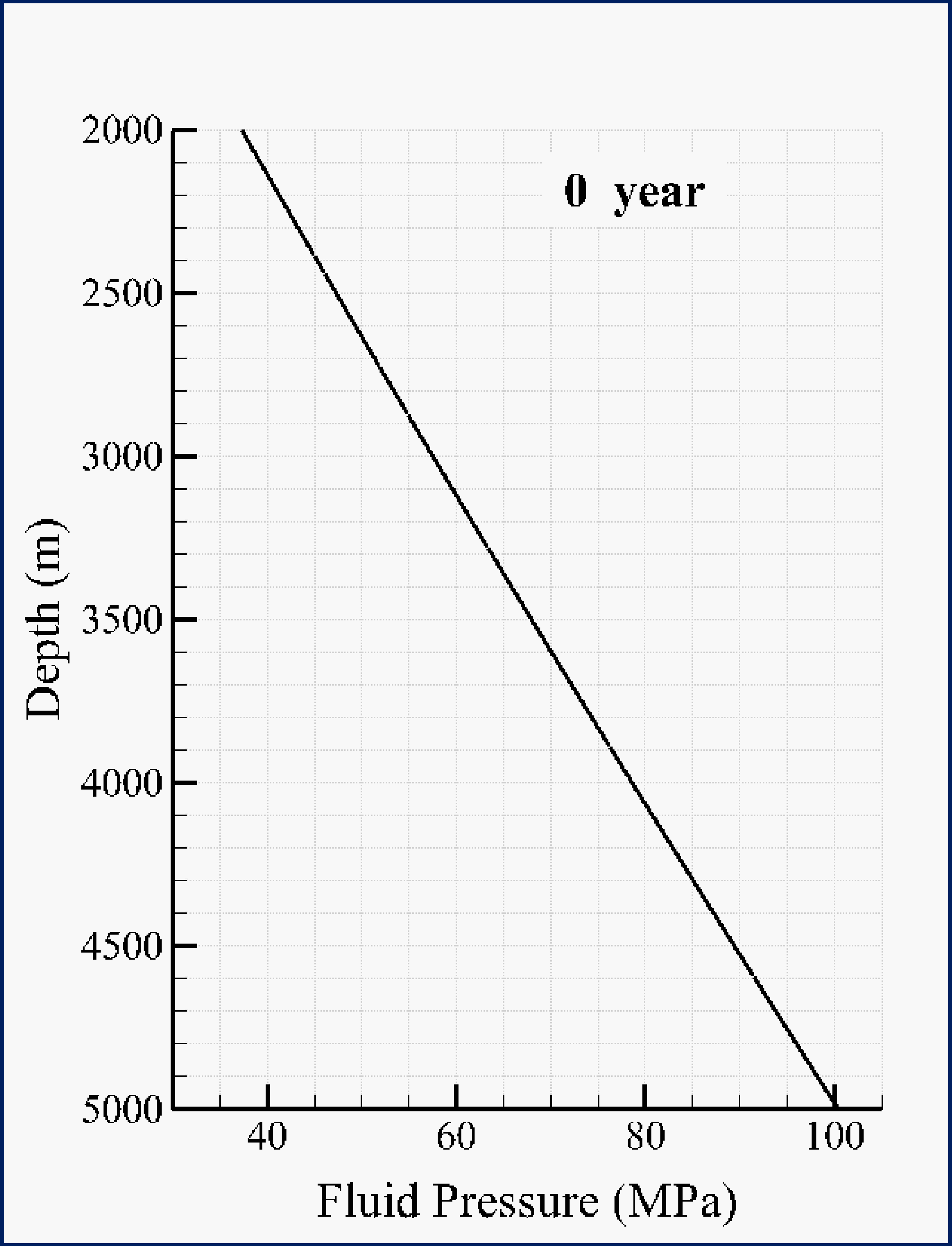
- Permeability is a sensitive function of effective stress

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

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

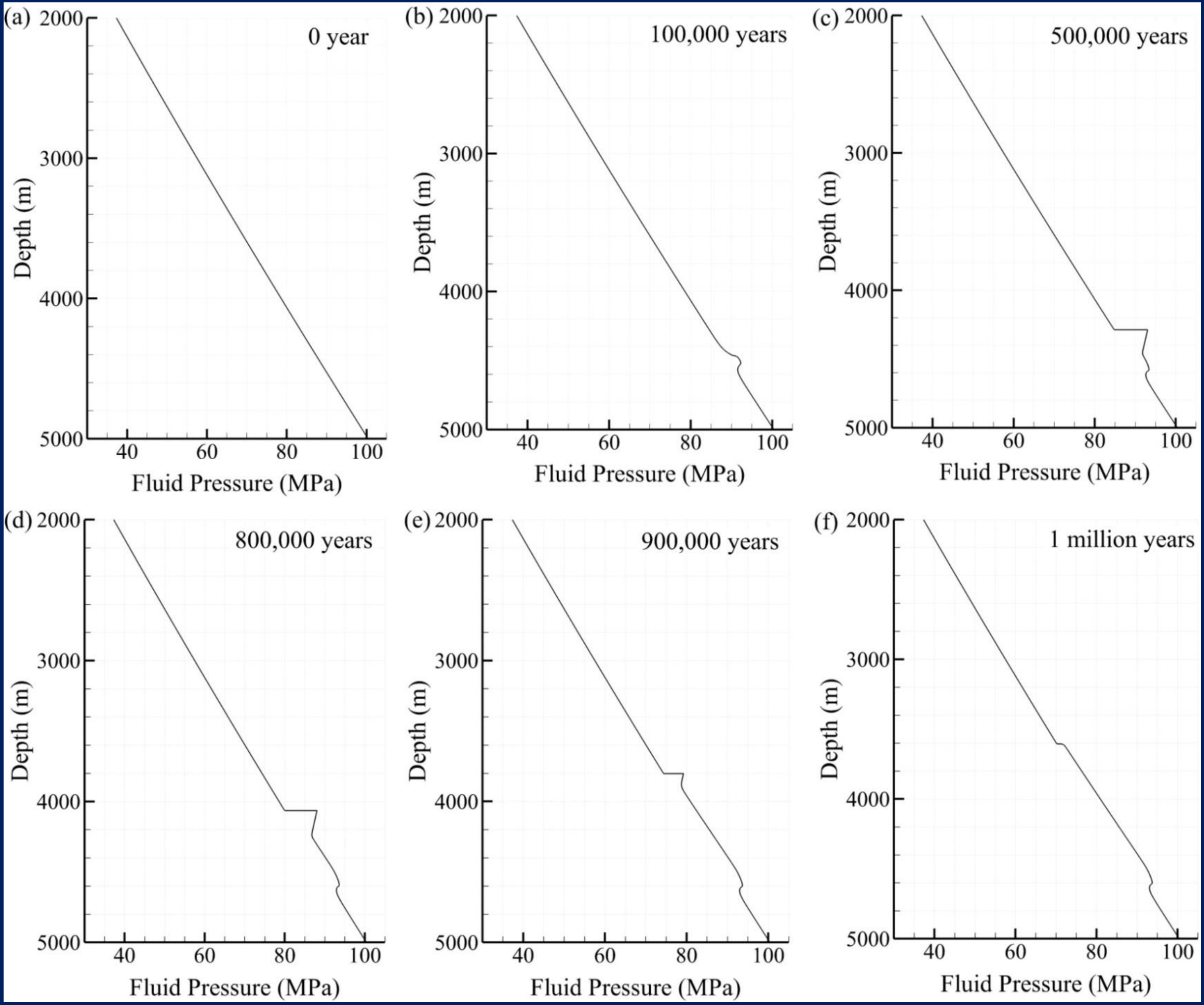
Oil-Saturated Solitary Wave Model

- 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 with a velocity of millimeter per year



Joshi et al, 2012

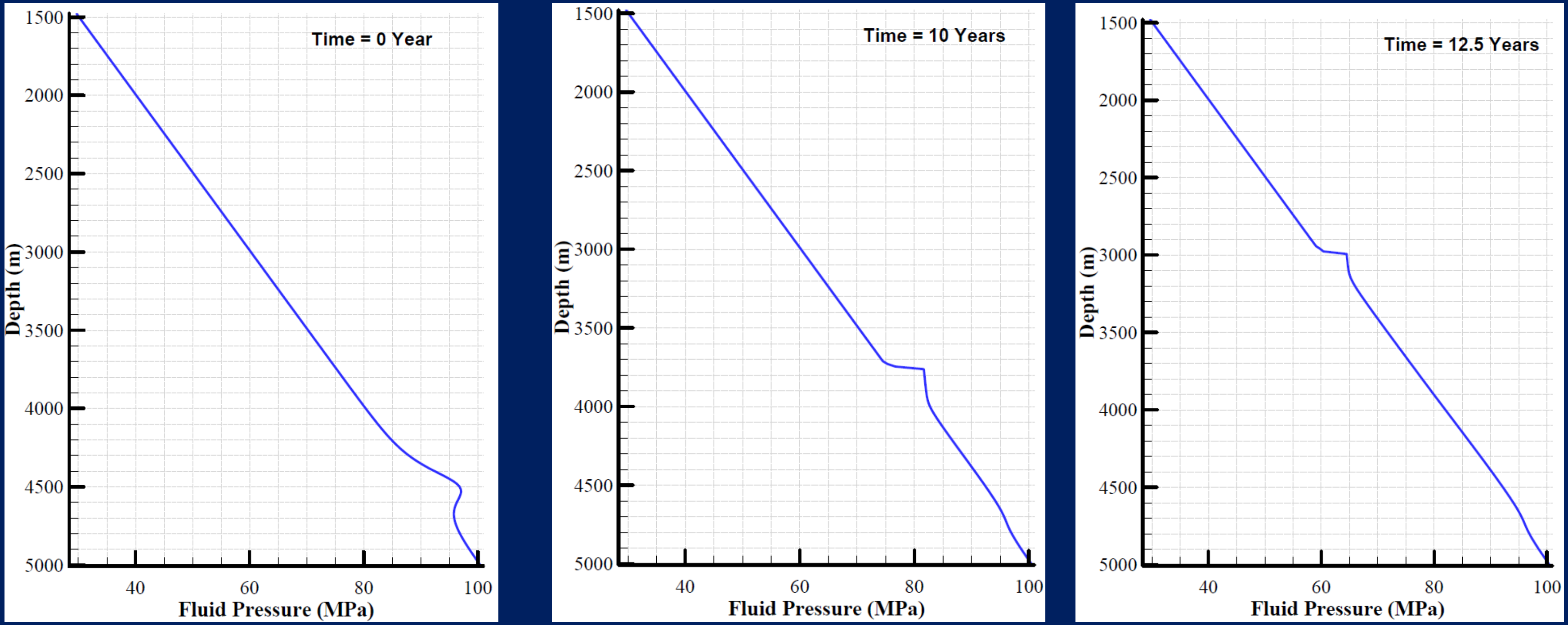
Oil-Saturated Solitary Wave Propagation



Methane-Saturated Solitary Wave Model

Methane-saturated solitary waves could be better in transporting hydrocarbons because of

- Higher wave velocity
- Greater travel distance



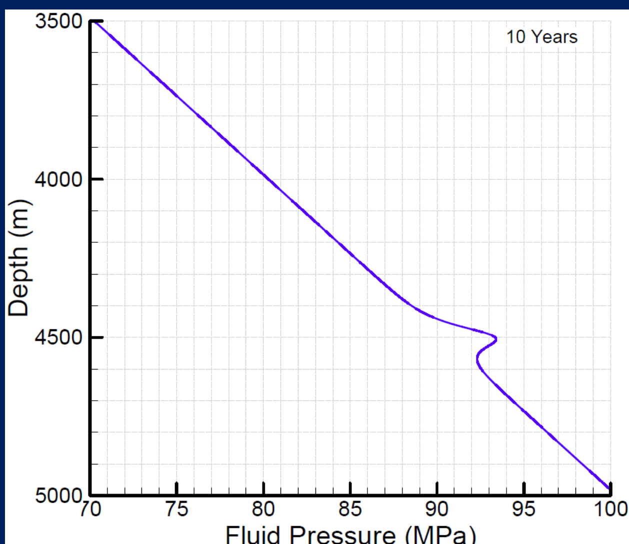
But very sensitive to time and nodal spacing so computational intensive

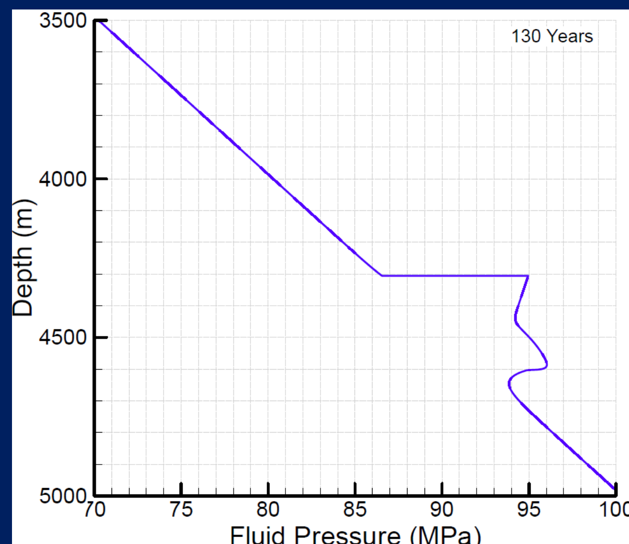
Mixed Methane-Oil Solitary Wave Model

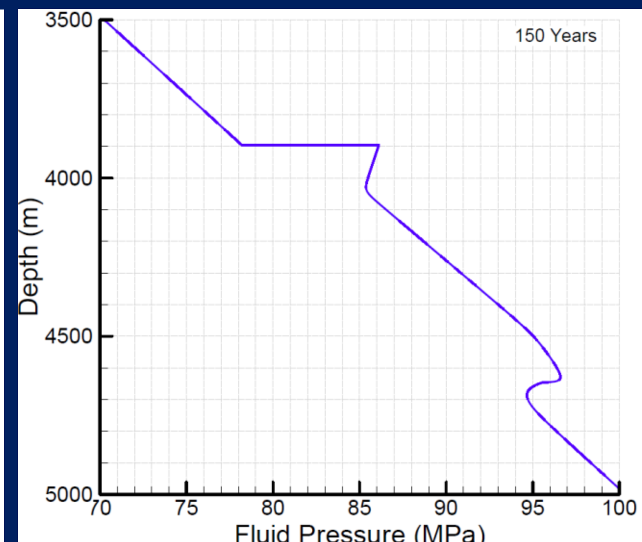
- Fluid properties resembling in between oil and methane

Fluid Density: 620 kg/m^3 Fluid Viscosity: 6.3×10^{-4} Pa.s

Fluid Pressure Rate : 0.3 MPa/year

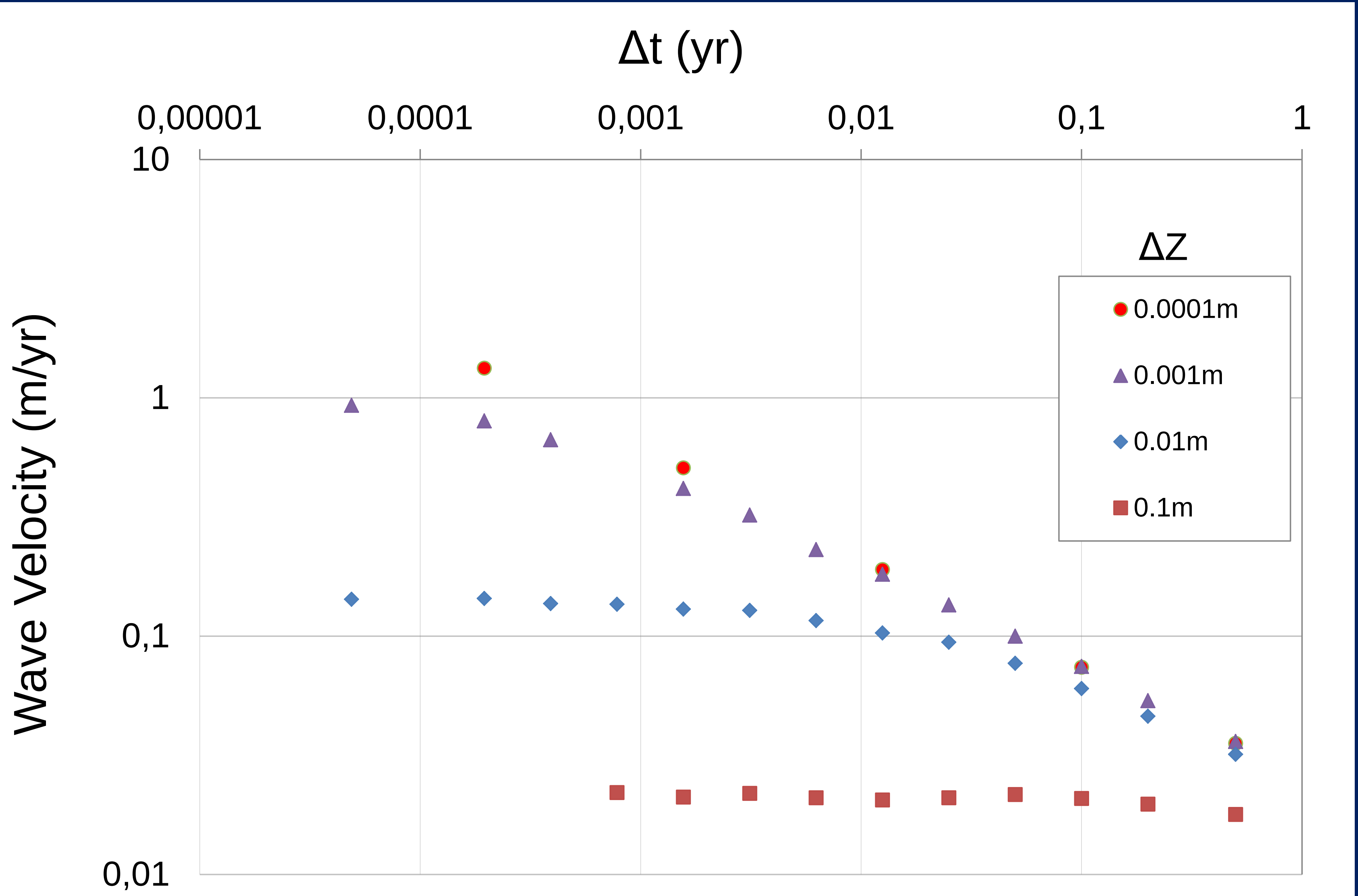






Approximately a meter per year of propagation velocity

Nodal and Time Sensitivity of the Model



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

Pressure diffusion rate is governed by the hydraulic diffusivity

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

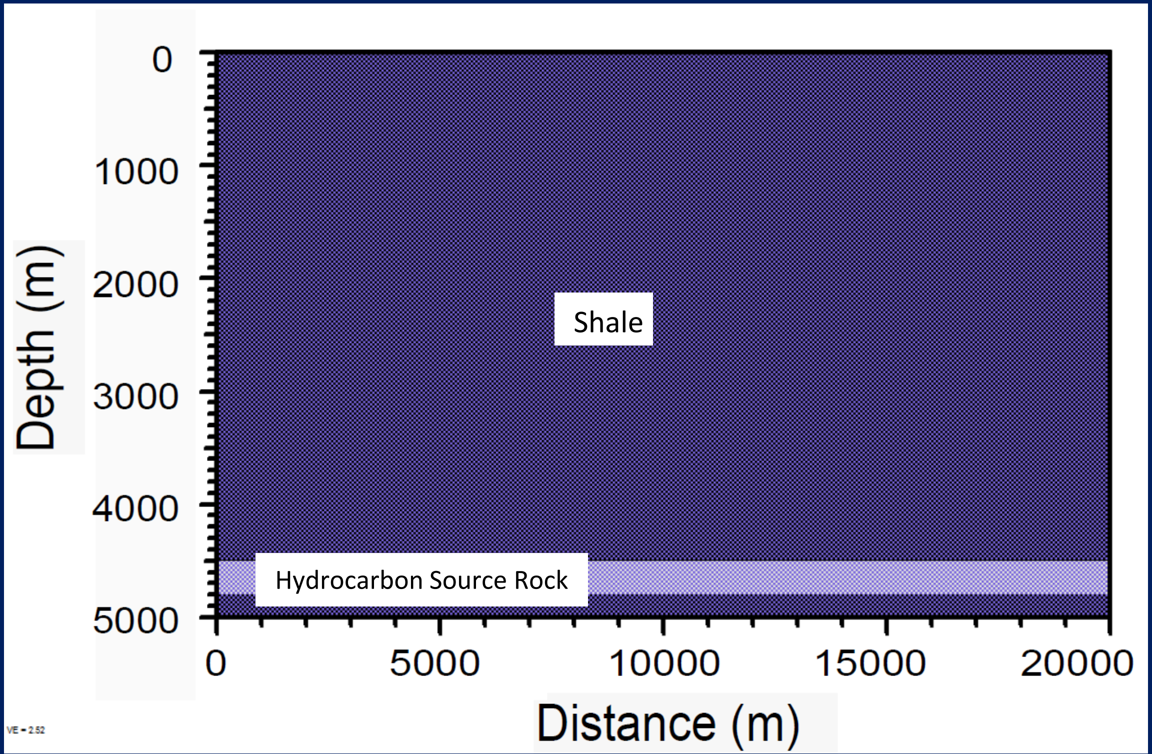
K = hydraulic conductivity

S_s = specific storage

Because methane is less viscous than oil, methane solitary waves require higher pressure generation rates than oil solitary waves

- rates needed to form methane solitary waves are 1000's to 10,000's times higher than predicted from modeling of compaction disequilibrium and hydrocarbon generation at Eugene Island

Hypothesis 2: Overpressures that high can be generated by compaction disequilibrium and hydrocarbon generation under geologically realistic conditions

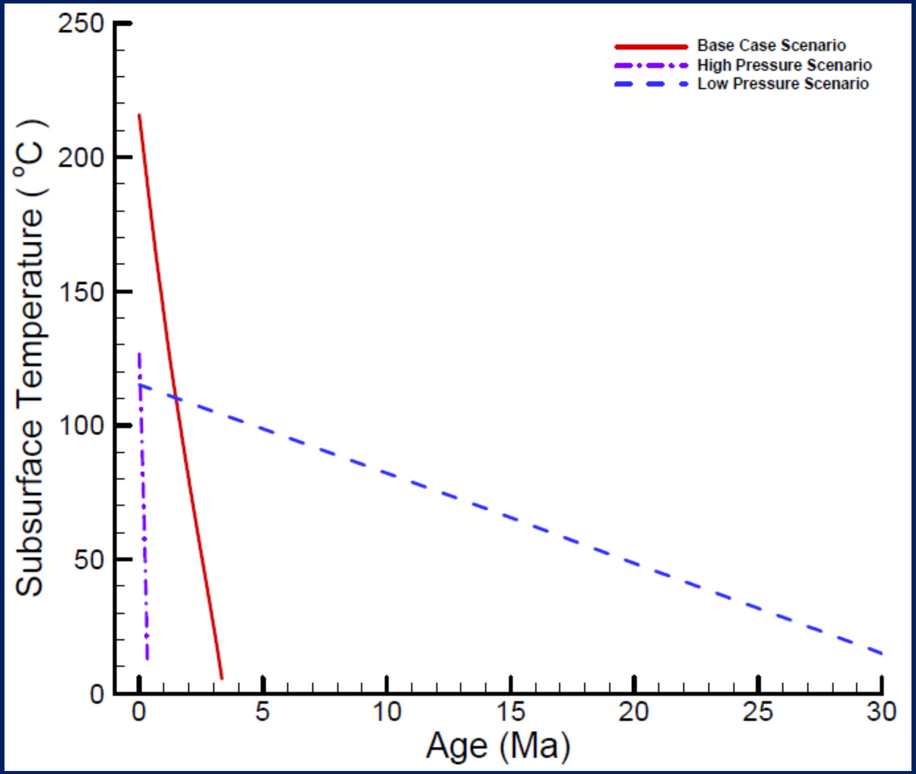


2D Modeling of Sediment Compaction & Overpressure Development

What could be the maximum possible overpressure rate from sediment compaction and hydrocarbon formation?

Three Different Scenarios

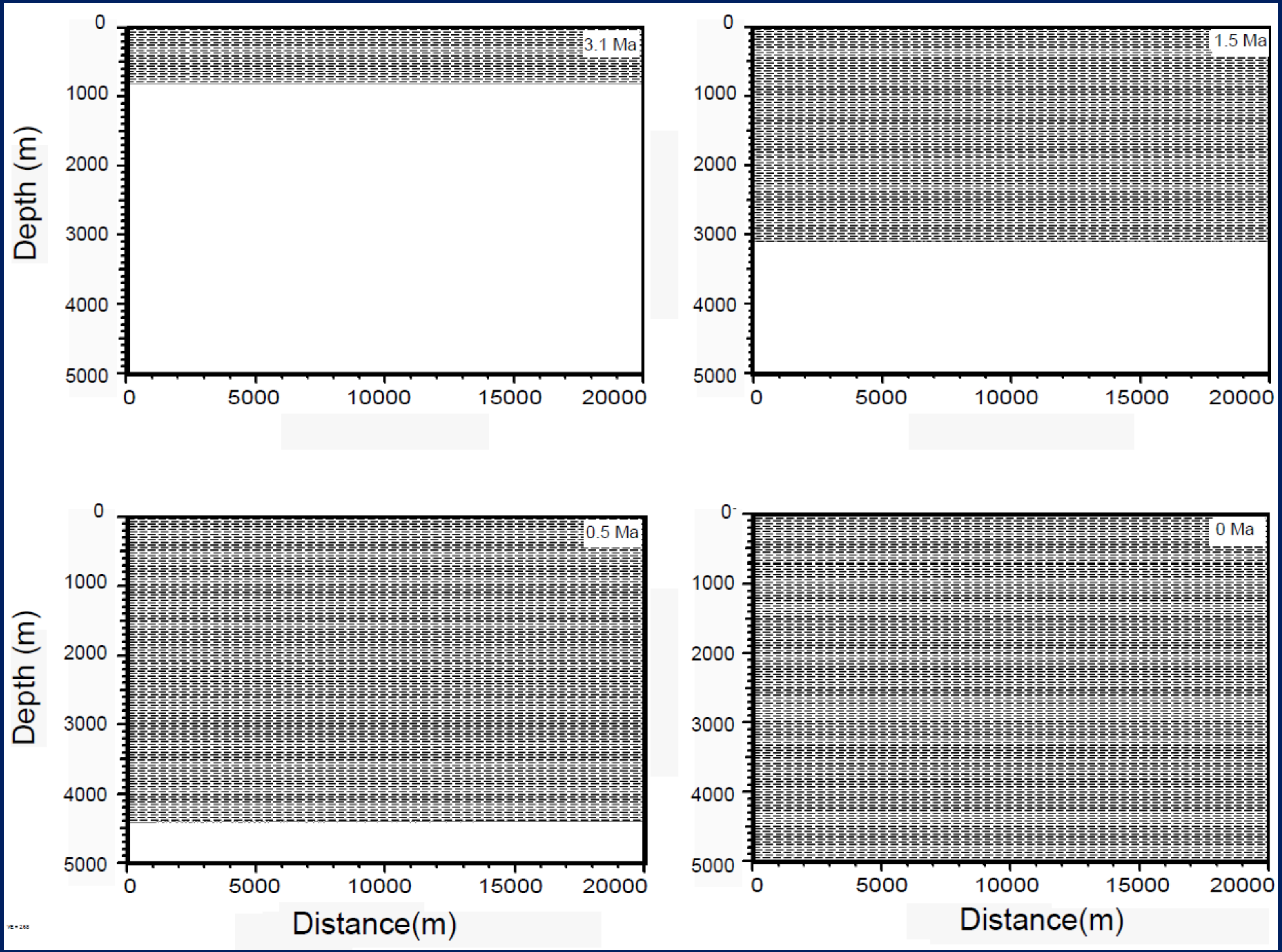
- Base Case Scenario
  - Basin properties resembling Eugene Island 330 basin
- High Pressure Rate Scenario
  - Basin properties that maximize overpressures
- Low Pressure Rate Scenario
  - Basin properties that minimize overpressures



Model Parameter Values

Model Parameters	Base Case	Low Pressure Rate	High Pressure Rate
Sedimentation rate (mm.year^{-1})	1.39	0.139	13.9
Porosity (%)	0.25	0.3	0.05
Matrix Thermal Conductivity (W.m^{-1}.C^{-1})	1.82	3.64	0.91
Surface Temperature (˚C)	5	2.5	10
Basement heat flow (mW.m^{-2})	60	50	100
Shale Permeability (m^{2})	10^{-18}	10^{-18}	10^{-18}
Shale Compressibility (Pa^{-1})	10^{-8}	10^{-8}	10^{-8}
% TOC	5	2.5	10
Kerogen Type	Type II (Burnham ’89)	Type II (Burnham ‘89)	Type II (Espitalie ’88 Viking Graben)

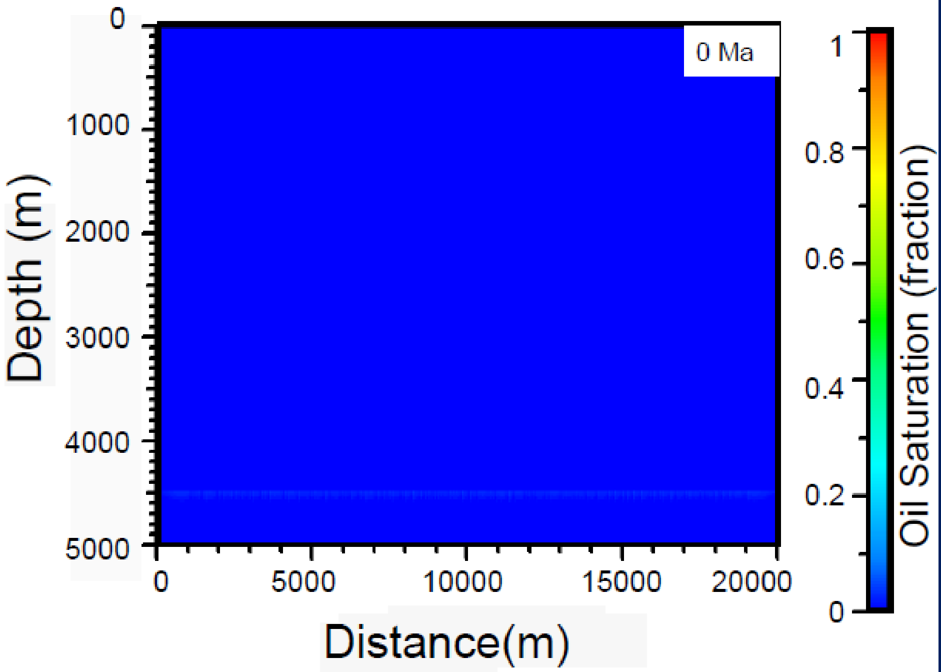
Stratigraphic Evolution of the Basin

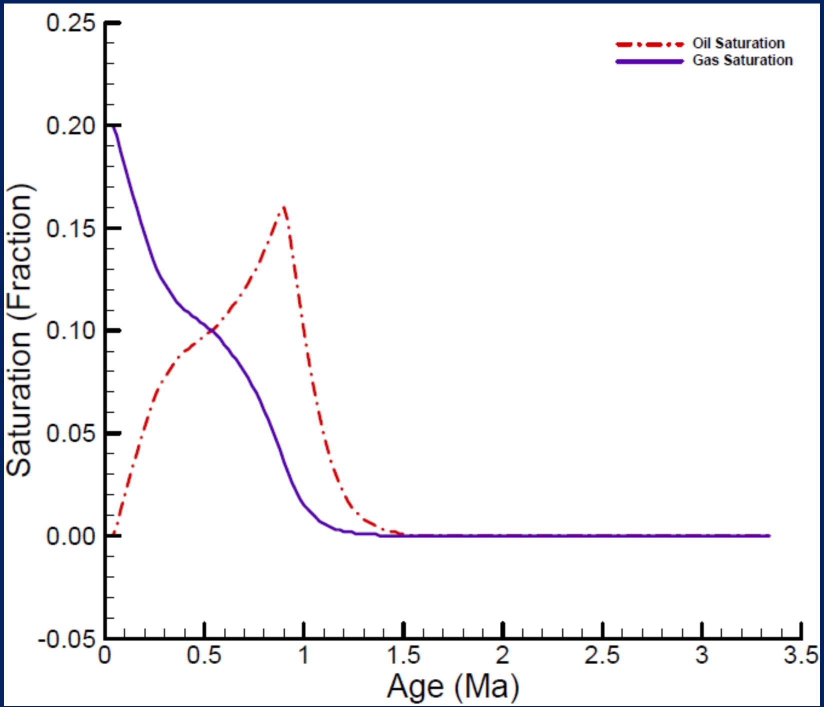


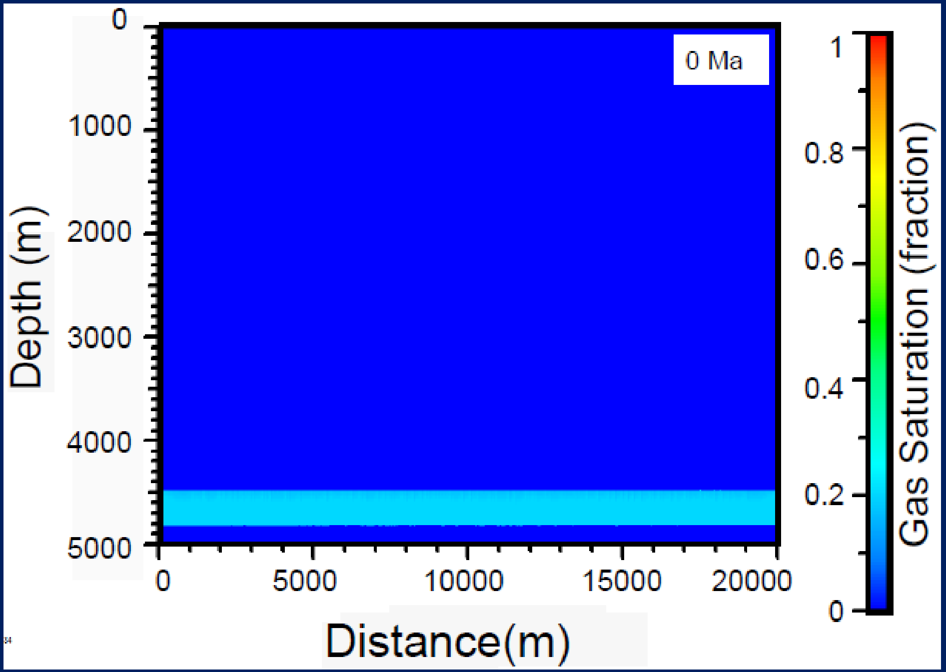
Hydrocarbon Saturation

- ➢Oil saturation peaked at 0.8 Ma and then declined

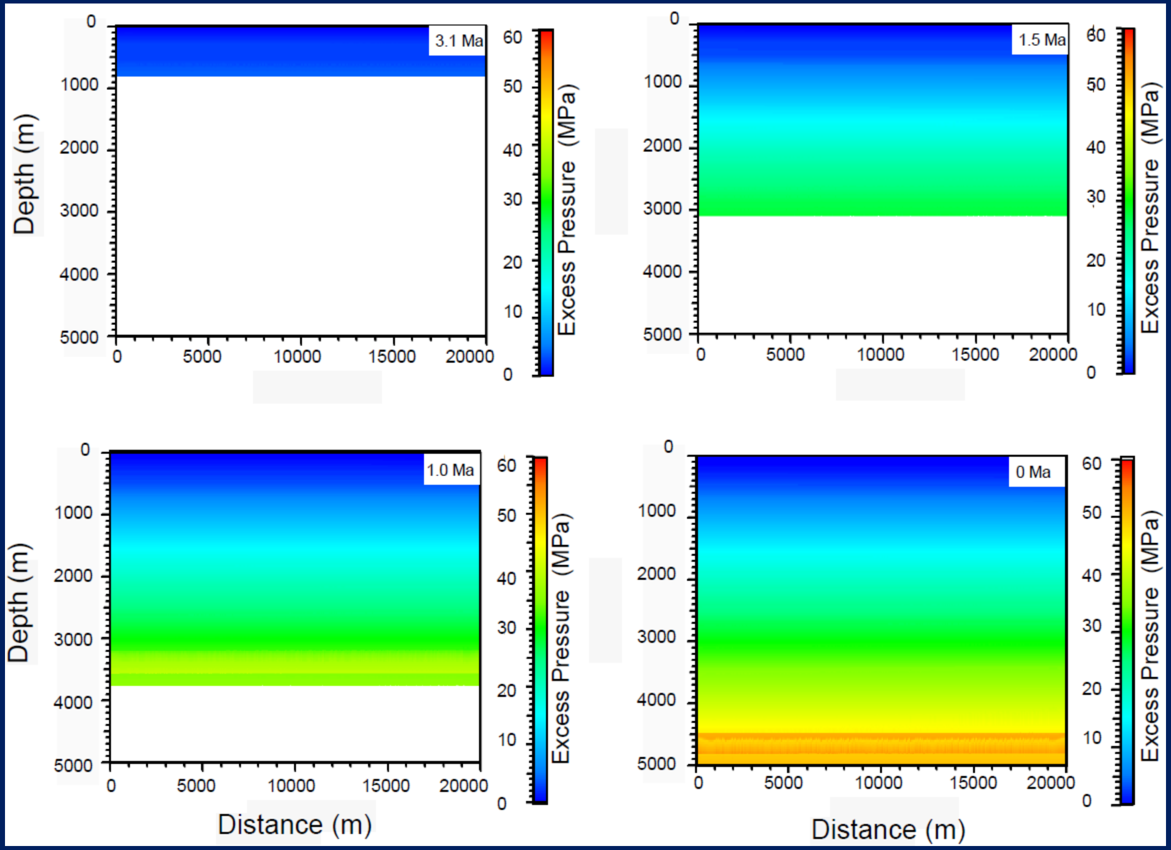
- ➢Gas saturation increased to the present day





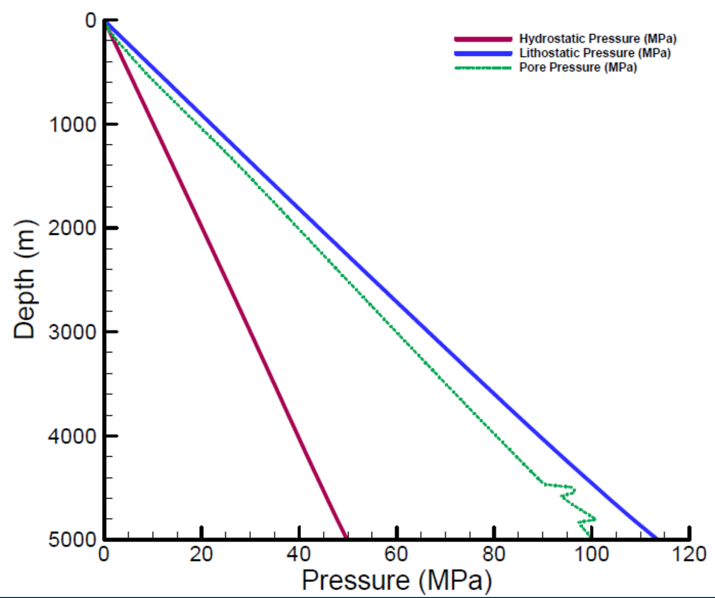


Excess Pressure Evolution in the Basin



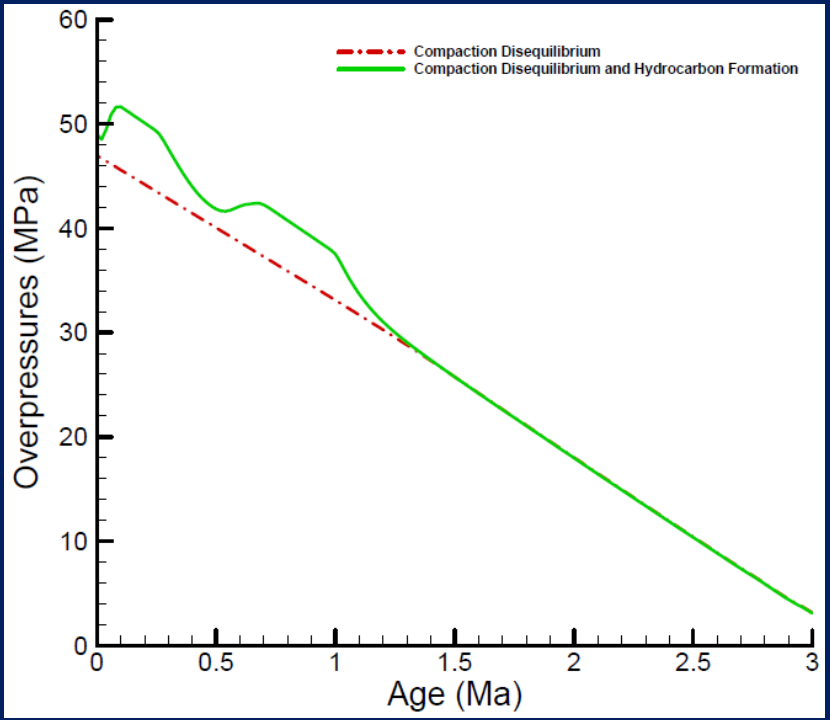
- ➢56 MPa of excess pressures at source depth in the present day

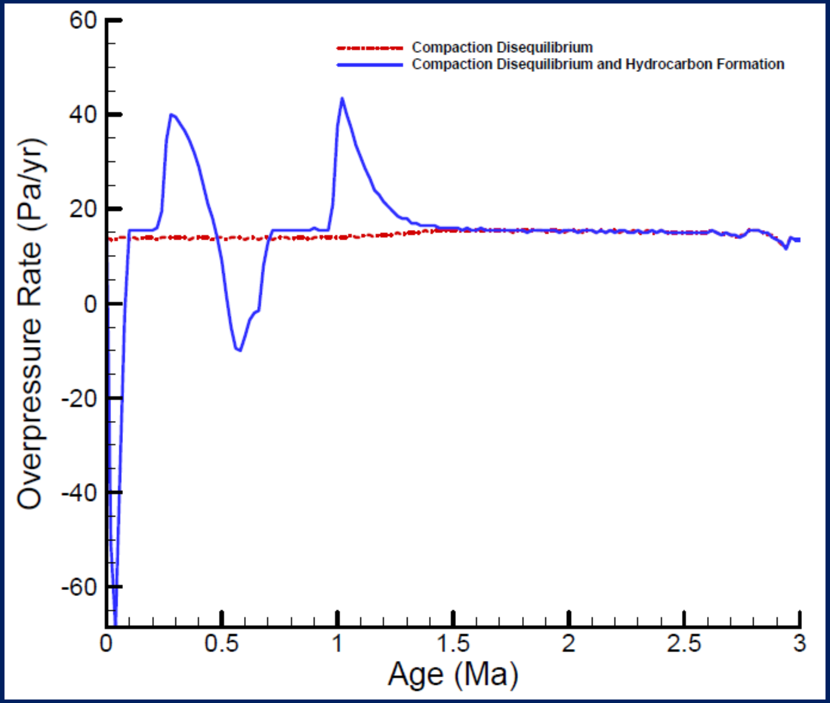
- ➢Pore pressures reached max. of 95% of the lithostatic within hydrocarbon formation region



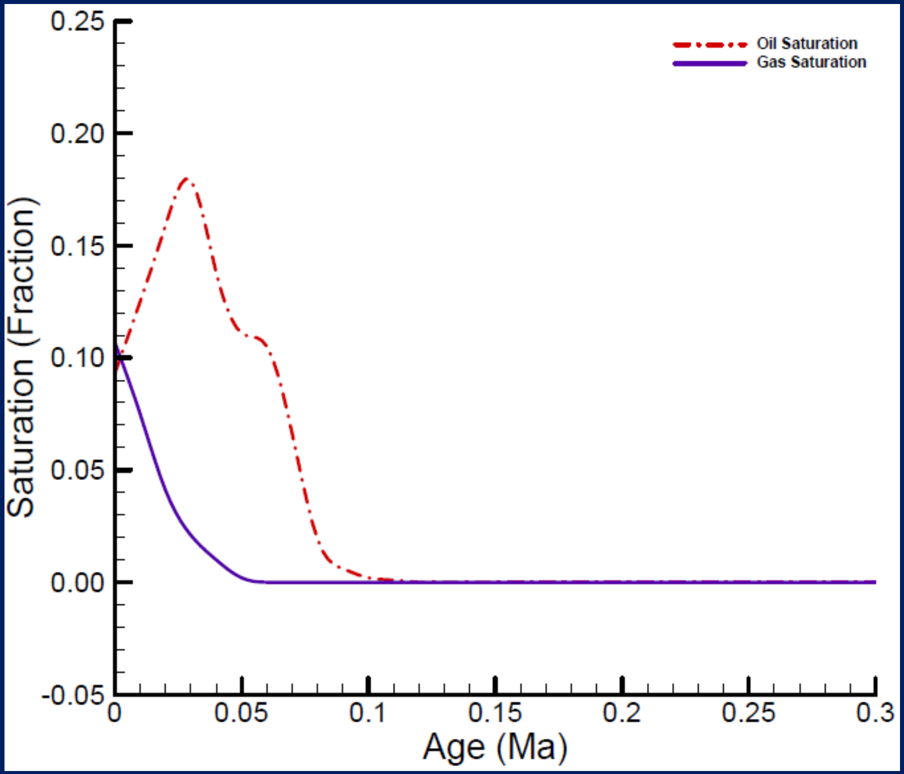
Hydrocarbon (HC) Generation & Overpressure Rates

- Compaction disequilibrium as a dominant overpressure mechanism
- 6 MPa of overpressures from HC formation
- Maximum overpressure rate of 40 Pa/year
- HC overpressure rate reached nearly three times the rate from compaction rate

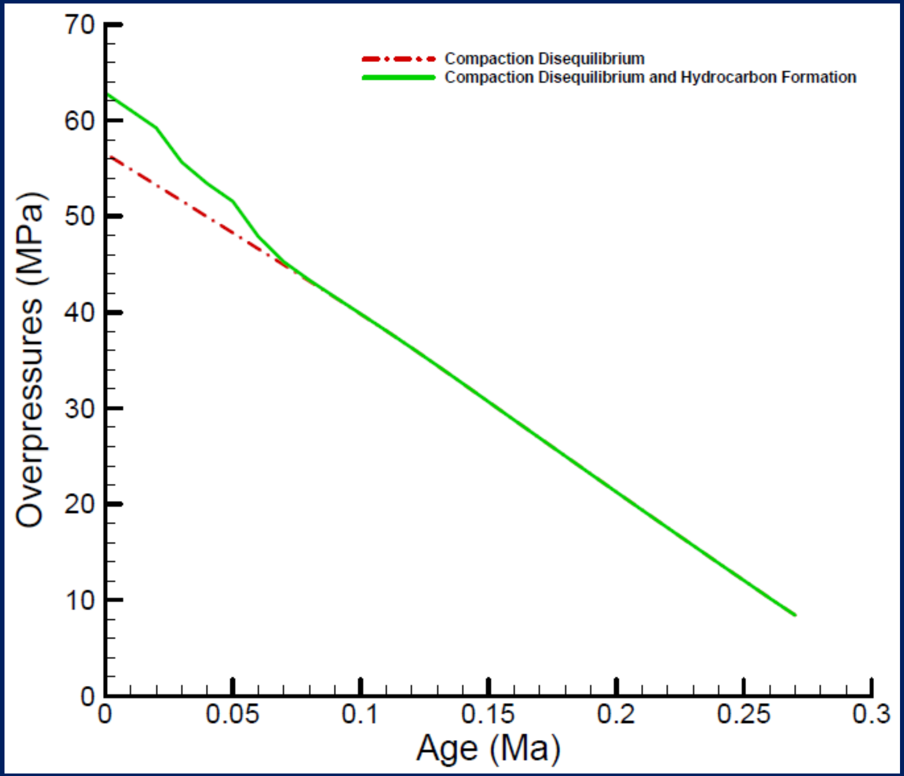




High Pressure Rate Scenario



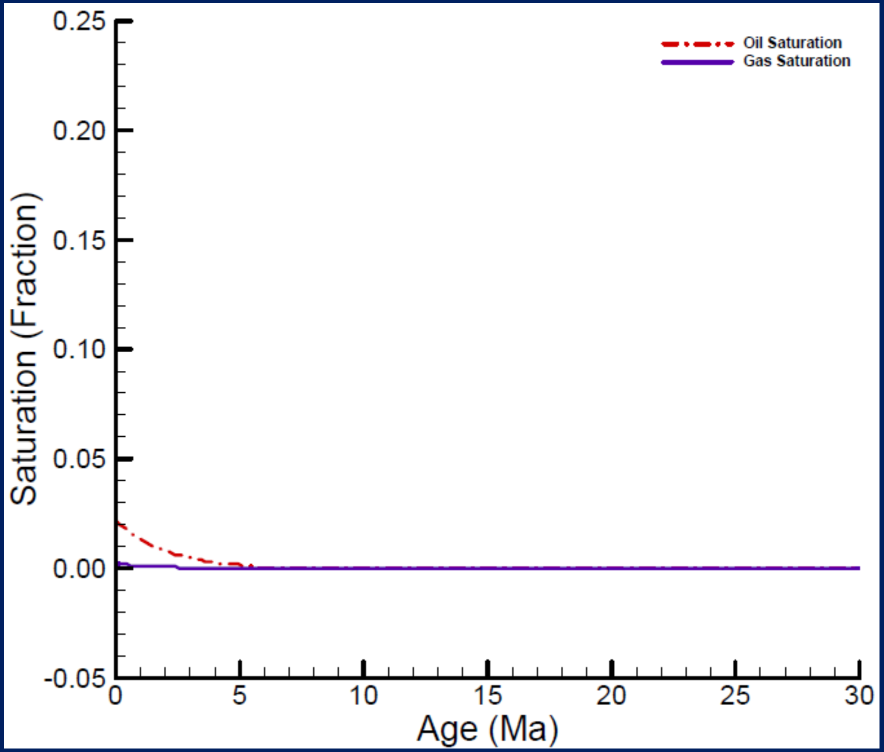
Oil saturation dominated the gas saturation

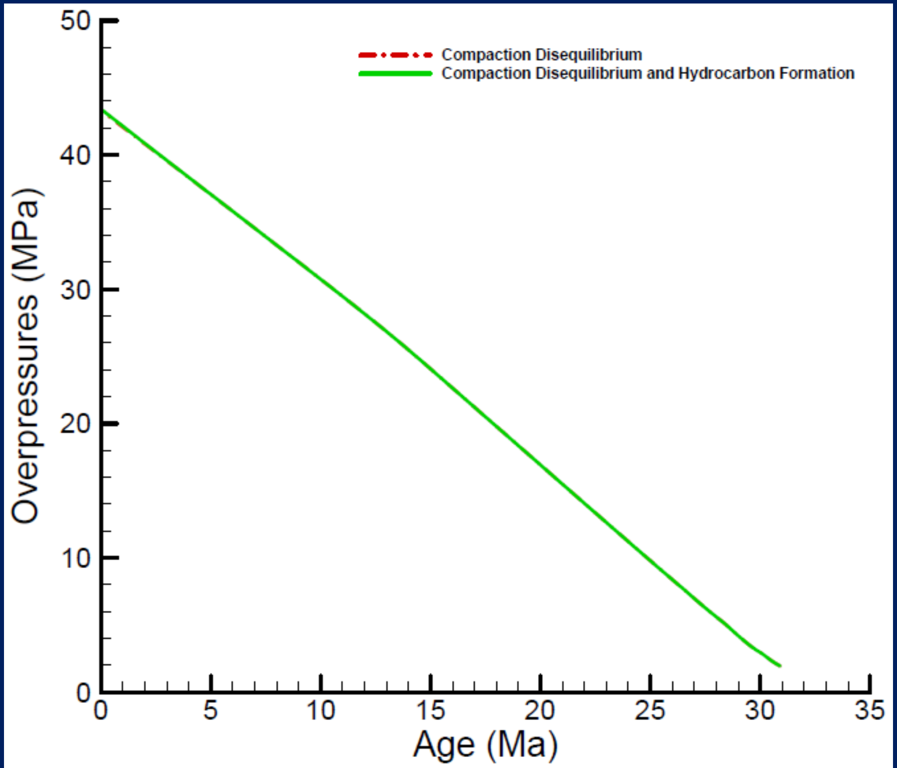


Hydrocarbon overpressures reached maximum of 6.3 MPa

Low Pressure Rate Scenario

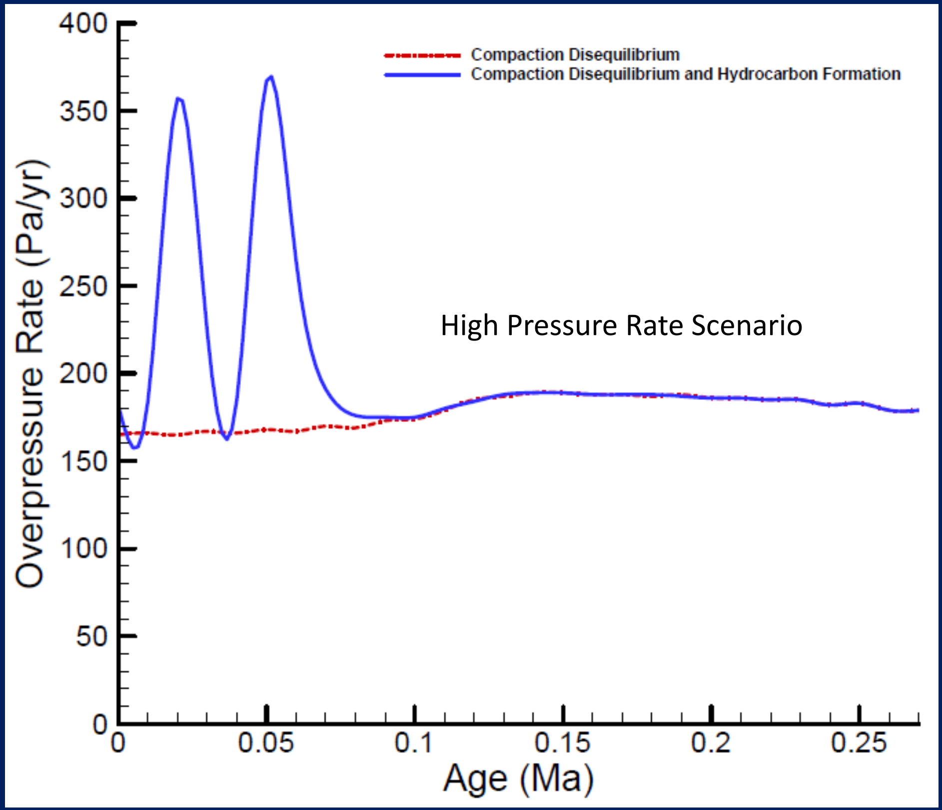
Minimal saturation of hydrocarbons



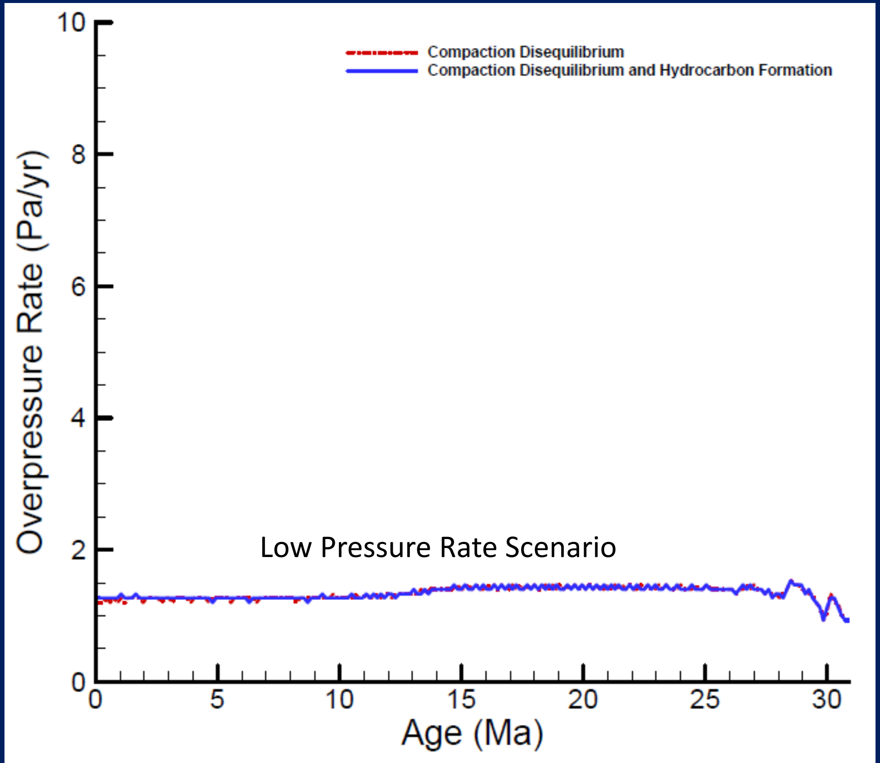


Negligible overpressures from hydrocarbon formation

Overpressure Rates



- Overpressure rate reached maximum of 367 Pa/year
- Two episodes of pressure rate increase



Minimum overpressure rate of ~ 1 Pascal per year

Solitary Waves vs Pressure Generation Rates

- Pressure rate at Eugene Island 330 basin increases at 40 Pa per year
- Sufficient to generate oil-saturated solitary waves
- Methane-saturated solitary waves require pressure generation rates 1000 to 10,000 times higher
- Under geologically realistic conditions, compaction disequilibrium and hydrocarbon generation pressure rates ranged from ~1 to 367 Pa/year
- Inadequate to form methane-saturated solitary waves

Could methane-saturated solitary waves form at Eugene Island?

- Could be possible if

  A) Assumed with presence of multiple fluids (oil or water) in geologic medium that could reduce relative permeability for methane decreasing the hydraulic diffusivity,

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

  B) Any other fluid pressure generating mechanism is present such as seismic loading (Wood and Steedman, 1992; Cox et al, 2012)

Conclusions

- Methane-saturated solitary wave travels at least 1 meter per year of velocity compared to 1 millimeter per year velocity of oil-saturated solitary wave
- But formation of methane-saturated solitary wave requires 1000 to 10,000 times higher pressure generation rate than obtained from modeling of Eugene Island basin
- Maximum possible pressure rate of ~ 400 Pa/year could be achieved from sediment compaction and hydrocarbon generation under best geological conditions
- Provided other pressure generating mechanism, methane-saturated solitary waves could be an efficient means for methane transport along the Red fault at Eugene Island