Sediment Diagenesis in the Gulf of Mexico Basin and its Role in Pore Fluid Pressure Evolution: Implications for Hydrocarbon Transport via Solitary Waves*

Ajit Joshi[1] and Martin Appold[1]

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[1] University of Missouri, Columbia, MO (aj2v4@mail.missouri.edu)

Abstract

Rapid, kilometer-scale vertical migration of fluids through low permeability sediments has been documented in numerous sedimentary basins around the world, including the South Eugene Island 330 Field in the Gulf of Mexico basin. Solitary waves, which can travel at speeds orders of magnitude greater than Darcian flow, are hypothesized to be a mechanism for rapid transport of fluids from deep overpressured source sediments to shallow reservoirs. Solitary waves occur as regions of high porosity and fluid pressure and may form in oil-saturated sediments when the ratio of fluid pressure generation rate (Pg) to hydraulic diffusivity (D) exceeds about 1.1×10^8 Pa m^{-2}. The main purpose of the present study was to investigate the rate and magnitude of fluid pressure generation from sediment compaction and hydrocarbon formation that can develop in sedimentary basins to assess the likelihood of solitary wave formation. Using the BasinMod2D™ software, a two-dimensional numerical model was constructed that calculated pore fluid pressure generation as a result of sediment deposition, burial, quartz cementation, and compaction, heat transport, kerogen maturation to form hydrocarbons, and associated flow of oil, gas, and water.

Results showed that sediment diagenesis in a hydrocarbon forming sedimentary basin could generate pore fluid pressures at rates of 1's up to a maximum of 510 Pa $year^{-1}$. Solitary waves that are capable of transporting oil could form at depths greater than 4 kilometers from kerogen-rich source rocks. However, the high hydraulic diffusivity of methane-saturated sediments would likely require high-pressure generation rates of at least 2000 Pa $year^{-1}$ in order to form solitary waves capable of transporting methane, which is unlikely to be achieved by hydrocarbon formation and sediment compaction but might be achieved by earthquakes.

References Cited

Alexander, L.L., and J. Handschy, 1998, Fluid flow in a faulted reservoir system; fault trap analysis for the Block 330 Field in Eugene Island, South Addition, offshore Louisiana: AAPG Bulletin, v. 82/3, p. 387-411.

Appold, M.S., and J.A. Nunn, 2002, Numerical models of petroleum migration via buoyancy-driven porosity waves in viscously deformable sediments: Geofluids, v. 2, p. 233-247.

Haney, M.M., R.J. Snieder, S. Sheiman, and S. Losh, 2005, A moving fluid pulse in a fault zone: Nature, v. 437, p. 46.

Joshi, A., Appold, M.S., and Nunn, J.A., 2012, Evaluation of solitary waves as a mechanism for oil transport in poroelastic media: a case study of the South Eugene Island field, Gulf of Mexico basin: Marine and Petroleum Geology, v. 37/1, p. 53-69.

Lin, G., and J.A. Nunn, 1997, Evidence for recent migration of geopressured fluids along faults in Eugene Island, Block 330, offshore Louisiana, from estimates of pore water salinity: Transactions Gulf Coast Association of Geological Societies, v. 47, p. 419-424.

Losh S., L. Eglinton, M. Scholl, and J. Wood, 1999, Vertical and Lateral Fluid flow related to a large growth fault, South Eugene Island Block 330 Field, Offshore Louisiana: AAPG Bulletin, v. 83, p. 244-276.

Rice, J., 1992, Fault stress states, pore pressure distributions, and the weakness of the San Andreas Fault, in B. Evans, and T.F. Wong, eds., Fault Mechanics and Transport Properties of Rocks: Academic Press, London, p. 475-503.

Revil, A., and L.M. Cathles III, 2002, Fluid transport by solitary waves along growing faults; a field example from the South Eugene Island Basin, Gulf of Mexico: Earth and Planetary Science Letters, v. 202/2, p. 321-335.

Roberts, J.S., Nunn, J.A., Cathles, L., and Cipriani, F.D., 1996, Expulsion of abnormally pressured fluids along faults, Journal of Geophysical Research, v. 101, p. 28231-28252.

Wang, C.-Y., and Y.-P. Chia, 2008, Mechanism of water level changes during earthquakes: Near field versus intermediate field: Geophysical Research Letters, v. 35, L12402, doi:10.1029/2008GL034227.

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Ajit Joshi
Martin S. Appold

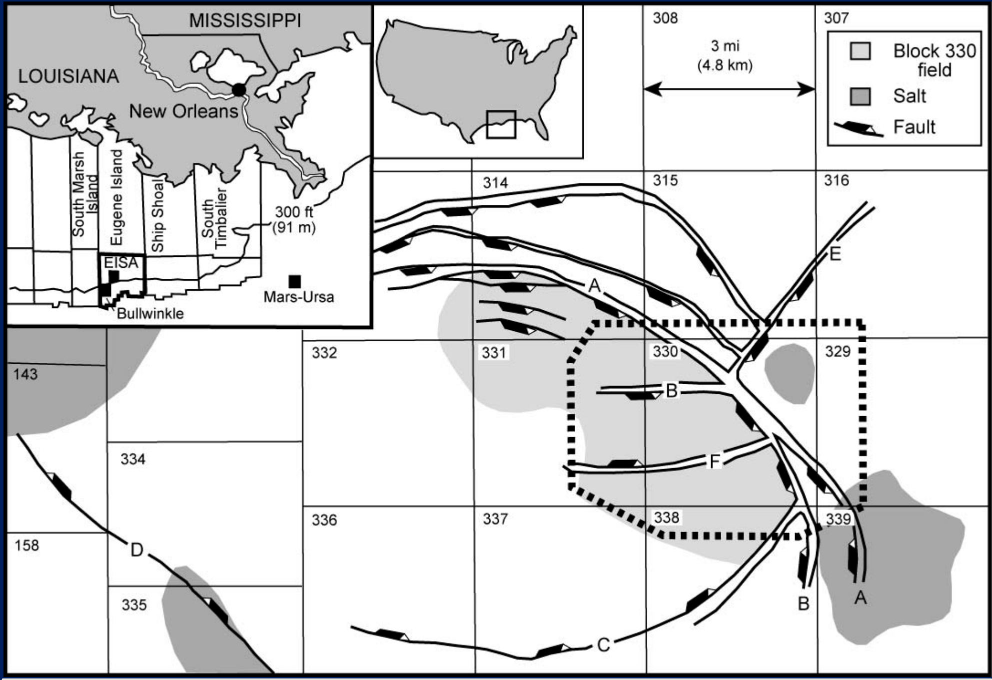
Department of Geological Sciences
University of Missouri

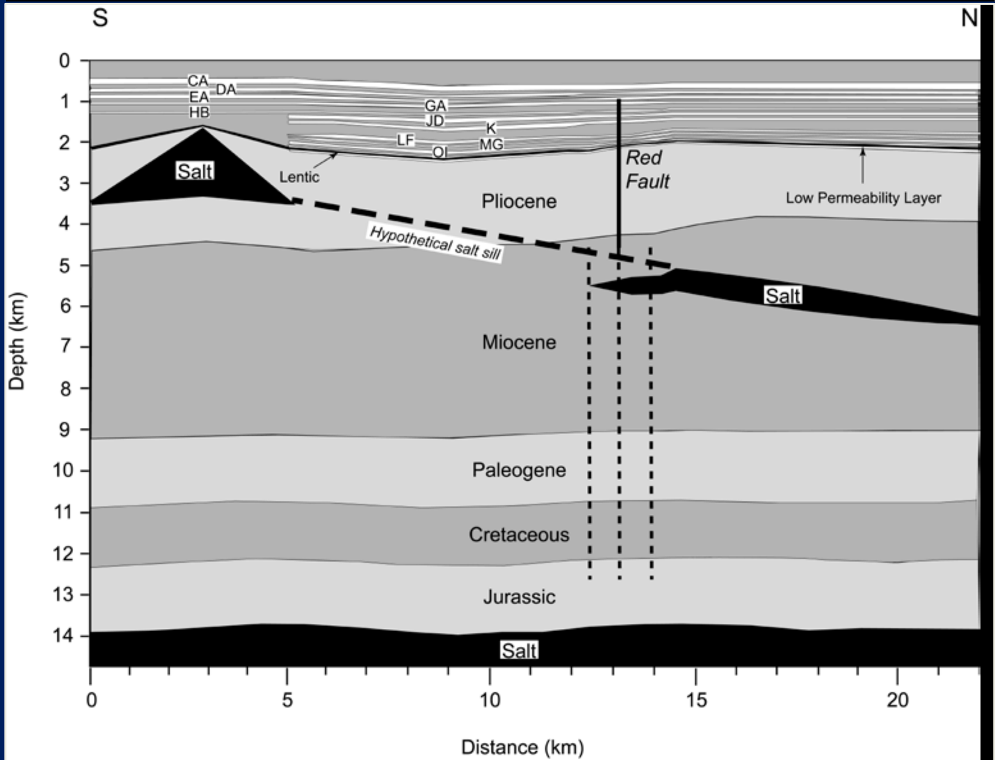
Rapid vertical fluid migration occurs in numerous sedimentary basins around the world

For example, the South Eugene Island field in the Gulf of Mexico basin

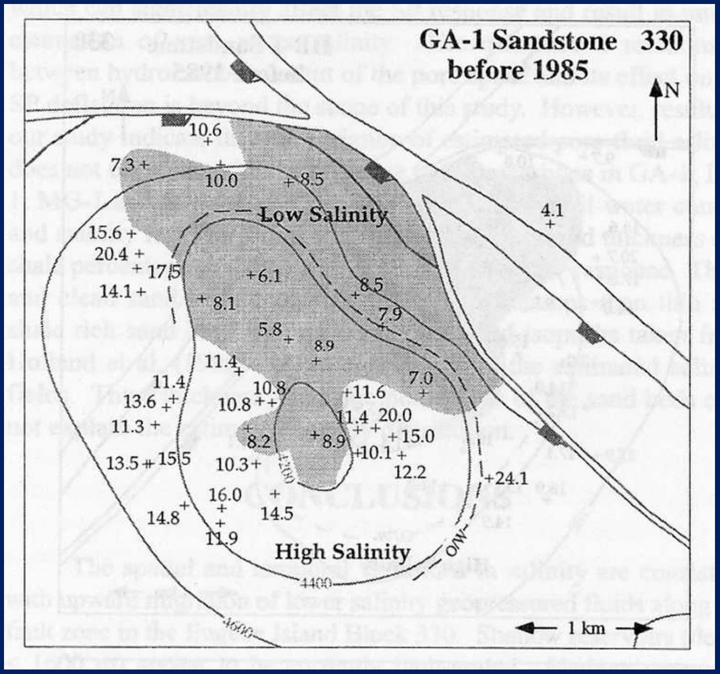
Fluids migrated at rates of mm/yr to as high as 100’s of m/yr

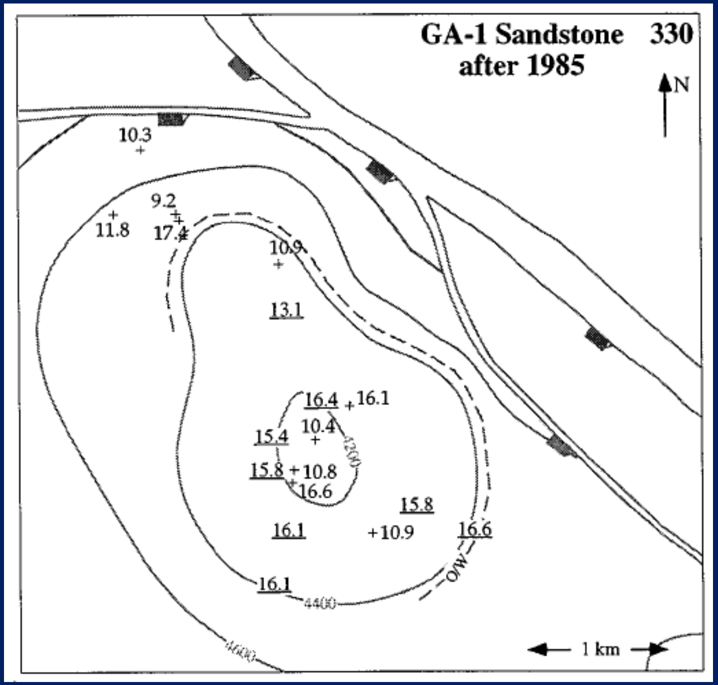
Alexander & Handschy (1998); Roberts et al. (1996)





Spatial and Temporal Variation in Pore Water Salinity around the Fault

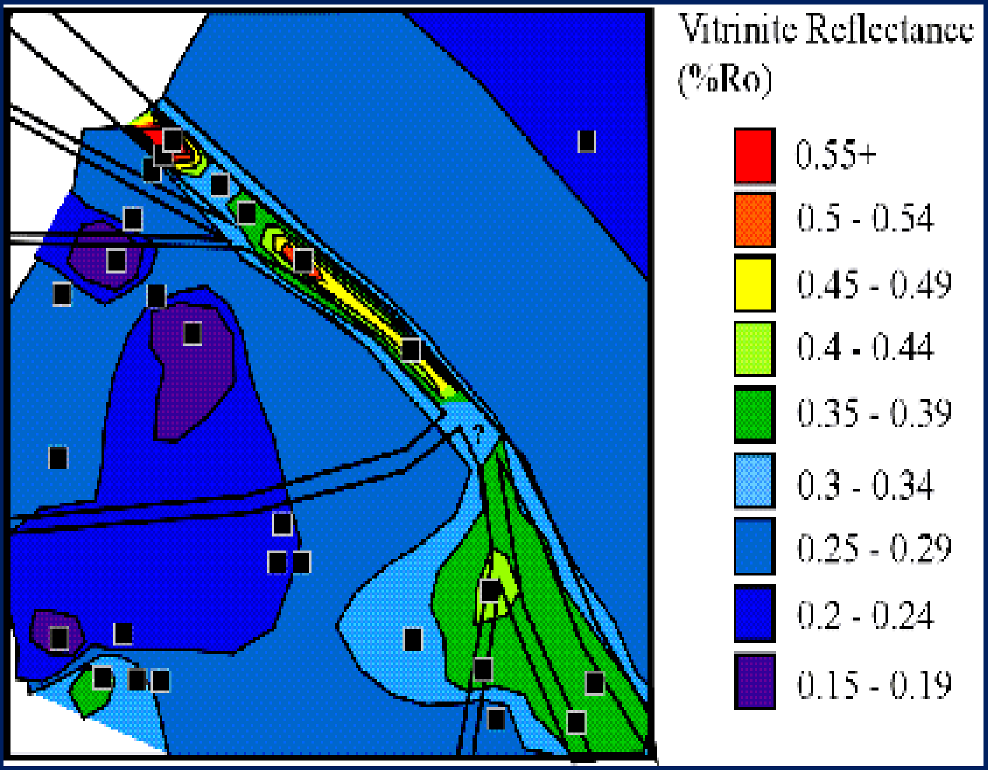




- Low salinity around the fault zone
- Salinity increases away from the fault
- Indicates fluid migration from deeper levels

Lin & Nunn (1997)

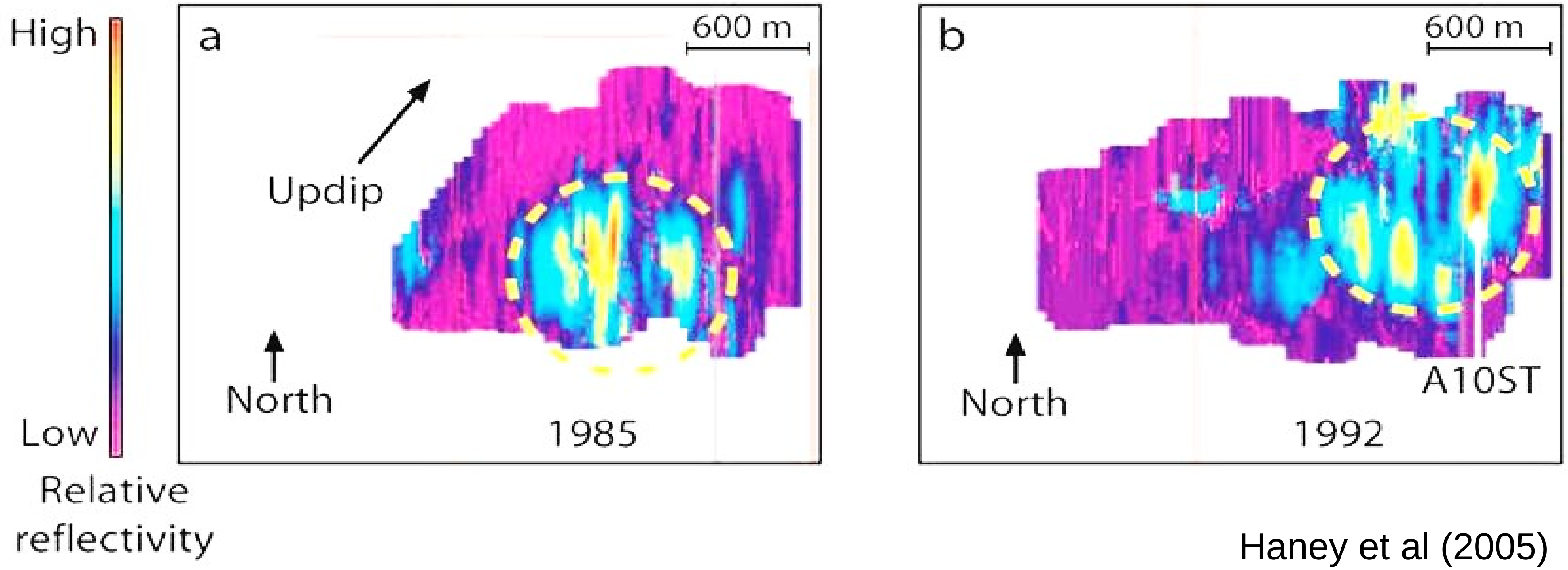
Organic Matter Maturity in the Fault Zone



Losh et al (1999)

- High organic matter maturity in the fault zone
- Paleothermal anomaly due to ascent of short lived (150 year-long) pulse of rapidly flowing fluid, up to km/year

Seismic Reflection Image along the Fault Zone



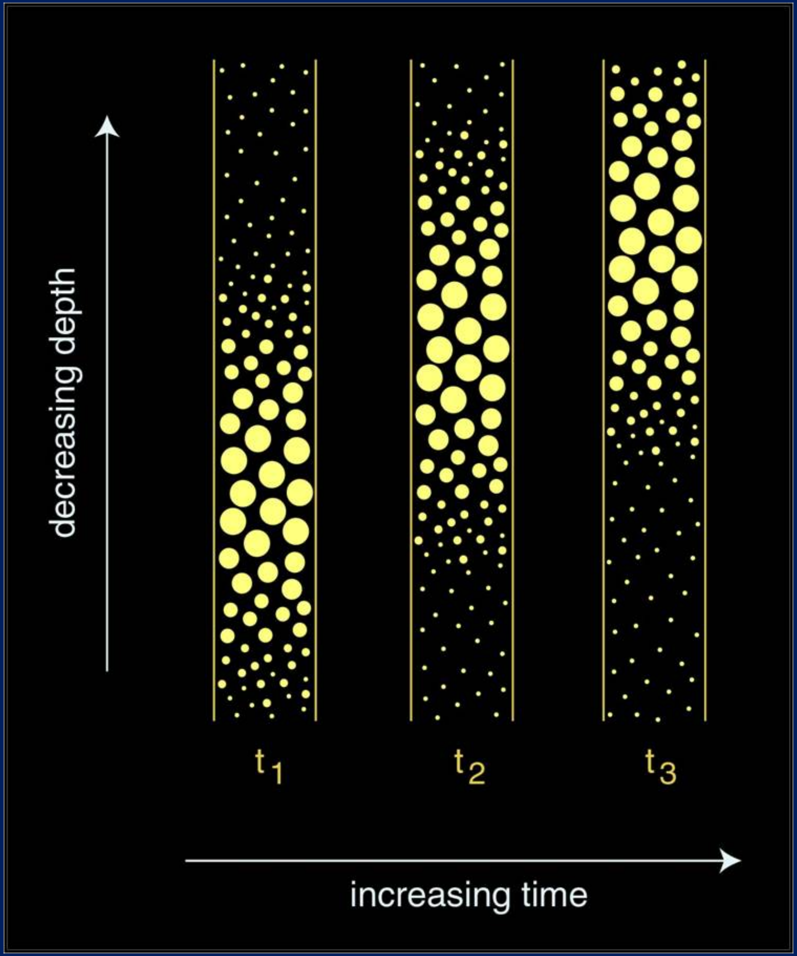
Haney et al (2005)

- High reflectivity zone interpreted as presence of high fluid pressure pulse
- Fluid pulse traveled at a velocity of 140m/yr

Solitary waves could be responsible for rapid fluid transport in low permeability sediments

- Manifest as pulses of elevated fluid pressure and porosity

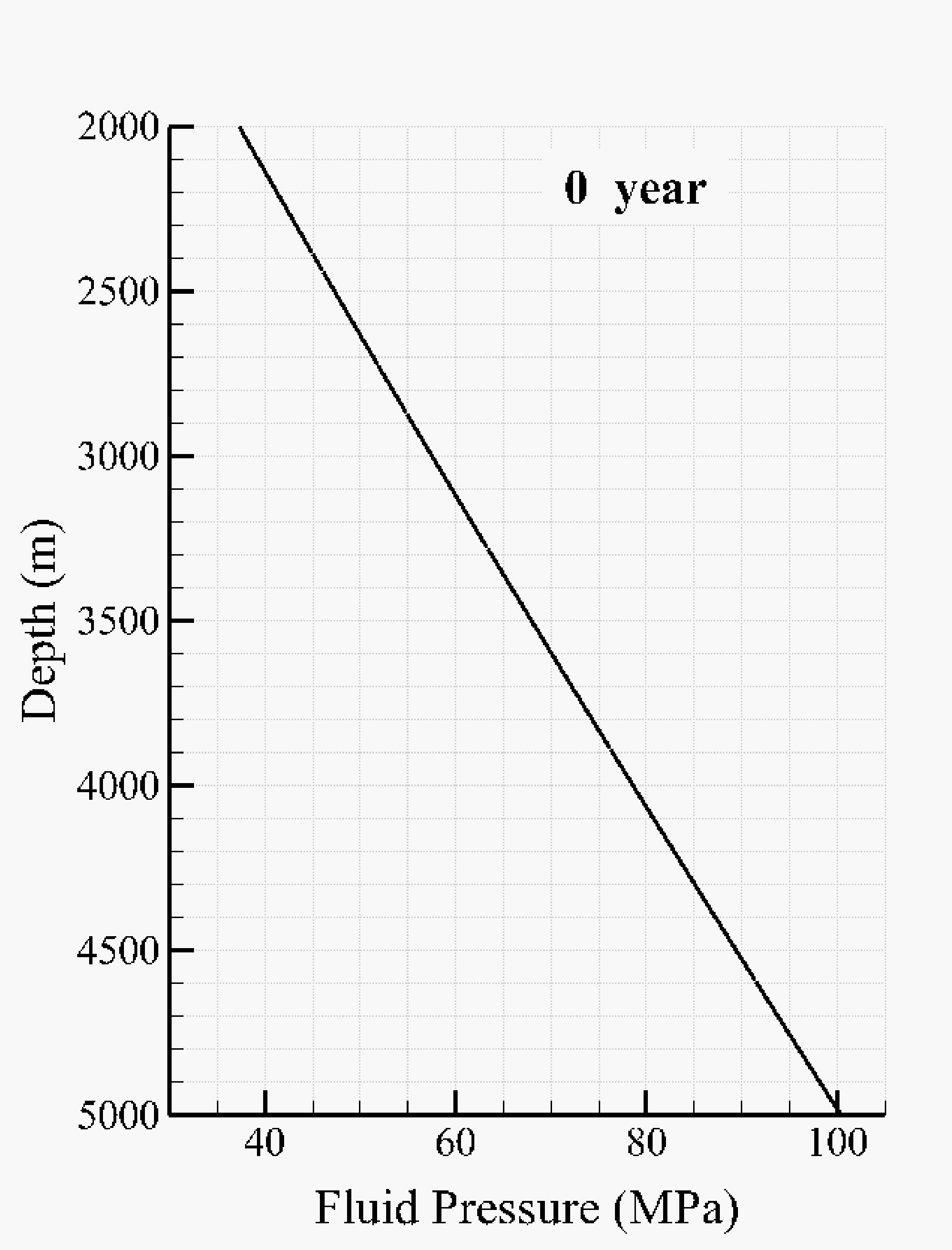
- Solitary waves could travel at faster, kilometer per year, velocity compared to the low background Darcy velocity



Rice (1992); Appold & Nunn (2002); Revil & Cathles (2002); Joshi et al. (2012)

Solitary Wave Characteristics

- Accelerates as it ascends but diminishes in amplitude
- Leaves behind a wake of elevated fluid pressure
- Forms when the rate of fluid pressure generation is high relative to the rate of fluid pressure diffusion



Joshi et al, 2012

For oil solitary waves to form and propagate,

$$\frac{P_g}{D} \geq 1.14 \times 10^8 \ {}^{Pa}/_{m^2}$$

(Joshi et al., 2012)

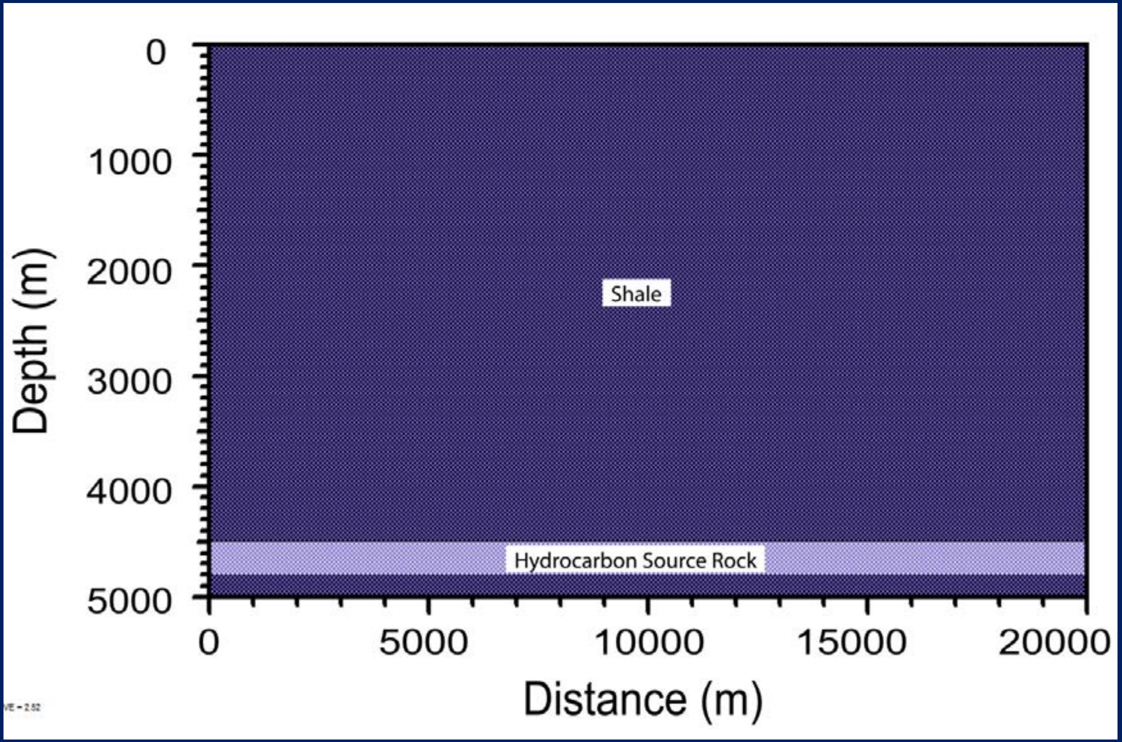
P_g = fluid pressure generation rate (10^{-6} Pa/s or 30 Pa/year)

D = hydraulic diffusivity for oil (m^2/s)

For methane solitary waves to form and propagate,

- If the above threshold ratio for oil is also valid for methane, then higher methane diffusivity requires a higher P_g of ~ 2000 Pa/year

Hypothesis: Fluid pressure generation rates high enough to form oil and methane solitary waves can be generated by sediment compaction & hydrocarbon formation under geologically realistic conditions

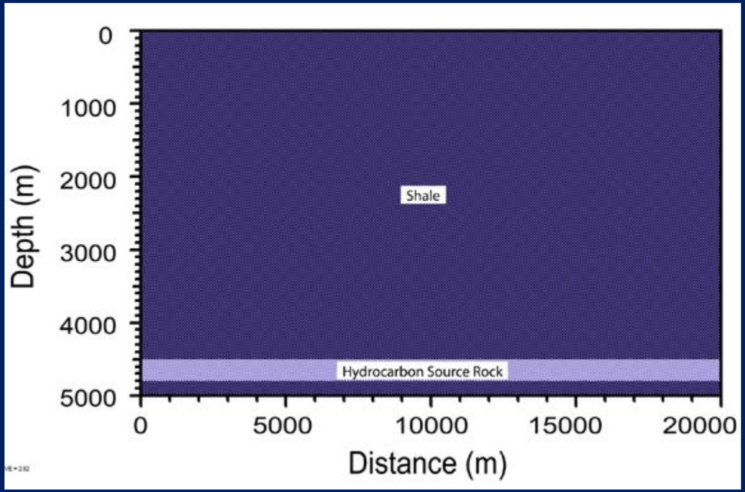


- 2D Modeling of Sediment Compaction and Fluid Pressure Evolution
- Used BasinMod 2-D^{TM} Software

What is the maximum possible pressure generation rate from sediment compaction & hydrocarbon formation in a sedimentary basin?

Three Scenarios Modeled

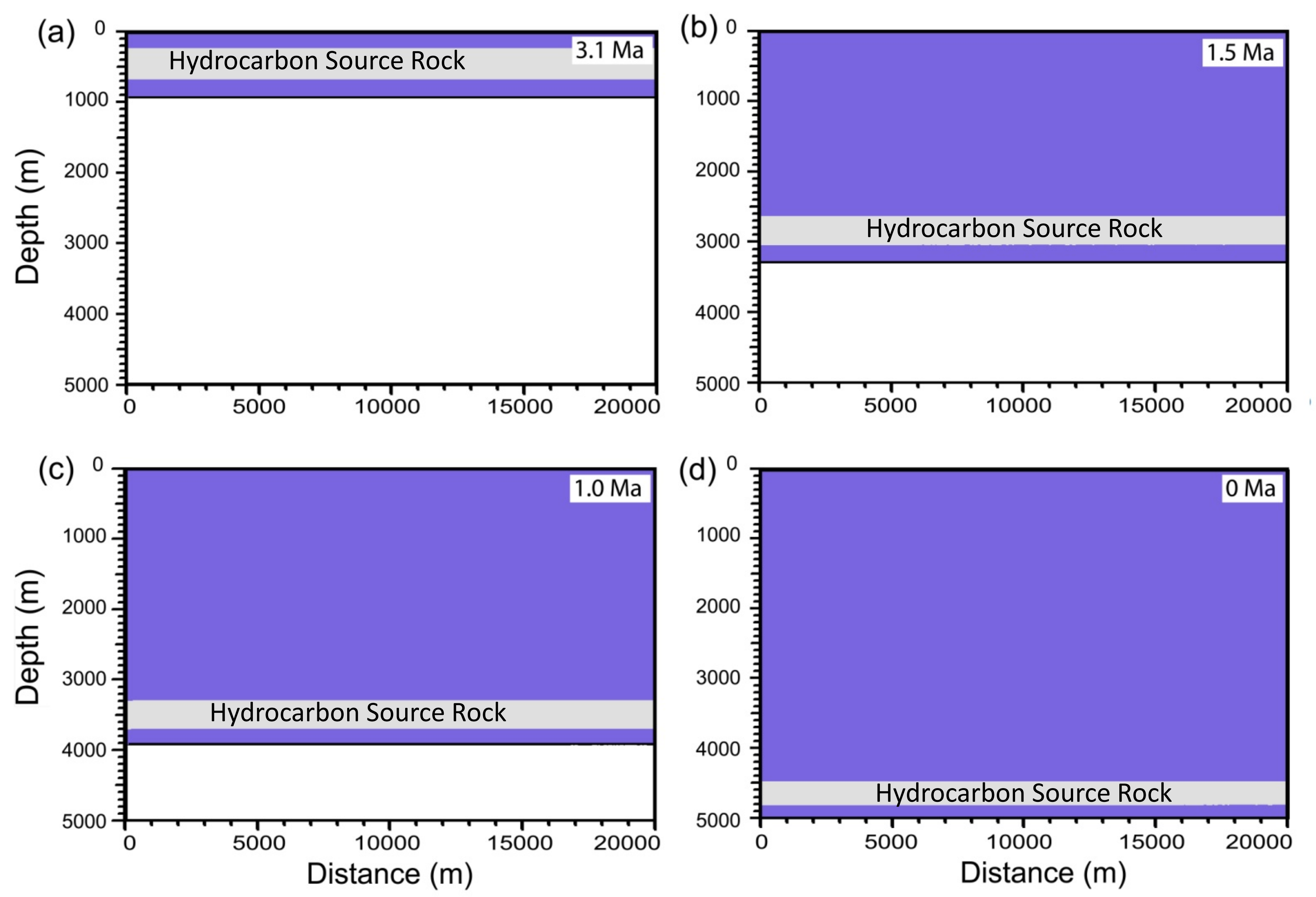
- Base Case Scenario
  - Basin properties resembling Eugene Island 330 basin
- High Pressure Generation Rate Scenario
  - Basin properties that maximize pressure generation
- Low Pressure Generation Rate Scenario
  - Basin properties that minimize pressure generation



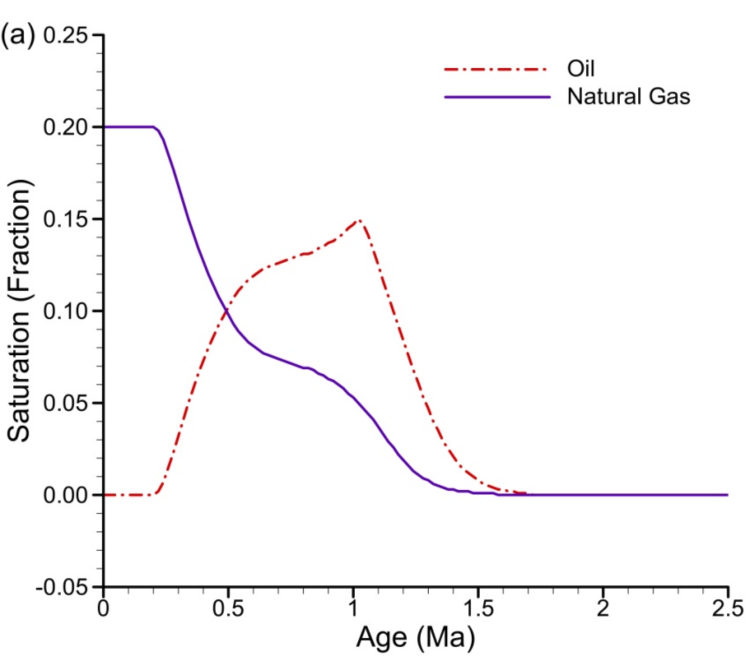
Model Parameter Values

Model Parameters	**Base Case**	**Low Pressure Generation Rate**	**High Pressure Generation Rate**
Sedimentation rate (mm·year^{-1})	1.39	0.139	13.9
Surface porosity (%)	0.4	0.5	0.2
Matrix thermal conductivity (W·m^{-1}·C^{-1})	1.82	3.64	0.91
Surface temperature (˚C)	5	5	10
Basement heat flow (mW·m^{-2})	60	50	120
Shale permeability (m^{2})	10^{-18}	10^{-17}	10^{-19}
Shale compressibility (Pa^{-1})	10^{-8}	10^{-9}	10^{-7}
% TOC	5	5	0.5
Kerogen type	Type II (Burnham ’89)	Type II (Burnham ‘89)	Type II (Espitalie ’88 Viking Graben)

Stratigraphic Evolution of the Basin



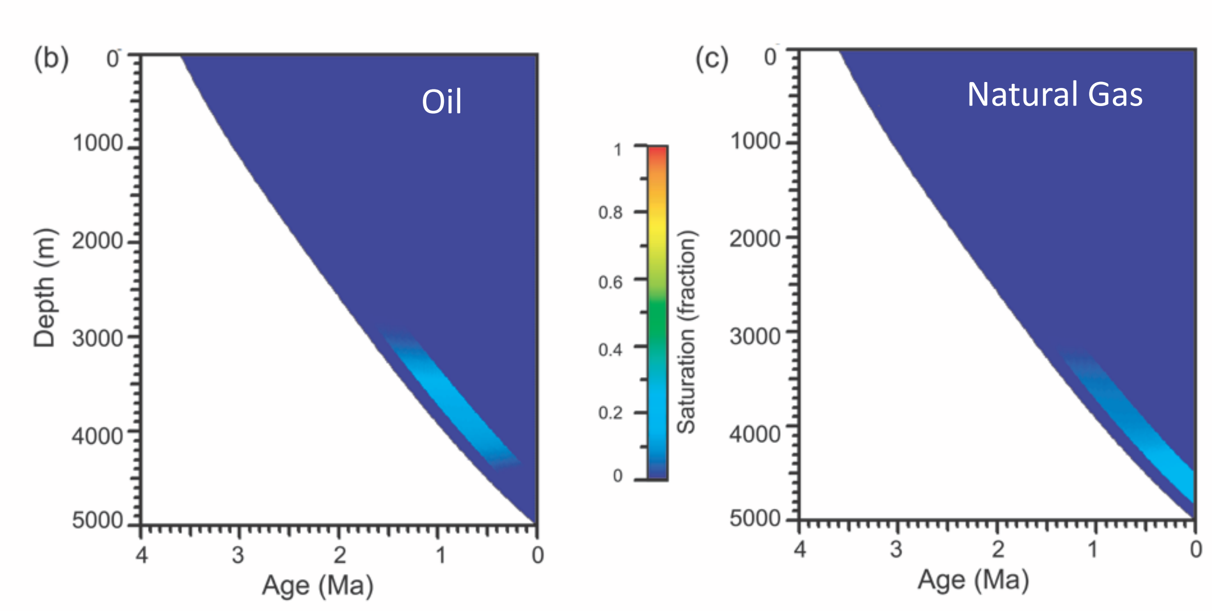
Hydrocarbon Generation



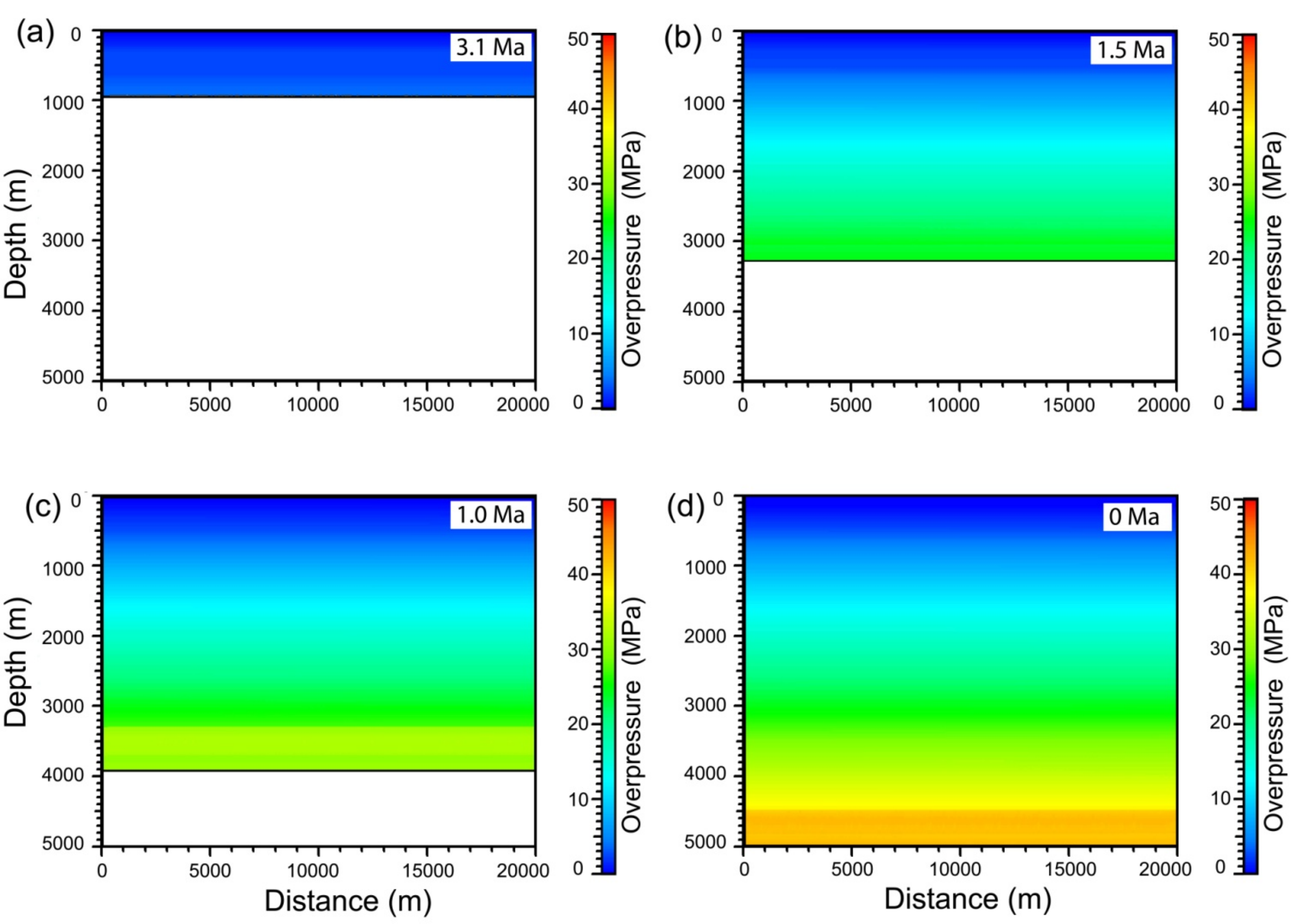
- Oil saturation peaks at 1.02 Ma and then declines

- Gas saturation increases to the present day

- Both oil and gas confined to the source rock

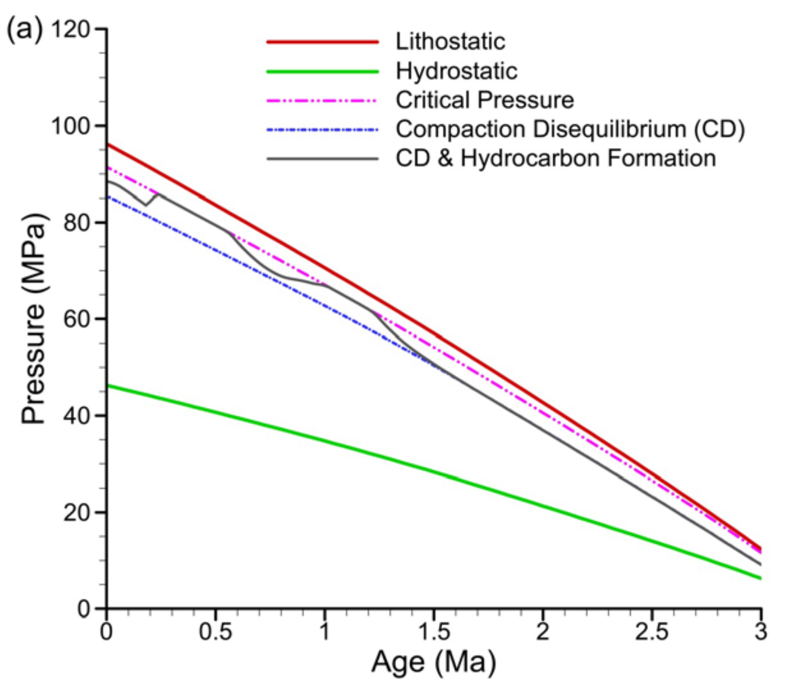


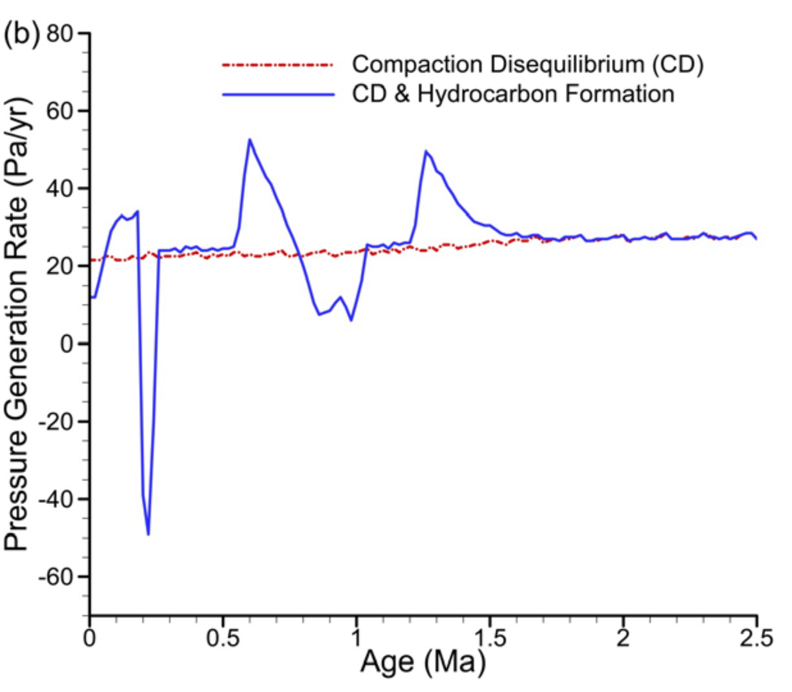
Overpressure Evolution in the Basin

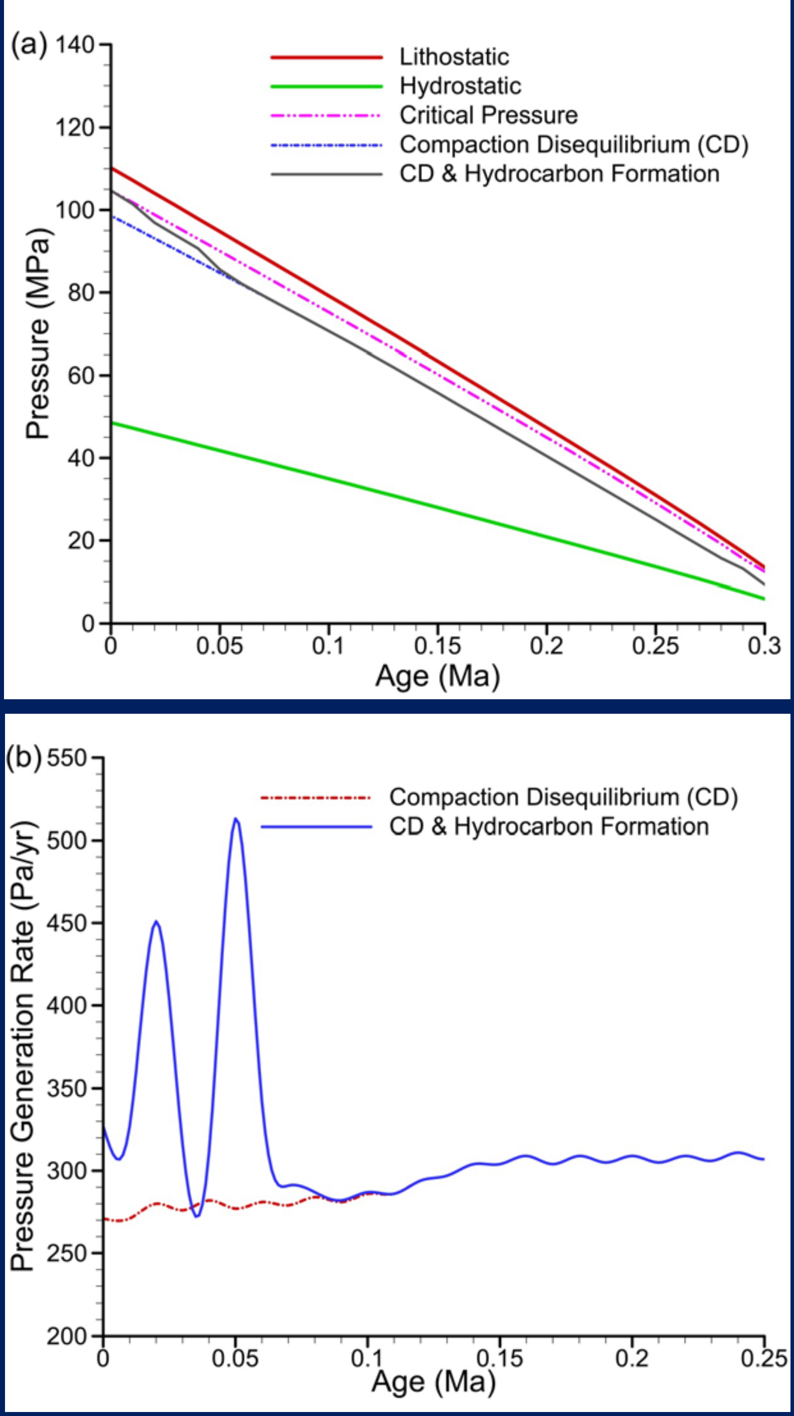


Pressure Generation Rate for Base Case

- Hydrocarbon formation contributed maximum overpressure of 5.6 MPa
- Compaction disequilibrium contributed 36.5 MPa
- Rates reach maximum value of 50 Pa/yr
- Three episodes of pressure rate increase



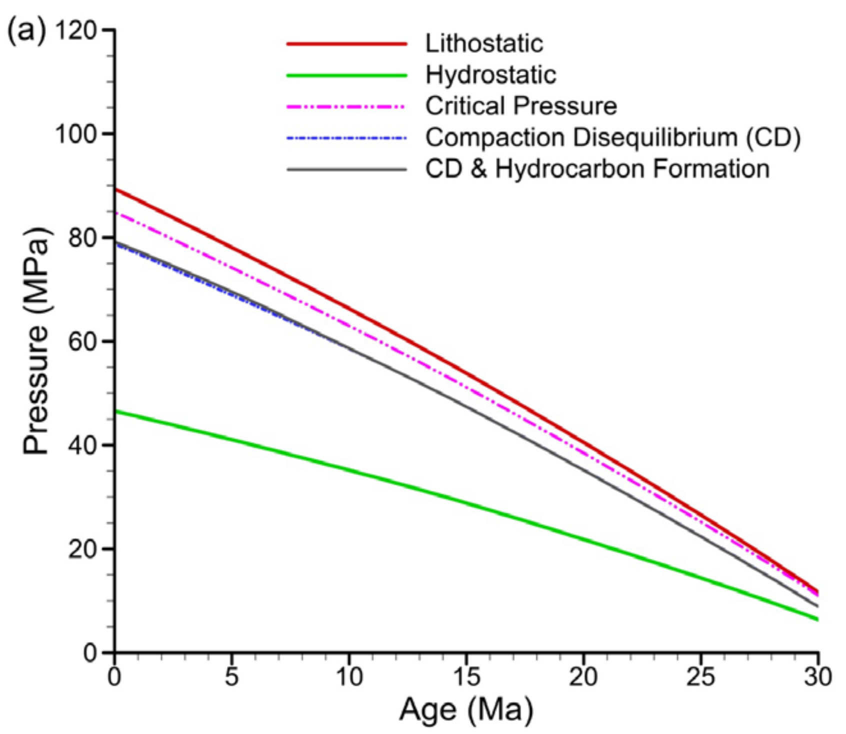


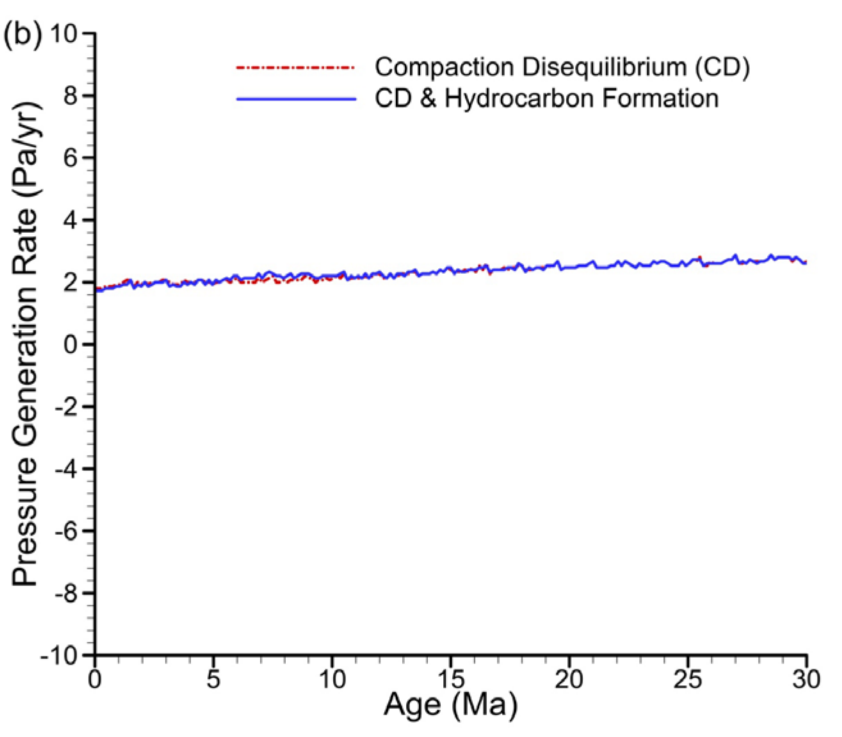


High Pressure Generation Rate Scenario

- ➢ Hydrocarbon formation contributed maximum overpressure of ~6.1 Mpa
- ➢ Two episodes of pressure rate increase
- ➢ Rates reach maximum value of 513 Pa/year

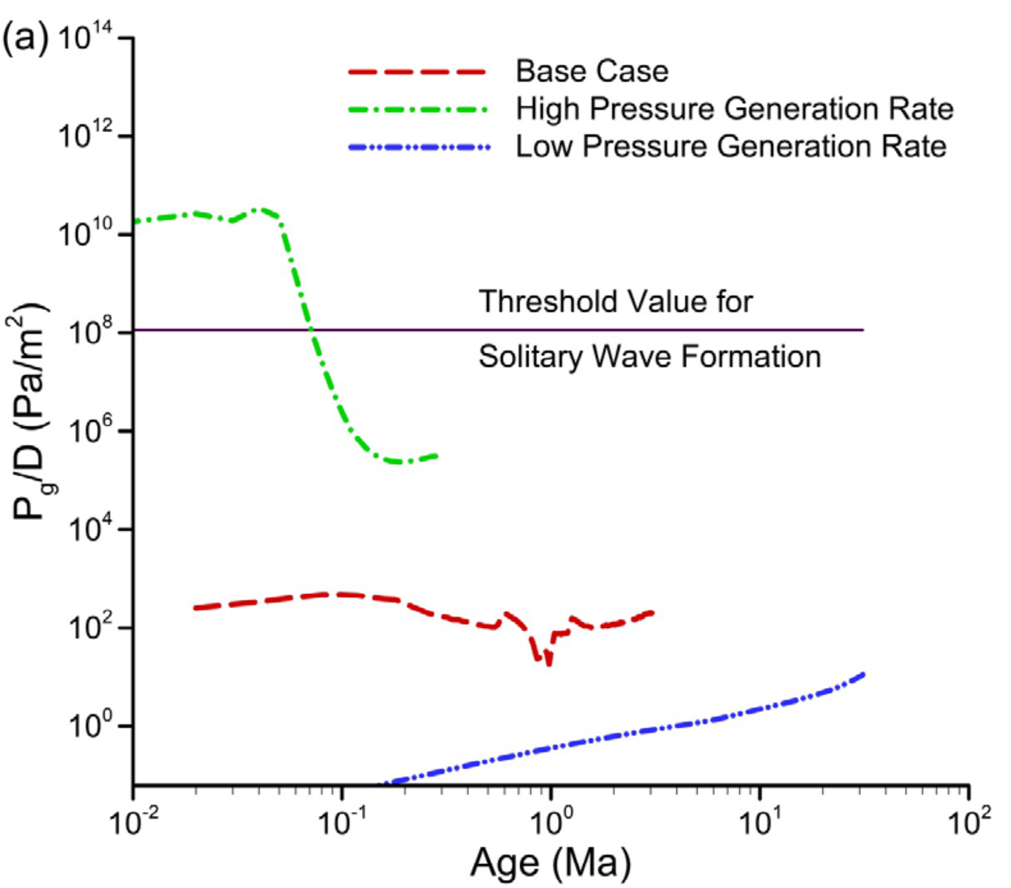
Low Pressure Generation Rate Scenario





- Negligible pressure generation from hydrocarbon formation

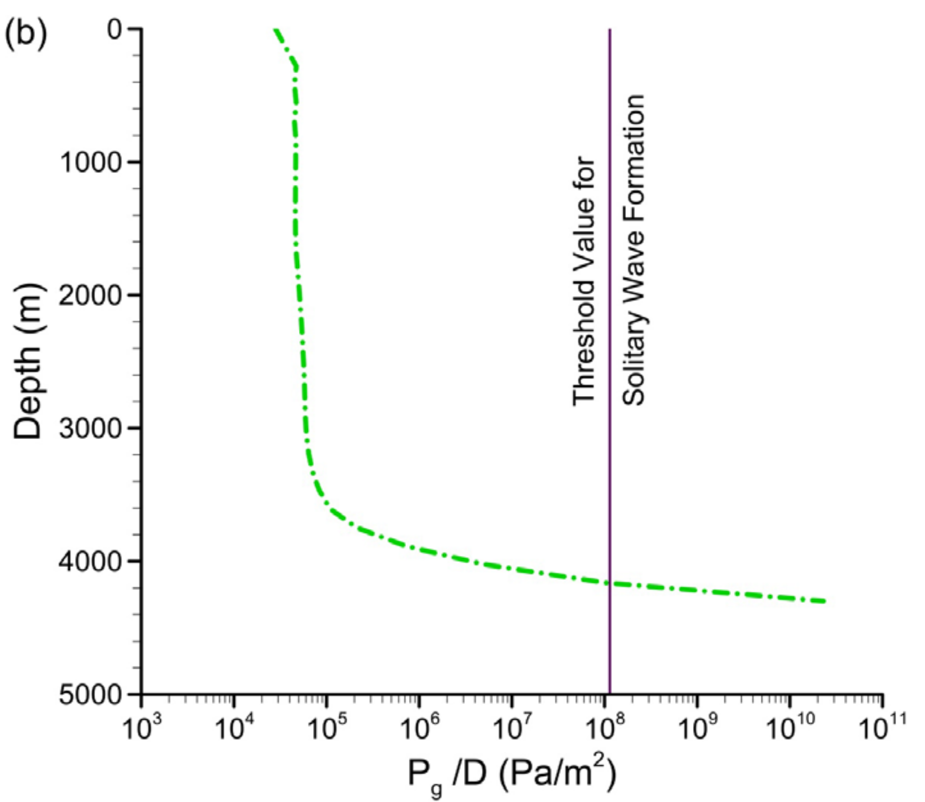
Temporal Variation of P_g / D Ratio



- Ratio for the high pressure generation rate scenario lies above the threshold value after 0.07 Ma
- Ratio for other two scenarios lies below the threshold value throughout the basin history
- Pressure generation rate at later times during hydrocarbon formation could produce solitary waves

Variation of P_g / D Ratio with Depth

- Solitary wave formation restricted to depths greater than 4.2 km



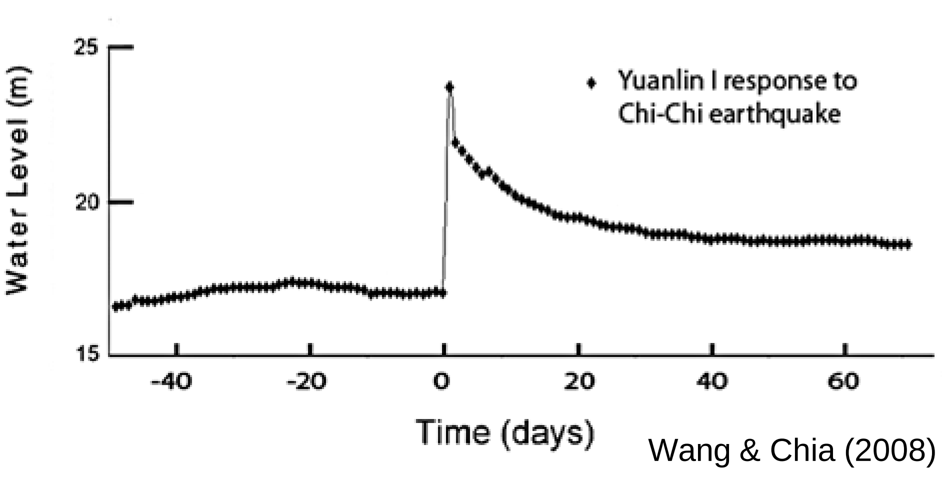
- At shallow depths, hydraulic diffusivity is too high for solitary wave formation

- Solitary waves could form at shallow depths if a more rapid pressure generating mechanism existed

Could methane solitary waves develop from fluid pressure buildup during sediment diagenesis in a sedimentary basin?

- Unlikely from sediment compaction and hydrocarbon formation
  - Required: Pg ~ 2000 Pa/year
  - 2D Basin modeling calculation: Pg ~2 to 513 Pa/year

- Could be possible from earthquakes that could cause instantaneous rise of pore fluid pressures



Wang & Chia (2008)

Conclusions

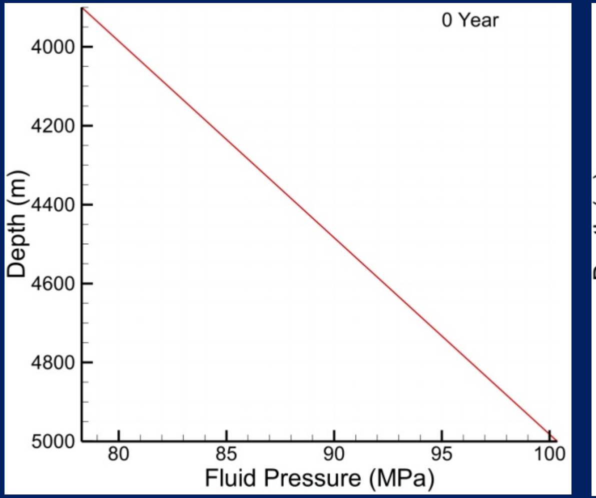
- Pressure generation rate from compaction disequilibrium and hydrocarbon formation in a sedimentary basin could vary from ~2 Pa/yr up to ~513 Pa/yr

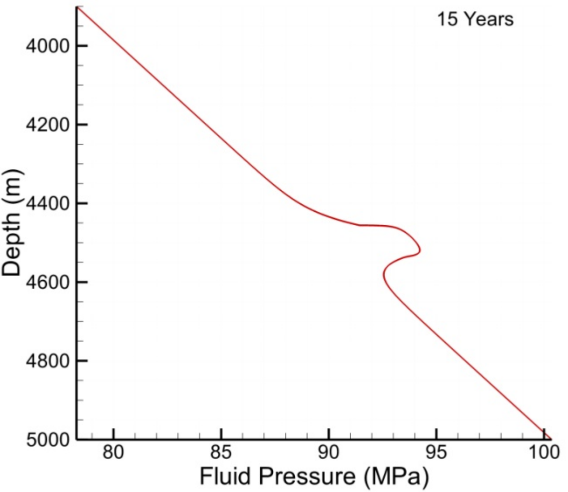
- Solitary waves could form and propagate at depths greater than 4.2 km as a result of pressure generated by compaction disequilibrium and hydrocarbon generation

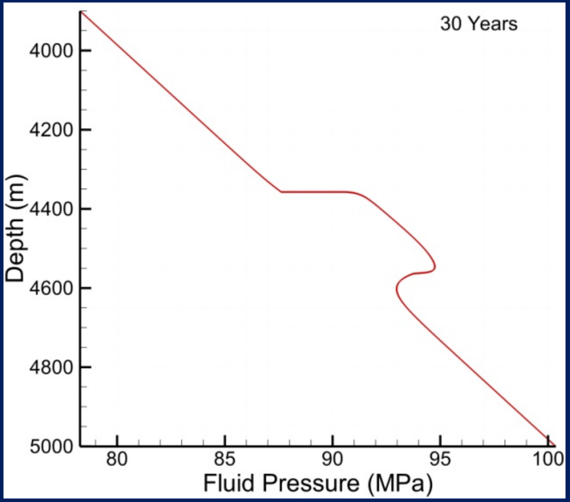
Conclusions cont'd

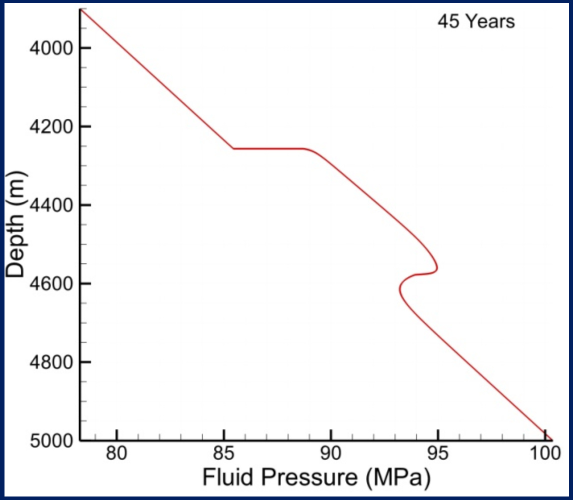
- Methane solitary waves could form in sedimentary basins if fluid pressure were generated at a rate more rapid than possible via compaction disequilibrium and hydrocarbon generation
- Earthquakes may also allow oil solitary waves to form at shallow depths in sedimentary basins

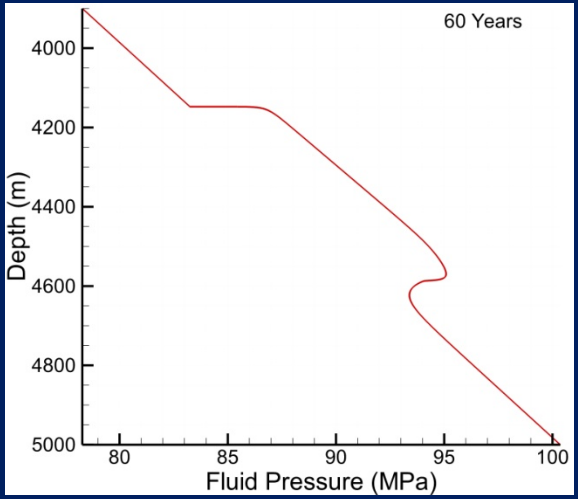
Current Research Work

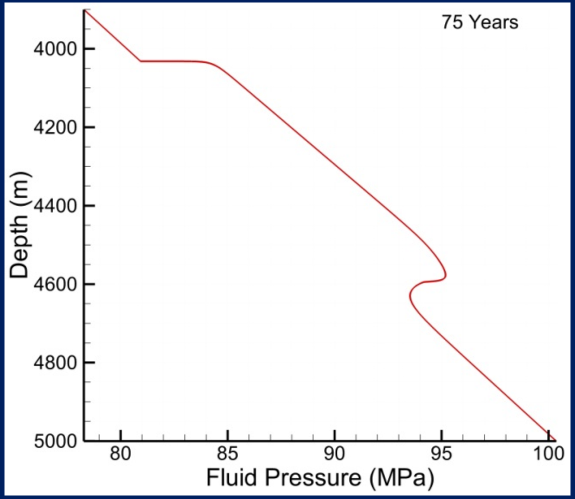








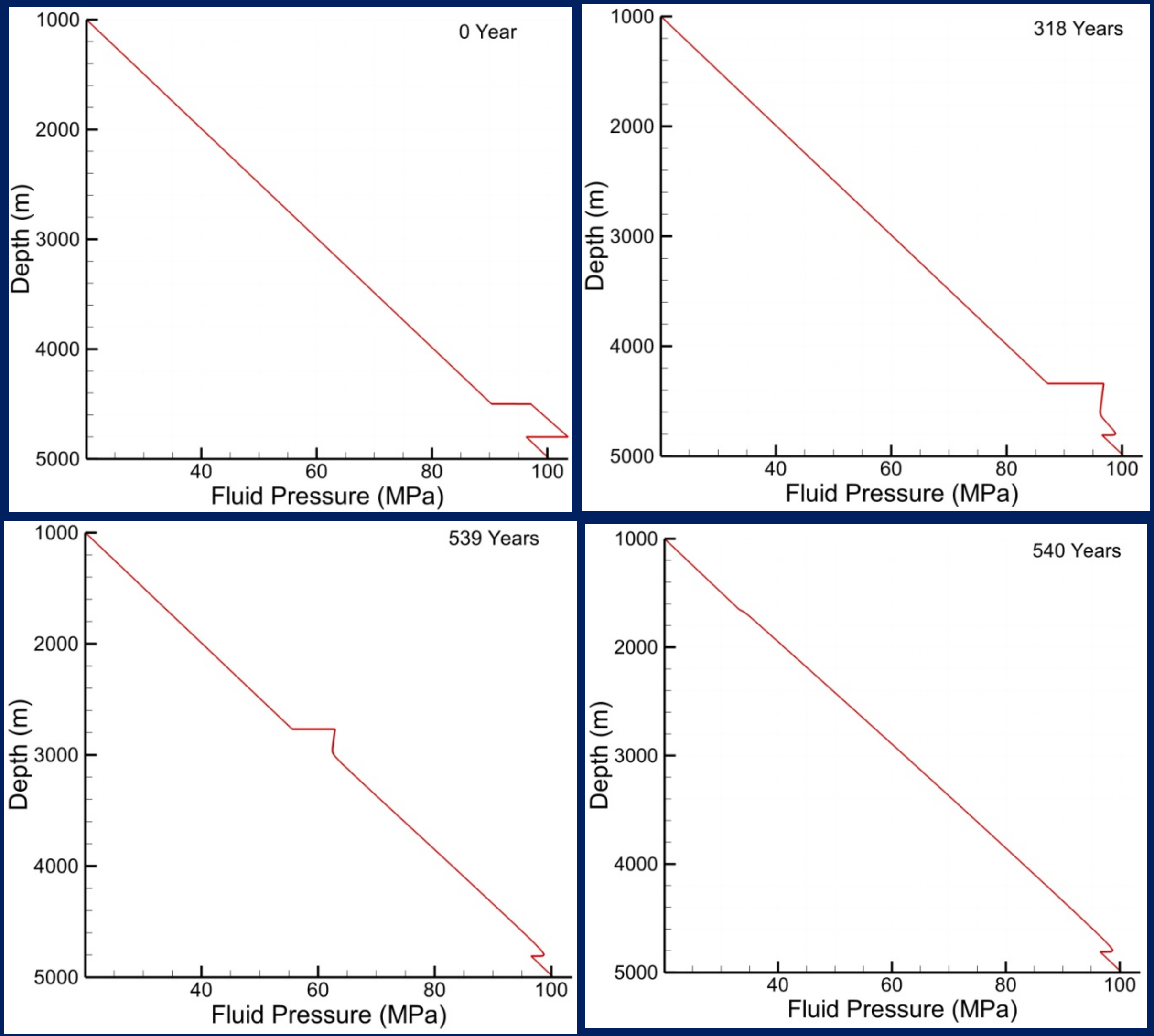




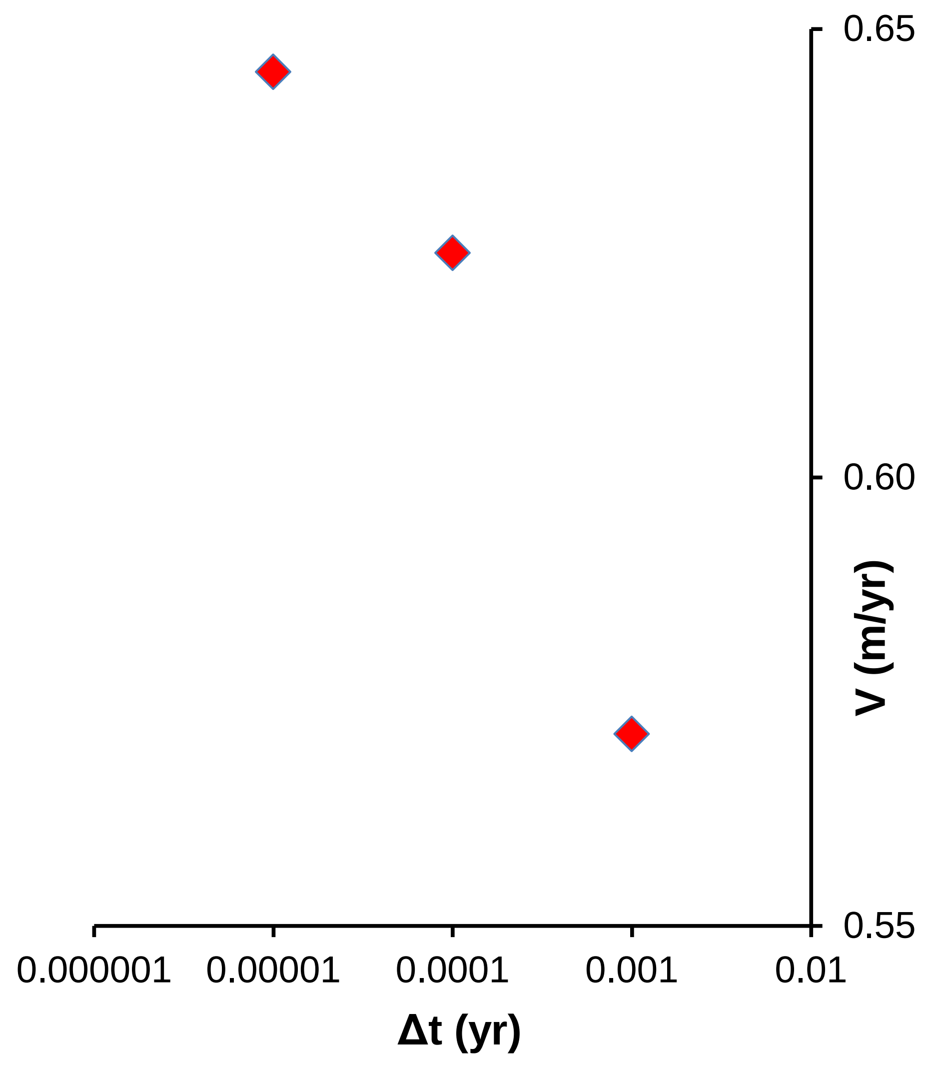
Solitary waves did not form at ~2000 Pa/year of pressure generation rate

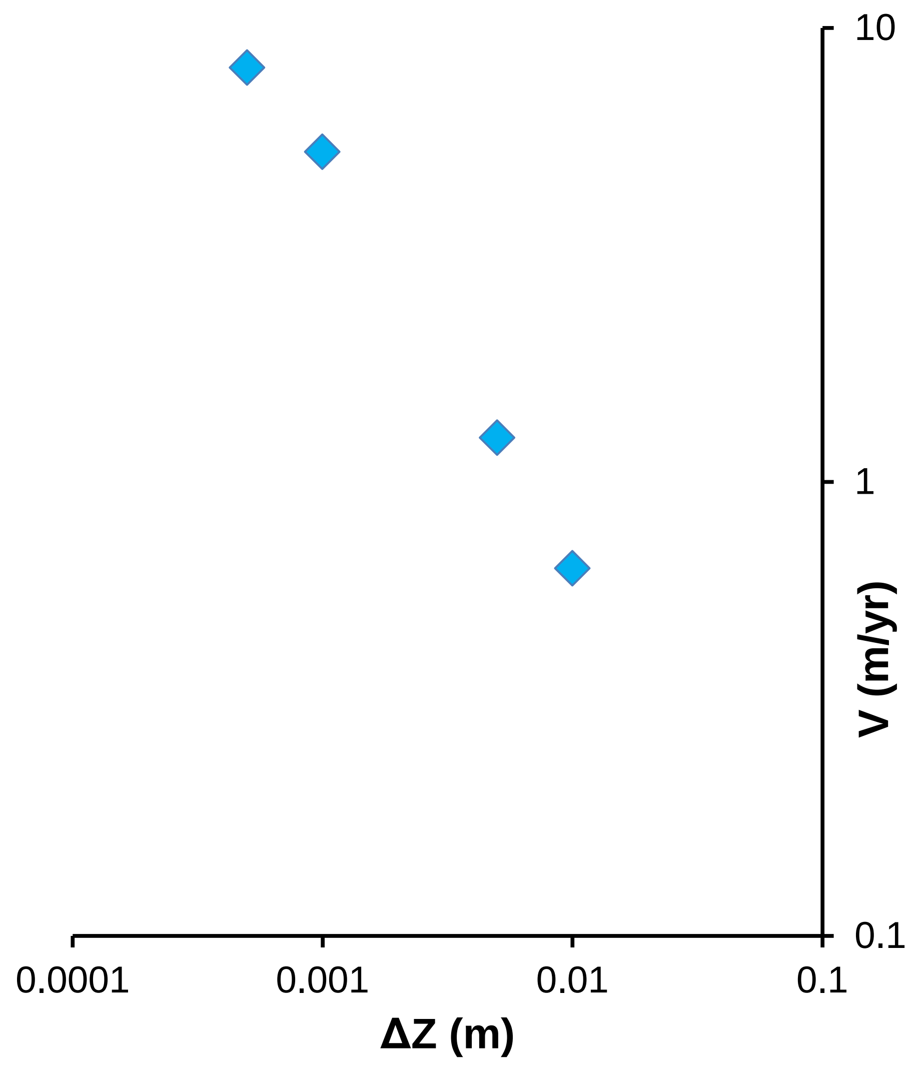
Methane Solitary Wave from Instantaneous Pressure Generation

- Instantaneous pressure generation source of 6.8 Mpa
- Solitary wave velocity of ~10’s of m/yr



Sensitivity of Solitary Wave Velocity





Thank You