Petroleum Geomechanics: Excursions Into Coupled Behavior

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ABSTRACT

Heavy oil will be a major future energy source as conventional oil production rates decline. Consideration of recent trends suggests that the next decade will see acceleration of heavy oil developments. The Canadian industry and governments should be consciously poised to take full advantage of these developments. In addition, because heavy oil development is geomechanically demanding, the role of petroleum geomechanics will be vital.

Are popular rock mechanics paradigms complete? No; they generally fail to consider proper coupling to the stress and pressure fields, to physicochemical factors (as in shales), and to dynamic effects. Coupling the mechanical behavior of the rock matrix with processes such as fluid flow, dynamic excitation, fabric liquefaction, and gas solution behavior is one of the most important innovations taking place in petroleum geomechanics research. Ongoing developments include new models to describe dynamic pressure pulsing effects, new models to describe Cold Heavy Oil Production (CHOP), and new models for shale stability that include mechano-chemical coupling. Valuable practical applications have paralleled these developments.

INTRODUCTION

Are current petroleum rock mechanics paradigms complete? Do existing models account for all first-order effects? Are there applications areas that have been ignored or missed? Why is geomechanics becoming a more important enabling discipline, particularly for heavy oil? Does heavy oil even have a future? This article will briefly explore some of these questions.

CONVENTIONAL OIL, HEAVY OIL

A consensus has emerged that worldwide production of conventional oil will peak in the next decade.[1] Thereafter, a gradual decline in light oil production will occur. The decline rate may be affected by new technologies such as gravity drainage and pressure pulsing. However, given the large amount of information on the world's sedimentary basins and the low probability of finding many large, easy-to-develop deposits, it is unlikely that the production decline will ever be reversed. In the past, there have always been new basins to explore; at present, there is at least seismic data on almost all of the world's sedimentary basins, if not exploratory wells and geochemical analysis. These data now allow reasonable bounds to be placed on the size distribution of undiscovered deposits in basins throughout the world. Simply put, we are running out conventional oil because we are running out of new basins. Furthermore, the difficulty of exploitation in difficult, remote basins (Antarctic fringe, Artic basins, deep offshore) means that only the larger finds will be developed.

Are we running out of energy or oil? No; only conventional oil is potentially in short supply. This is apparent for several reasons. First, over the span of centuries, new energy sources systematically displace previous ones (e.g. cow dung, wood, charcoal, coal, oil, nuclear, natural gas, solar, hydrogen cycle); this will happen with oil. Second, conventional oil represents only a small fraction of the hydrocarbon resources in basins (Table 1); technology developments and price will permit economic access to other HC resources. Third, if demand for oil continues indefinitely, oil can be made from natural gas or coal. The technology for coal and gas conversion already exists, even if it is not currently commercially viable. Fourth, oil can be fabricated from renewable sources such as plants; Japan in the last year of the Second World War produced an oil from trees (albeit of poor quality). Fifth, given a source of energy such as solar power, HC molecules can even be manufactured from the basic elements (H from electrolysis, C from CO_2 or plants).

HC Resource Type	Estimated % of total HC in sedimentary basins
Conventional light oil	2-3%
Heavy oil	4-6%
Natural gas	4-6%
Gas hydrates	2-8% (extremely uncertain)
Kerogen and oil in shales	40-60%
Coal and lignite seams	30-50%

Prophets of doom who claim that the world is irrevocably and greedily consuming irreplaceable resources ignore technical progress, market pressures, and the historical record.[2] Commodities have never been cheaper. Substitution may be effective; for example, oil replaced coal. Today, cell phones replace copper land lines, plastics supplant metals, and natural gas may substitute in part for oil. Technology continually improves; new large jets consume far less fuel, and large reductions in the amount of oil consumed per passenger kilometer in personal vehicles will take place if the price rises. Furthermore, recycling can even help generate HC molecules; deep biowaste injection may help generate CH_4 (trial projects in this direction are likely to start in the year 2000).

Projections of impending doom are predicated on static technology. For example, Ehrlich[3] predicted in the 1960's (and continued to predict into the 1990's) that famine would soon be rampant. However, the "green revolution" and the advent of genetically modified plants have invalidated this concern. The "Club of Rome", using assumptions based on exponential growth extrapolations with static technology, predicted massive commodity shortages before the year 2000.[4] Prices in fact have dropped and supply has met demand. Nevertheless, many continue to make such predictions, although their time frame has been extended and their predictions are laced with caveats. Given that technology is not static, given a market-driven commodity economy, and given proper environmental concern, these pessimistic predictions are simply incorrect.

It is obvious that there is a limit to the amount of conventional (light) oil in sedimentary basins. This is relevant to the oil industry in the short term (10-30 years) but is inconsequential to the energy industry in the long term (50-200 years).

What are the ramifications for heavy oil? As peak light oil production is approached, economic pressure will increase to develop other sources, and the next most economic and technologically feasible source of oil is heavy oil. In the short term (1-5 years), price spikes will always happen as local disparities between supply and demand occur. However, in the long term (>5 years) prices can rise only to the limit where another technology can be economically developed to replace the higher-priced one. If the price of conventional oil stays above ~$USD20.00, it is almost certain that massive heavy oil development will occur in Venezuela and Canada. Heavy oil is profitable at this price; therefore, higher prices cannot be sustained indefinitely. Technology will be refined and other sources of oil will be developed, placing downward pressure on temporarily elevated prices.

Let us put Canadian heavy oil resources into an understandable form. Given the resource size ($\sim 350\times10^9\ m^3$) and assuming a stable US and Canadian consumption rate of $10^9\ m^3/yr$, there is enough heavy oil in Canada to meet 100% of this demand for~100 years if the overall extraction efficiency is ~25%. Oil sand mining recovery efficiency is far higher than this figure; in situ thermal and non-thermal recovery efficiency is somewhat lower (10-25%). Even with existing technology, it appears that extraction efficiency on the order of 25% will be normal in the near future.

However, in the more distant future, new energy technology will replace heavy oil. Canada will change from an oil-based energy economy as the rest of the world moves on to the next replacement. This has happened everywhere in the world; new technology inevitably displaces old technology. For these reasons, it seems wisest to adopt a royalty and taxation regime to promote heavy oil development. If we delay for whatever reasons, we will simply be left with the resource in the ground as the world moves to new energy sources.

The near future perhaps looks something like Figure 2: increasing heavy oil production is inevitable for decades to come. The economic implications for Canada are substantial; and, at >$USD20.00/bbl, profitable heavy oil production in Canada is limited only by upgrading capacity.

There is no realistic limit to heavy oil production, given the developments in the last few decades (cyclic steam for some reservoirs, SAGD for others, cheap horizontal wells, CHOP[i], cheaper mining methods), the new technologies now being developed (pressure pulsing, VAPEX, hybrid schemes), and the technical progress that will continue.

Why is this of great interest to Petroleum Geomechanics? Heavy oil development is far more geomechanically demanding than conventional oil development. Formation and casing shear, dilation, cement integrity in thermal projects, deep mine wall stability, waste disposal, sanding, dynamic excitation, and many other geomechanical issues are more important than in conventional oil exploitation.

GEOMECHANICS: COULOMB, TERZAGHI, BIOT

The first fundamental statement in geomechanics was Coulomb's observation that strength is proportional to force (stress). In other words, shear strength for a geomaterial is related to confining stress, σ_3'. Terzaghi proposed his famous partitioning relationship, $\sigma = \sigma' + p$, and also said that $\Delta\sigma = \Delta\sigma' + \Delta p$. These laws are fundamental and form the basis of geomechanics. Terzaghi assumed that in most cases mineral compressibility ($\sim 2\times10^{-9}\ kPa^{-1}$) is far less than water compressibility ($\sim 450\times10^{-9}\ kPa^{-1}$), and skeleton compressibility in soils ($>10\times10^{-6}\ kPa^{-1}$) is far greater than water compressibility, so he made a reasonable simplification: if boundary loads and temperature are constant, $\Delta p = \Delta\sigma'$. This allowed development of the first coupled flow-stress solutions, known as consolidation theory. This assumption also forms the basis of all analytical flow equations in petroleum engineering, starting with the Theis solution. His solutions

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[i] CHOP: **C**old **H**eavy **O**il **P**roduction with sand influx

were extended by Muskat, and further developed by Gringarten, Entov, and many others. (See Barenblatt et al.[5] for a theoretical basis and pertinent references for this section.)

Biot (ibid.) recognized that matrix and mineral compressibility could be important, and extended quasi-static stress-flow coupled theory to include these effects. Note that Terzaghi fully understood the implications of his simplification, but restrictive assumptions were necessary at the time to develop tractable mathematical solutions. Solutions based on static Biot theory are now *de rigeur* in most petroleum geomechanics because the high confining stress at depth and the low porosities make rock skeleton compressibility of the same order of magnitude ($100\text{-}1000\times10^{-9}$ kPa^{-1}) as water or oil ($\sim1500\times10^{-9}$ kPa^{-1}). The new generation of flow-coupled geomechanics simulators will be able to handle many problems, including the vital component of overburden and underburden deformations that arise from production, thermal processes, solids injection and even sand production.

A major current challenge is to develop physically rigorous CHOP models that include the following aspects: foamy oil flow (bubble phase), sand liquefaction, full stress interaction, flow of a sand-oil-gas bubble slurry toward the wellbore, and non-equilibrium solution gas behavior.[6,7] Figure 3 is an attempt to sketch the major process physics aspects.

However, coupled flow-stress analysis, even for CHOP, remains based on Darcy theory ($q \propto \partial p/\partial \ell$). This is a quasi-static construct; there are no inertial terms in the formulations, despite titles implying the contrary.[8] Recent extensions to fluid flow that include thermodynamically rigorous inertial effects have provided new insights that may prove vital to petroleum production.

DYNAMIC COUPLING IN PORO-MECHANICS

For wave propagation in porous media, the theoretical framework developed by Biot[9] (modified by Gassmann) has been the basic paradigm for three decades. Biot wave theory was based on assumptions that seemed sufficient for many years, but have recently been proven incomplete.[10,11] This research by Spanos and his co-workers[12] at the University of Alberta has formed a theoretical basis for new discoveries in flow through porous media.

In Biot theory, it was assumed that the energy state could be represented by a single-valued functional for a representative elementary volume (REV). This is not correct: for N continuous contiguous interpenetrating phases, N functionals are required. A simple proof is the existence of two-phase countercurrent flow in the same REV (non-coaxial flow of three phases can also be demonstrated). A separate pressure gradient must exist for each phase, but a single valued energy functional can only have one gradient. In fact, to achieve analysis capability, given this problem, petroleum engineers have devised the concept of relative permeability and actually solve separate flow equations for each phase, coupled through mass conservation and equilibrium compositional assumptions.

Another basic limitation is the failure to recognize that porosity is a thermodynamic state variable, not a static constant. If porosity is not included as a state variable, it is not possible to couple diffusion and dynamic processes together in a thermodynamically rigorous manner.

The new theory[9,10,11] corrects these limitations; the general equations developed honor all basic physical conservation laws (continuity, conservation of mass, energy, momentum transfer), kinetic laws (equations of motion for solids and fluids), and thermodynamic laws (equations of heat for solids and fluids).

Biot theory predictions, once calibrated, are assumed to give adequate results for dynamic frequency ranges where liquids behave compressibly, >10 Hz for typical cases. The wave equations contain second-order time differentials, $\partial^2 p/\partial t^2$, giving rise to inertial terms. Darcy theory gives adequate results for low frequencies (e.g. below 10^{-4} Hz) where the liquids behave incompressibly, and the differential term $\partial p/\partial t$ arises in typical solutions to transient (but still quasi-static) flow. In intermediate cases, around the frequency range where the liquid begins to behave compressibly, it is apparent that a differential equation combining first and second order time differential terms is necessary; both give rise to first-order components of fluid motion (Fig. 4). The full formulation contains the appropriate differential terms, and is developed in the quoted references.[9,10]

Common strain waves are the compressional, shear and Stoneley waves, and if interfaces are involved, Love and Rayleigh waves. The new theory predicts the existence of a slow wave of porosity dilation[11] that cannot be derived from Biot-Gassmann formalism. A physical explanation is warranted.

Imagine that, with a rapid rise time, the liquid pressure can be locally increased in a solidly connected porous medium (i.e. a medium with static rigidity). This causes a pore dilation that is transmitted to the connected solids, propagating a wave of dilation that travels through the medium. This is a spreading wave that attenuates strongly if there is free gas in the pores (gas cannot behave incompressibly at the relevant frequencies). It propagates at ~10 m/s in a high-porosity (33%), low-stress (1 MPa) laboratory cell[13], but in more consolidated media at depth, the velocity is ~75-150 m/s, on the order of 1/40th the velocity of the compressional wave. If there is no interconnected liquid-filled porosity, the wave attenuates immediately, as in the case of gas in the pores, or is converted to other waves, as in the case of non-connected porosity.

The porosity dilation wave can be compared to a tsunami in the open ocean. A tsunami is a displacement wave that travels about 1/40th the velocity of the compressional strain wave in water. The porosity dilation wave is a liquid displacement wave that travels through media with an interconnected, liquid-filled pore space. The most efficient manner of generation is a sharp pressure impulse on the fluid.

IMPLICATIONS OF DYNAMIC COUPLING

Three years of laboratory tests and one year of full-scale field trials in heavy oil reservoirs have shown many potentially beneficial effects from the strong fluid-solid coupling that arises through pressure pulsing.[ii] The pulsing must be done in the right frequency range and at the right amplitude to maximize the effects in each case. The major findings are listed here in point form without extensive discussion; some articles have been written (see references), others will be published.

The beneficial effects of pressure pulsing, based on over 160 laboratory tests, are clear: [13,14,15]

- Dynamic excitation of a porous medium experiencing liquid flow increases the flow rate as much as several hundred percent when using optimal excitation (no pumping or changes in external pressure head are involved). Figure 5 shows the general type of results obtained.
- Flow rate increases occur in single or multiphase flow, in fine- and coarse-grained systems (20-2000 µm), over all tested viscosity ranges (e.g. oil from 35 to 10,600 cP), with different liquids (oil, water, glycerin), and with different conditions of wettability and phase saturation.
- Viscous fingering is substantially suppressed; the length of fingers is reduced and displacement is more stable. Figure 6 schematically shows results in two-phase flow with a low viscosity liquid displacing heavy oil.
- Channeling in permeable zones is reduced, retarding low-viscosity phase breakthrough (e.g. waterflood).
- Residual oil can be partially mobilized if excitation is executed following a particular sequence.

One clear negative aspect is that the presence of free gas suppresses the phenomenon of enhanced flow because of rapid porosity dilation wave attenuation.

Field trials in heavy oil were carried out by generating waves of porosity dilation using continuous high amplitude excitation in a well surrounded by offset producers. These trials have provided large-scale confirmation of several phenomena:

- As the process propagates outward (spreading is rate-controlled by viscosity), offset producing wells show substantial rate enhancement.[13]
- Used in workover mode, pressure pulsing removes mechanical skin, and in the case of CHOP wells, usually leads to large gains in production rate.
- Reduced water cuts suggest that water channels can be at least partially collapsed or healed by pressure pulsing.

[ii] Dynamic flow enhancement through pressure pulsing is the subject of a number of patents and patents pending.

- Preliminary trials suggest that workover chemical placement while pressure pulsing will give much better dispersion (less fingering and channeling).
- In both full-field excitation and CHOP well workovers, pressure pulsing helps re-establish gravitational drive and helps link the well to undepleted zones.[16,17]
- Recent results (Oct 99) have confirmed that waterfloods in high viscosity oils (10,000 cP) can be executed with success through pressure pulsing.

CLOSURE

It seems that the future of heavy oil (and therefore petroleum geomechanics) on the 10- to 15-year scale is exceptionally promising because of the impending peak in conventional light oil production. The economic opportunities presented to Canada are large, and are based on technology innovations and discoveries made in Canadian industry and research establishments.

Several new technologies developed in Canada are beginning to have a major impact on oil production. In addition to developments such as long horizontal wells and SAGD, there are several that are intimately linked to the static and dynamic geomechanical behavior of the reservoir. These include CHOP[18] and dynamic flow enhancement by pressure pulsing.

Spin-off ideas are developing. For example, the discovery that it is possible to produce large amounts of sand in heavy oil wells has led to trials of limited sanding in offshore high-rate oil wells and even gas wells.[19] These trials (over 200 wells by 1999) show increased production, reduced completion costs, and reduced workover costs.

Apparently, the area of coupled stress-flow (geomechanics) is extremely fertile for generation of new approaches in petroleum production. Another example of a new idea based on geomechanics is the cavity completion method for coal bed methane,[20] a concept based fundamentally on coupled stress-flow principles.

Quasi-static analysis of porous media flow requires incorporation of correct geomechanics coupling, including overburden stress redistribution effects. In cases of massive sand mobilization in heavy oils, this requires addressing slurry flow, sand liquefaction, and the non-equilibrium thermodynamics of solution gas behavior (foamy flow). Dynamic coupling is based on a more complete theory that has been recently developed; initial field applications that have resulted from this theory are very encouraging. This new dynamic coupling paradigm in geomechanics and fluid flow has the potential to change oil exploitation strategy, including primary and enhanced recovery methods.

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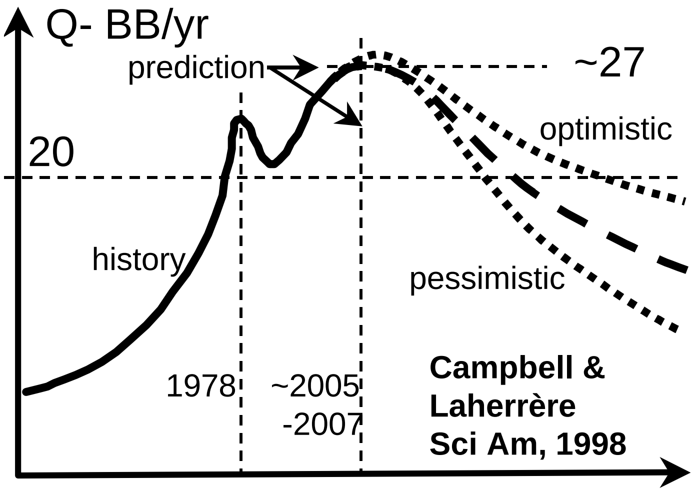


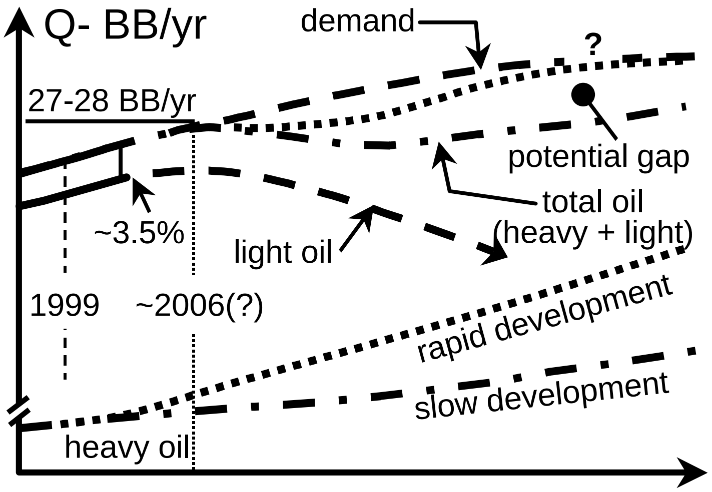
Optimistic Q:
New basins prolific
Better light oil recovery

Pessimistic Q:
Basins difficult, less oil
Recovery tech. static

Options:

- ➔Oil from heavy oil
- ➔Consumption ↓ ($)
- ➔Oil from natural gas
- ➔Oil from coal
- ➔Oil from shales
- ➔Substitutions

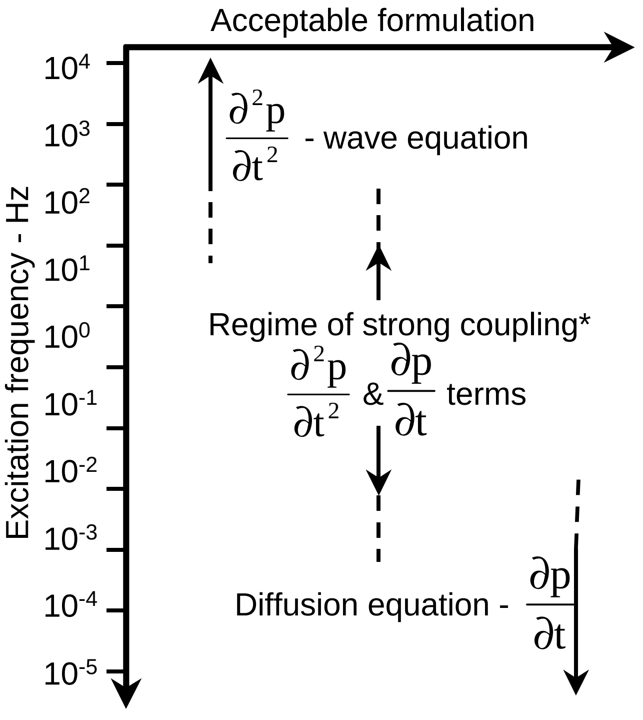
Figure 1: Conventional Oil Production Peaks in the Next Decade and Declines Slowly



Assumptions:
Demand ↑ by 1.5%/yr (historical is ~2%/yr)
Part of shortfall met by gas, other sources
Most of shortfall to be met by heavy oil
Environment issues met by new methods

Concerns and limitations:
Massive infrastructure, investment needs
New upgrading technology would be nice

Figure 2: A Scenario for the Next 30 Years



*Specific values depend on viscosity and compressibility of the phases

Figure 4: Frequency and Process Regimes

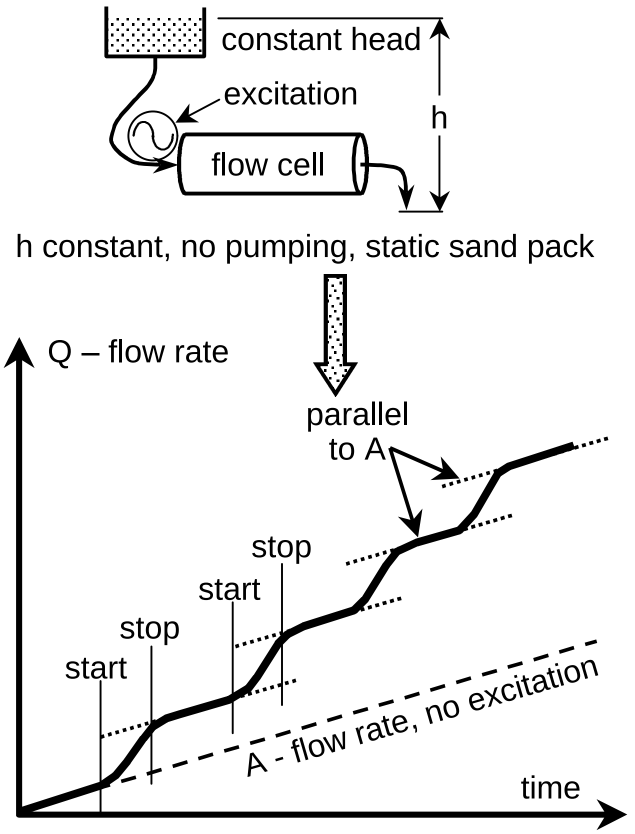


Figure 5: Flow Enhancement Demonstration

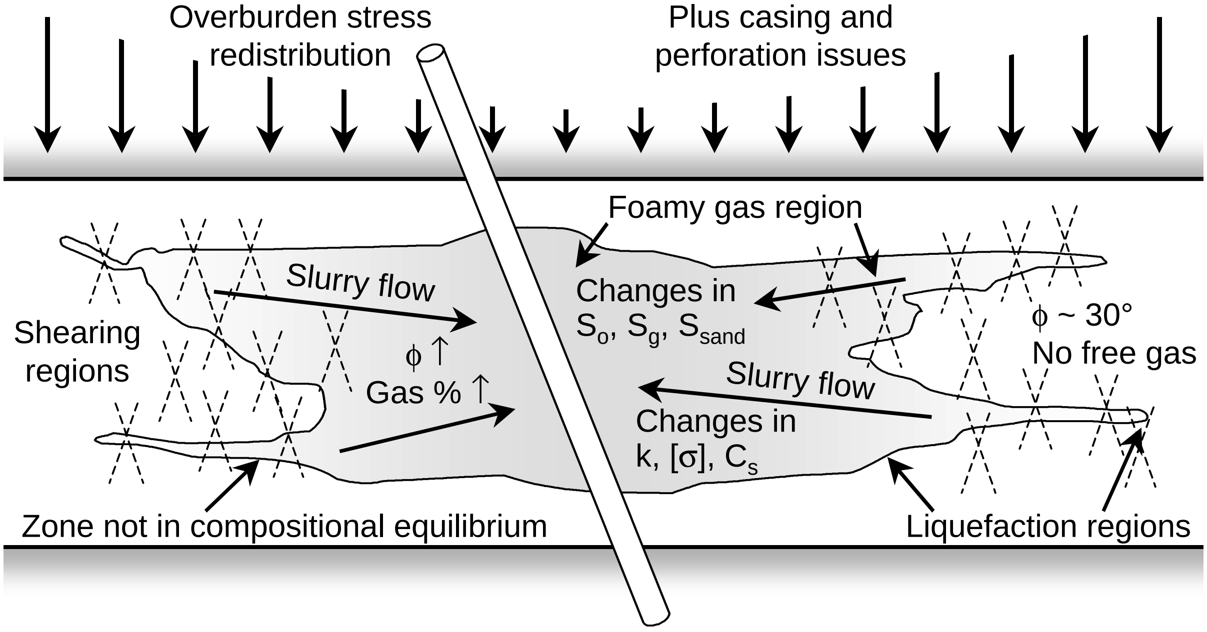


Figure 3: The Complexity of Physical Processes in Cold Heavy Oil Production

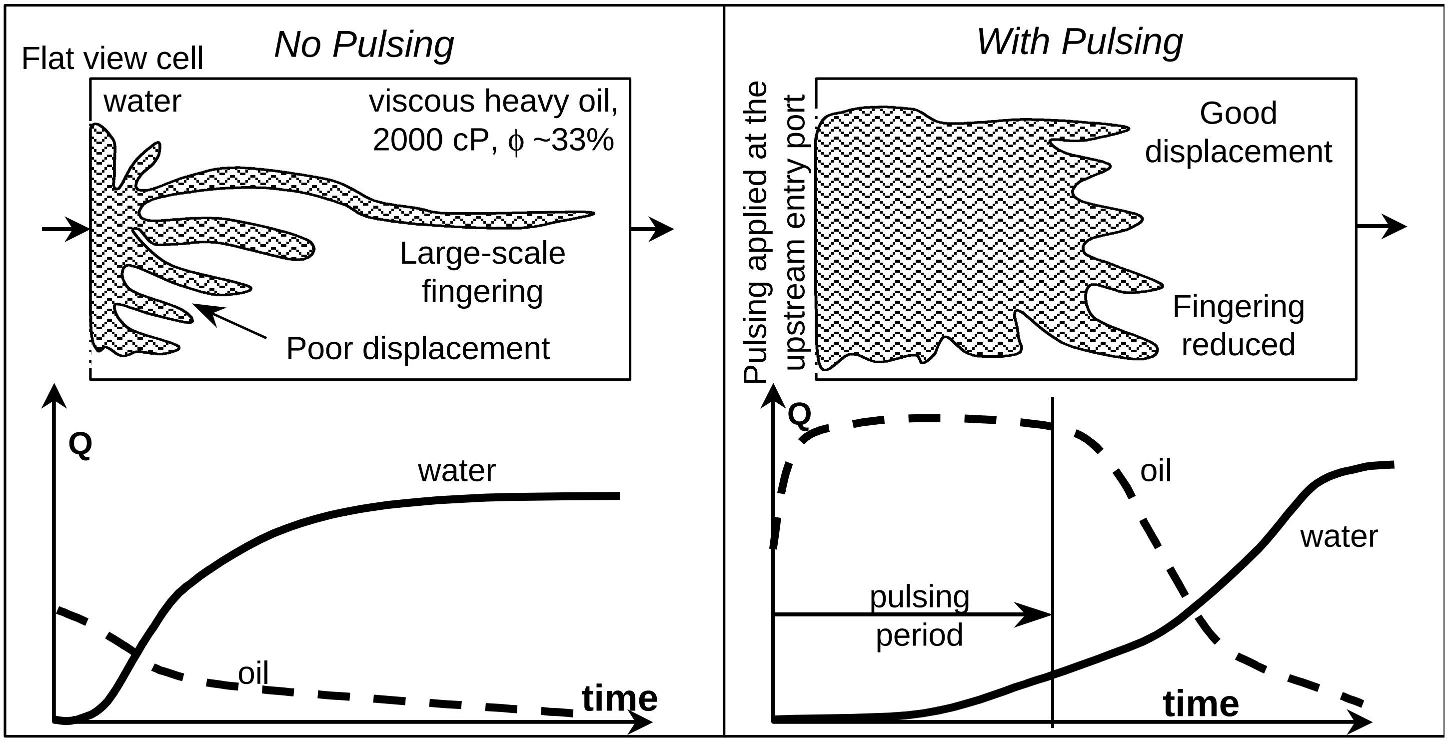


Figure 6: Dynamic Excitation Produces More Oil Faster, and Reduces Viscous Instabilities