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Short Note

5th dimension warning for 4D studies

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MOTIVATION

It has been well documented that reservoirs show sometimes staggering amounts of compaction over years of production. The aquifer under Las Vegas, the Ecofisk development, and the Lake Maracaibo area are all examples where the subsidence of porous reservoirs have undergone a compaction observable to the naked eye.

Studies of the elastic deformation of the surrounding country rock have shown the distribution of failure types to be associated with the volumetric collapse of a reservoir structure (Segall, 1998). However, the prediction of the nature and timing of the compaction of the reservoir itself need also be understood. Zoback (2001) has made inquiries into the nature of the compaction of granites, Ottawa sand, and the Adamswiller sandstone. This work focuses on an elastic deformation model that does not take into account time progression and creep behavior.

The motivation for the study of the creep behavior of reservoir rocks is a fundamental problem of available time. This uncertainty manifests itself in two questions: Over what time scale do reservoirs compact? Can lab measurements capture meaningful parameters to understand the nature and development of reservoir compaction? Simply put, are compaction studies measured in the lab valid at all? After these difficult questions are answered, then next logical step is to ask what impact this can have on repeat seismic experiments that are all the rage in the new millennium.

With the publishing of lab compaction data in Dudley and Myers (1994), the case is clear that meaningful measurements can be made despite implementation on time scales orders of magnitude shorter than significant to either geologic time or reservoir life. This results in our ability to make and trust compaction measurements on unconsolidated sand material. While this may solve engineering problems such as pore volume compressability and drive, it introduces a major wrinkle into the 4D seismic experiment that must be recognized. As a reservoir continues to compact over a decade of production, the best models for fluid substitution or pressure dependence of a seismic attribute are meaningless if the rock frame has changed significantly.

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COMPACTION

The uniaxial compaction coefficient is defined as

$$C_z = \frac{d\epsilon}{d\sigma_z}. \tag{1}$$

Thus if the total amount of strain, ϵ, is different for tests in which the residence time of the stress, σ, varies we will measure a suite of compaction coefficients depending on our test parameters rather than inherent properties of the rock. Intuitively, we would expect this to happen; surely holding pressure constant for a longer period of time will result in more compaction.

To investigate this problem, several uniaxial strain experiments were measured by Dudley and Myers (1994) by increasing axial stress and holding for 1.5 hours, 1 day, 1 week and 1 year. The three shorter duration tests were repeated for 12 stress and hold cycles, while the year-long experiment was only conducted once. Figure 1 shows three such tests with 750 psi stress step. All samples are brine saturated and allow fluid to flow out of the sample with applied stress.

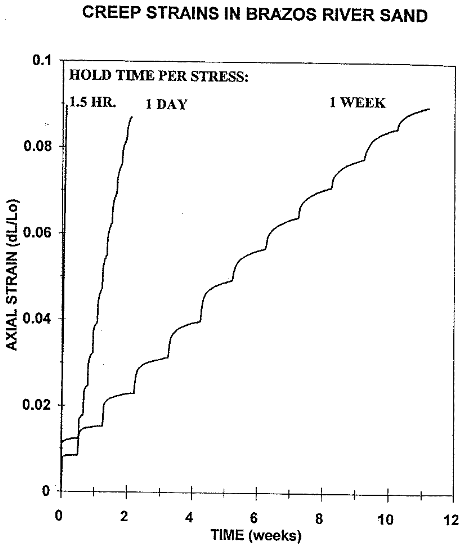

Figure 1: Apparently unrelated stress-strain behavior of samples to uniaxial strain experiment.(Dudley and Myers, 1994) brad1-creep [NR]

Figure 2 shows an example of the raw data from one stress cycle. Notice the extraordinary fit of the exponential curve to the integrated strain measurements over time. Figure 3 shows the surprising fact that by simply normalizing the time axis by the length of the hold time, the creep graphs all become coincident. This means that creep rate for longer experiments is slower than that for shorter experiments. This is simply amazing.

Several unsettling problems arise from these observations:

- Why does a growing exponential, that has no upper bound, fit data so well?

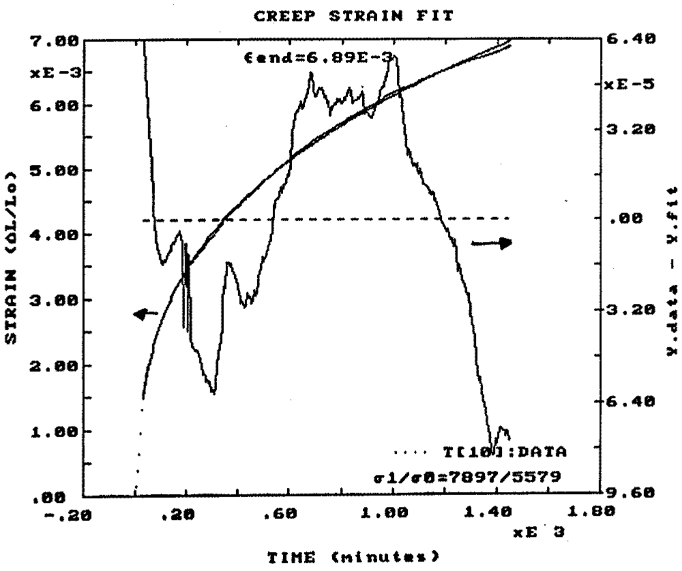

Figure 2: 24 hour hold time test for cycle to 8500 psi. Exponential fit of the form $\epsilon(t) = kt^d$ overlay the integral of the strain data.(Dudley and Myers, 1994) brad1-raw [NR]

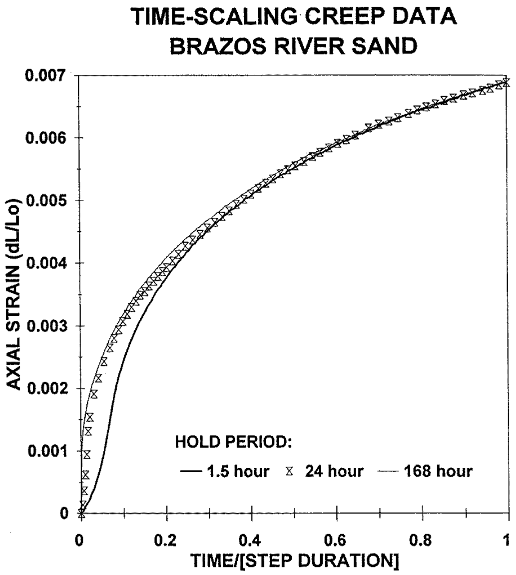

Figure 3: Amazingly, all three tests show the same exponential increase of strain as a function of normalized time. More important: all tests attain the same final strain value despite two orders of magnitude difference in residence time. Mismatch of 1.5 hour test assumed to be a result of time for 750 psi pressure ramp-up being a significant (13%) portion of total hold time.(Dudley and Myers, 1994) brad1-norm [NR]

- What does final strains being equal afford us?
- Why do normalized data overlay?

SEARCH FOR MODEL

Intuitively, we know that the creep behavior of the samples must reach a maximum that we can call *compressed*. The lack of an upper bound is troubling. Fortunately similar behavior has been seen in other phenomena and gives us a clue. Vialov and Zaretsky (1973) showed exponential creep deformation of clays. Gross (1947) showed that this exponential form is equivalent to a Voigt-type material model [2] that includes a very broad Gaussian range of parameters. Juarez-Badillo (1985) showed a Cole-Cole type deformation model that will be explored here to unite all of these observations.

The empirical relation developed by Juarez-Badillo is of the form

$$\epsilon(t) = \frac{\epsilon_{final}}{1+(\tau/t)^d} \,. \tag{2}$$

Knowing that we need to find a power-law form to fit the observations, we can analyze this equation under the limit where the time of the experiment, t, is much less than the characteristic compaction time, τ, defined as when the sample has undergone exactly half of the final strain limit. This seems appropriate as we are making an effort to do lab experiments at much less than the time that we imagine these processing happening in the field. Equation 2 then becomes

$$\epsilon(t) = \frac{\epsilon_{final}}{(\tau/t)^d},$$

$$\epsilon(t) = \frac{\epsilon_{final}}{\tau^d} t^d.$$

We notice now that the strain at time 1

$$\epsilon(1) = \frac{\epsilon_{final}}{\tau^d}$$

and therefore

$$\epsilon(t) = \epsilon_1 t^d \,. \tag{3}$$

Not only does this equation fit well with the observed data, but considering only progressive quartiles of the data, constant and stable values for the regressed parameters ϵ_1 and d are obtained. This provides further justification in the selection of this model as this was one of the significant problems with use of the other models.

Now, assuming that our adoption of the Juarez-Badillo creep mechanism is correct, we have a model that helps explain our data. This fit implies several things:

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[2] Yet another problem noticeable with these results is the apparent inconsistency of arriving at a Voigt-type model during a uniaxial strain test. Mavko (2001) indicates that the Voigt model is normally associated with iso-strain, uniaxial stress experiments.

- All tests are operating well in accordance with the assumption that $t \ll \tau$. Even the data shown in Figure 4 fit the exponential model nicely.
- Under these time constraints we cannot hope to solve for both ϵ_{final} and τ, but only for their quotient.
- Further research is needed to understand how a sample can achieve such self-select its mode of operation.

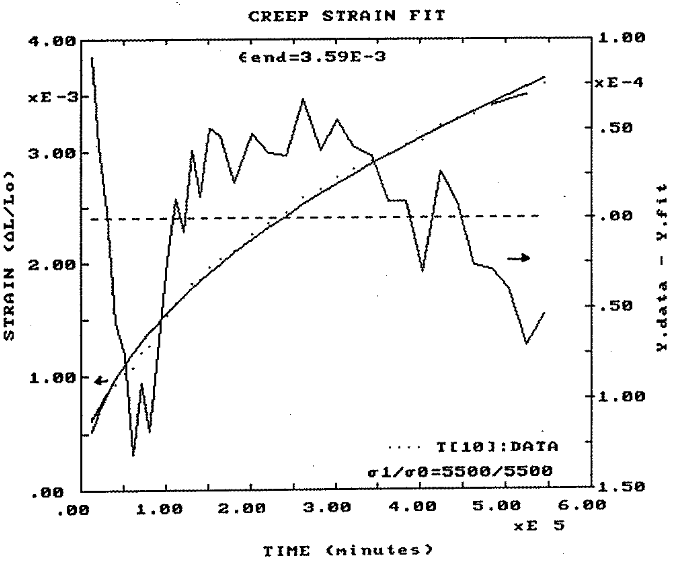

Figure 4: One year hold uniaxial creep test. Exponential function still fits meaning $t \ll \tau$ and implying that reservoir material must have a characteristic creep time on the order of decades.(Dudley and Myers, 1994) brad1-year [NR]

TIME SCALING AS SAVIOR

One of the initial interests mentioned earlier was the use of these experiments to determine the compressability of reservoirs. As we noted above that it seems unlikely we will be able measure ϵ_{final} and τ, let us hope that we can at least accomplish this. The unconsolidated deep water reservoirs commonly found today can compress so significantly as to

- cause costly tubing collapse and demand pressure maintenance, and/or
- obviate water flood necessity for production efficiency.

These two seemingly contradictory results make it quite important to understand the validity of these tests in order to make correct decisions.

As was shown in Figure 3, that the final strain value of each test cycle was identical and independent of the hold time, we see that each test results in the same stress-strain behavior in Figure 5. We are now free to calculate the compaction curves as a function of pressure.[3] This

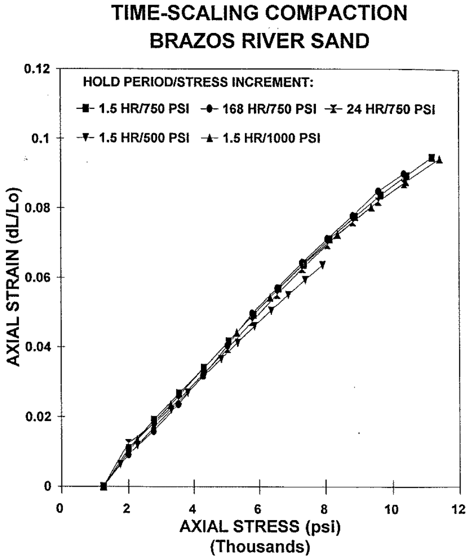

Figure 5: Time scaling nature of the normalized hold-cycles results in each sample attaining the same strain value at the end of the hold time. Plotting final strain values from all cycles tested shows overlay of stress-strain behavior.Also important in this testing methodology is the pre-stressing of samples to pseudo-depth pressures. This removes 'closure' errors from consideration of the results.(Dudley and Myers, 1994) brad1-ss [NR]

result will tell us the expected uniaxial compaction of a reservoir during the drainage phase that increases the vertical effective stress (VES) as pore pressure draws down ($VES = \sigma_1 - P_{pore}$), under the caveat that the production time does not approach the characteristic time τ. If we violate this assumption, we will over-predict the amount of compaction the reservoir will experience. [4] This allows us to present plots of the regressed parameter ϵ_1 versus pressure such as Figure 6.

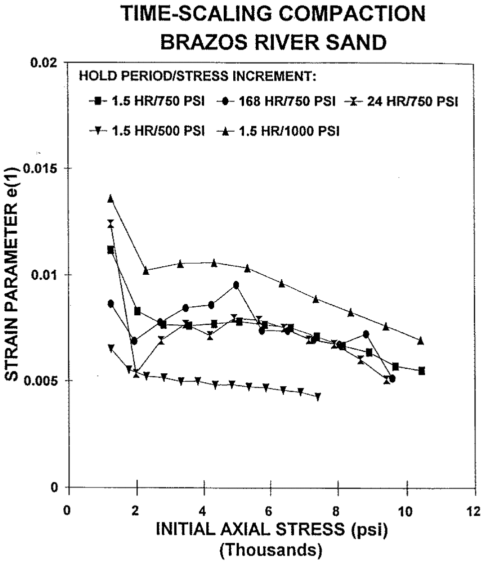

Figure 6: Parameter $\epsilon(1)$ from all tests. All 750 psi steps overlay.(Dudley and Myers, 1994) brad1-e1 [NR]

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[3] We must remember that this is not an elastic phenomenon, and no work has been done thus far to determine to what extent there may or may not be hysteretic effects when attempting to reverse this process. This concept could be especially important for aquifer studies and late-stage pressure maintenance projects.

[4] It is also good to remember for the porosity loss due to compaction that the pore volume compaction is related to the uniaxial compaction by $C_p = C_z/\phi$.

Data from several pressure step magnitudes are presented. By dividing by the magnitude of the pressure step, we effectively calculate C_z from equation 1 and watch the curves collapse onto one another.

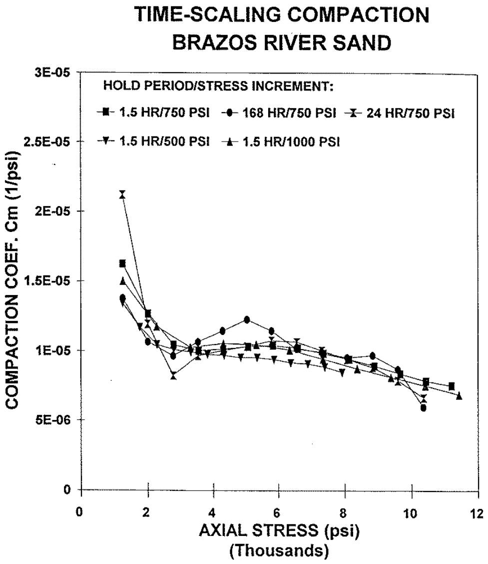

Figure 7: Remarkably, uniaxial compaction coefficient C_z as calculated by 5 different testing methodologies remain consistent.(Dudley and Myers, 1994) brad1-cz [NR]

Figure 7 shows the quite compact distribution of the C_z parameter for 5 different samples each calculated with different stress-step and hold-time combinations. Thus the time scaling nature of these tests results in the pressure scaling of the tests as well due to the compulsion that the different tests must satisfy identical stress-strain behavior (as shown in Figure 5).

MECHANISMS

So far, sufficient evidence has been accumulated to comfortably apply laboratory compaction tests of any convenient hold time [5] to faithfully characterize the reservoir. However, it is unclear to me as to physically how this seemingly *double-slit* style interaction manifests itself in the changing rocks. There seem to be very few available mechanisms for accommodating creep behavior. Shown in Figure 8 are cartoons illustrating the three available to the rock without grain crushing. The problem then is how, through these limited mechanisms, can the rock realize the necessary broad distribution of characteristic relaxation times? It seems reasonable that both mechanisms may enjoy some breadth in time-scale simply as function of heterogeneity of mineralogy and sorting. To truly achieve the smooth single mode distribution required however implies that the ductile grains act as impulse sensitive springs and the grain rotation is almost fractal. These requirements seem difficult enough to achieve without the further requirement that they overlay and interact nicely together. The experiments shown here are all done on manufactured plugs of frozen loose river sand described as sub-angular, moderately well sorted, feldspathic and fine grained. Similar tests on Gulf turbidite reservoir

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[5] Convenient does not necessarily mean shortest. Notice that if a hold time of hours is left or forgotten for a longer time period, the sample ill begin to re-scale its creep mechanism toward the longer option. Weird? Yes.

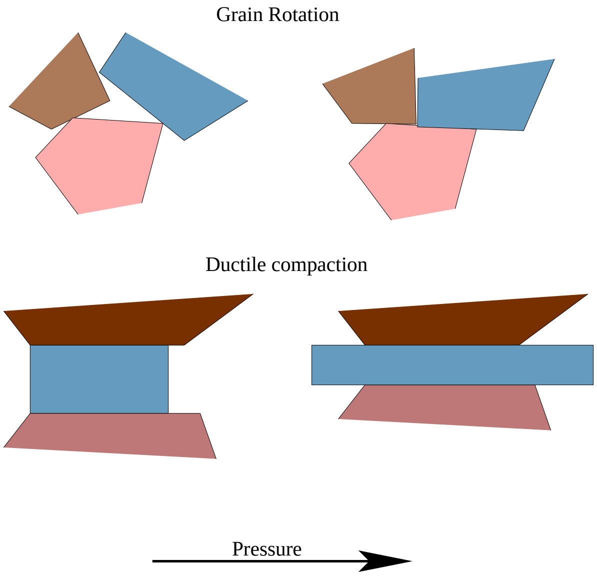

Figure 8: Three compaction, without crushing mechanisms: 1) grain rotation, 2) ductile compression of grains, or 3) compression of pressured pore space (the transition of an over-pressured state to a grain supported frame). brad1-mech [NR]

core samples show similar results. It is my suggestion then to perform a similar suite of tests on manufactured grain packs in an effort to understand how the various mechanisms are responsible for which parts of the scaling phenomenon. To this end samples of various sorting, grain size, grain shape, mineralogy, and combinations of all of the above could be manufactured and tested under uniaxial strain tests. A further help in identifying the processes involved would be to take intermediate images of the sample to show the nature and state of the undergone transformations similar to Cadoret's partial saturation experiments (from Mavko (2001)).

Further, once these processes and their limiting and defining characteristics are well understood, the development of type curves for various material would be very valuable.

IMPLICATIONS TO 4D

Accepting the previously outlined rock physics conundrum, we can now think about the implications of this creep behavior, and our ability to capture it in the lab, to the repeat seismic experiment. As most of the rock physics field has historically been dedicated to the application of acoustic manipulations and pressure dependencies there is much work available concerning the elastic sensitivities of rock, packs, and beads to various pressure regimes (Mavko, 2001). All of this understanding however hinges on the basic immutability of the mineral frame (elastic deformation) until a yield point from which a sample cannot recover (fracture or grain crushing). We begin to realize that our discussion thus far begins to impinge on the underlying assumption for the classic rock physics justifications for 4D seismic: namely that the rock frame does not change. The previous sections show that it does. Thus there are no constants to hold on to for any experiment, be they fluid substitution or seismic. We might as well be dealing with an entirely new reservoir. To add to the conclusions to the creep investigation section above, it is imperative to perform experiments to not only understand the creep

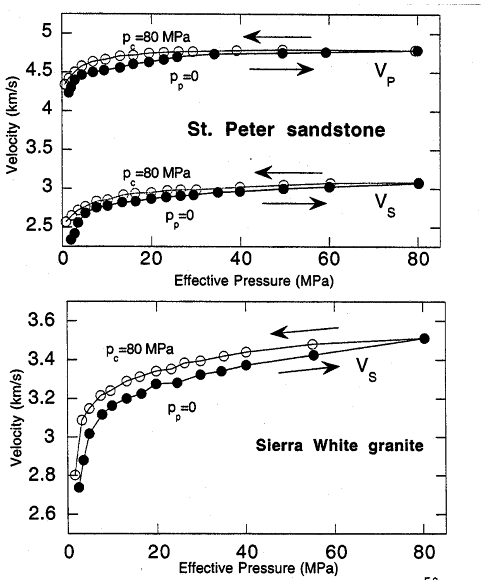

Figure 9: Experiment illustrating the effective pressure law by increasing and decreasing effective pressure while keeping the pore pressure constant. Minor hysteresis observable, but obviously an elastic phenomenon.(Mavko, 2001) brad1-pres [NR]

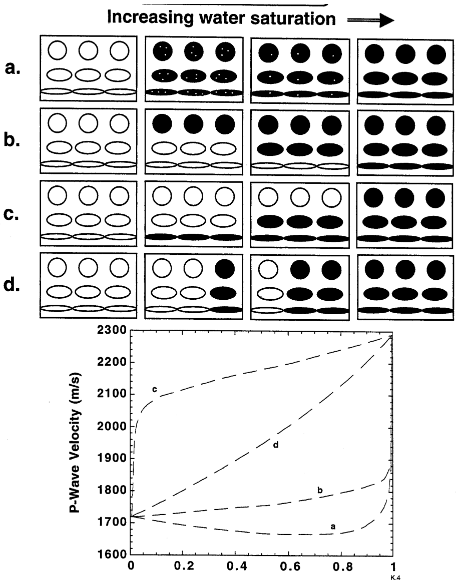

Figure 10: Different micro-distributions of pore fluids and gas within the porosity of the rock frame significantly effect the velocity dependence on water saturation.(Mavko, 2001) brad1-sat [NR]

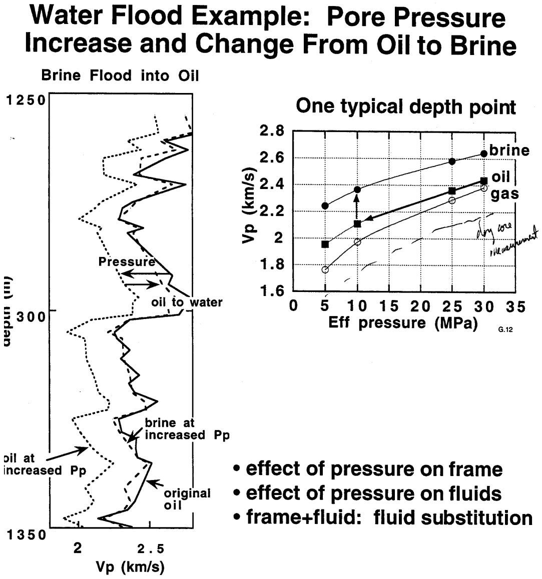

Figure 11: If fluids and elastic pressure dependence are understood, the seismic evolution of a reservoir can easily be modeled with a few simple plots. Fluid substitution calculated in this instance with Gassman model from dry lab data.(Mavko, 2001) brad1-model [NR]

mechanisms, but also their effects on sonic velocities or acoustic moduli. It is obvious that the various transformations depicted in Figure 8 will result in new elastic moduli as we are basically manufacturing a new rock sample. This is quite troubling when the second conclusion of Juarez-Badillo creep behavior is remembered. Solving for ϵ_{final}/τ rather than for the two independently removes our ability to predict end-state compaction and the time (supposed to be analogous to production life of a reservoir) to achieve it. While this seemed a disappointing but not insurmountable obstacle previously, it could be a real show stopper in the 4D context. To that end, the experiments mentioned previously need be undertaken with the addendum of velocity measurements along the way. It is very possible that while the samples can show time-scaling of creep mechanisms, parts of the distribution of mechanisms may indeed exhibit very different manifestations in elastic parameters.

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