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IMPACT OF ROCK MICRO- AND MACROSTRUCTURE ON THE BEHAVIOR OF TWO-PHASE FLUID FLOW

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ABSTRACT

We demonstrate that in the weak, high porosity and almost impermeable rocks, the rock microstructure changes dramatically during hydrocarbon production and water injection. In the North Sea chalks and the California diatomites, rock damage is a phenomenon of crucial importance to ultimate recovery and profitability. There is overwhelming field evidence of ubiquitous rock damage in the diatomite. (1) Water production rate increased *manifold* before *waterflood*, i.e., the intra-particle water was released from the grains crushed by the changing effective stress. (2) Aqueous tracer breakthrough times are two-three orders of magnitude shorter than expected for flow in the intact diatomite. (3) Some newly drilled wells free-flow before hydrofracturing at rates impossible to sustain by the undamaged diatomite. (4) Surface subsidence continues at a substantial rate, despite seemingly balanced injection and withdrawal, i.e., water is injected only into few diatomite intervals and does not provide uniform pressure support. (5) Produced water is an almost constant fraction of the injected water in both fields regardless of the operator, waterflood stage, and location. (6) More water injection causes more subsidence. (7) Hydrocarbon production is an S-shaped function of subsidence, i.e., compaction remains a dominant production mechanism. The classical models of elasto-plastic rocks cannot capture the dramatic rearrangements of rock microstructure caused by fluid withdrawal and injection. New micromechanical approach is required to understand and predict reservoir behavior in the diatomite and chalk, and limit well failures.

INTRODUCTION

Today, we face an interesting time in subterranean mechanics: the science of flow, deformation and fracture in natural rock-fluid systems. Important practical problems with water supply, oil and gas recovery, and more recently with the disposal of nuclear and chemical wastes are forcing researchers to reconsider and modify the established multiphase flow theories that, with relatively minor changes, have dominated earth sciences since the late thirties. These modifications lead to substantially new physical and mathematical formulations, and are required to tackle problems with, e.g., oil production from the North Sea chalks and the diatomites in California, liquid nuclear waste seepage at Hanford, WA, or with nuclear waste isolation under the Yucca Mountain, NV.

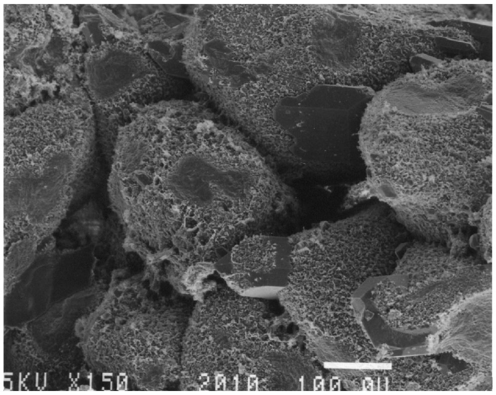

Figure 1 – The inter-locking grains of a sandstone form strong "support beams" (SEM photo by K/T GeoServices, Inc.).

In classical approach, the equations governing mass, momentum and energy conservation of the solid and the fluids in a region of a porous, permeable and deformable rock are volume-averaged and continuum approximations of the fluid distributions and the solid are obtained. Mass, momentum, angular momentum and energy conservation

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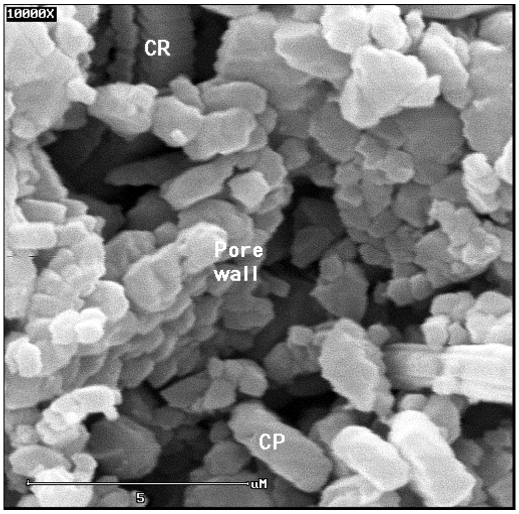

Fig 2 – Chalk coccoliths make mechanically weak "mosaic" pore walls (SEM photo by Jess Milter).

laws and their invariance properties are insufficient, however, to obtain a closed consistent system of equations of fluid flow in real rocks. To obtain such a system, it is necessary to provide all continua with physical properties. This means that a model of each continuum is employed, which is adequate for the class of motions of interest. Such models, called *constitutive equations*, provide the necessary relationships between the properties of the motion, or the states of the continua, and acting internal forces.

A constitutive equation becomes a fundamental physical law if its constants are *universal*. In particular, this means that once determined from experiment, these constants are the same within a wide range of conditions. For elastic isotropic rocks, such constants are Young's modulus and Poisson's ratio. For complex rocks, such as chalks or diatomites, the researchers have tried to extend the classical models by including more constants. A good example is the five-constant Drucker-Prager model [1] (with spherical cap [2]) of elastic and plastic rock deformation. The increasing complexity of determining the new constants and the loss of their clear physical sense are not the worst outcomes: the biggest limitation of the Drucker-Prager model of diatomite and chalk is that its constants cease to be universal, i.e., their range of universality may be so narrow as to eliminate the model's predictive abilities.

To describe soft, prone to damage rocks, we use an alternative approach that appeared in science and engineering in the last four decades [3, 4], [5-7]. In this approach, the properties of the material microstructure, directly observable or computable from the fundamental conservation laws, are explicitly introduced as a part of the rock model. In particular, the damage understood as the average fraction of broken bonds is introduced. The macroscopic conservation equations and the equations governing the kinetics of microstructural transformation are solved simultaneously. This micromechanical approach is the essence of our work on damage of the soft reservoir rocks.

ROCK MICROSTRUCTURE

The microstructures of the North Sea Chalks or the California diatomites are fundamentally different from, say, sandstones. **Figure 1** shows the scanning electron microscope (SEM) image of sandstone magnified 150 times. The pores are the dark regions surrounded by up to six grains similar to beach sand in size. The interlocking grains form a network of strong beams that together protect the pore space from the increase of effective stress. The SEM image of a North Sea chalk in **Figure 2** is magnified 10,000x. The chalk grains are of the size of very fine dust. The pore walls are made of hundreds of coccoliths that form a poorly cemented mosaic. These coccolith mosaics are mechanically weak and collapse with the decreasing pore pressure. The chalk porosity is 40-50%, and it is practically impermeable (0.1-5 md). The low (600x) and high (5000x) SEM images of the outcrop diatomite, **Figure 3**, reveal a disordered microstructure with little interlocking and cementation. When intact, the diatomite has overall porosity of 50-70% and like chalk it is practically impermeable (0.1-1 md).

To make any appreciable fluid flow possible, the chalk and diatomite microstructures must be changed. These changes can be caused by changes of effective stress leading to the collapse of pore walls. As a result, a system of connected microcracks is created, which radically changes the mechanical and flow properties of the two rocks. It then follows that both water injection and oil withdrawal cause a significant and irreversible changes of the microstructures of both rocks. The disintegration of chalk and diatomite implies increased rate of compaction during waterflood.

The increased rate of compaction of waterflooded chalks has been recognized for quite some time, e.g., [8]. The increased rate of diatomite compaction in waterflood is coming to light just now [9].

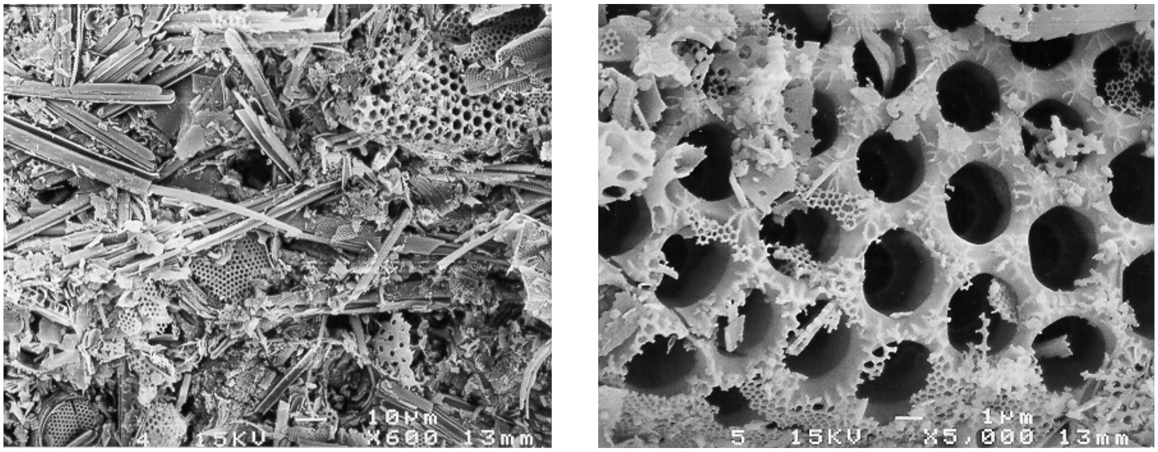

Figure 3 – SEM microphotographs of the diatomite rock show its complex and fragile microstructure. When compared with chalk, the diatomite has a higher porosity and is weaker mechanically (SEM photos taken in CEE EM Lab).

FLUID-ROCK INTERFACE MICROSTRUCTURE

In an oil and gas reservoir, the microstructure of fluid-fluid and fluid-solid interfaces is as important as that of the rock. For example, it is important to know in which pores the oil resides, and which pores are filled with water. The fluid microstructures in chalks and diatomites could be checked in principle with freeze-SEM imaging, but to our knowledge were not. One would expect, however, the oil to be present in the largest pores, microcracks and fractures, and water to reside in the micropores and intra-particle pores. From this point of view, the undamaged chalk and diatomite will slowly produce oil with little water. As the reservoir pressure decreases around the well or "hydrofracture," the rock collapses, and the water trapped in the small pores is released, **Figure 4**. The suddenly abundant water production may also mean that the fractures are predominantly oil-wet, in agreement [10] with a substantial asphaltene presence [11] in the crude oil.

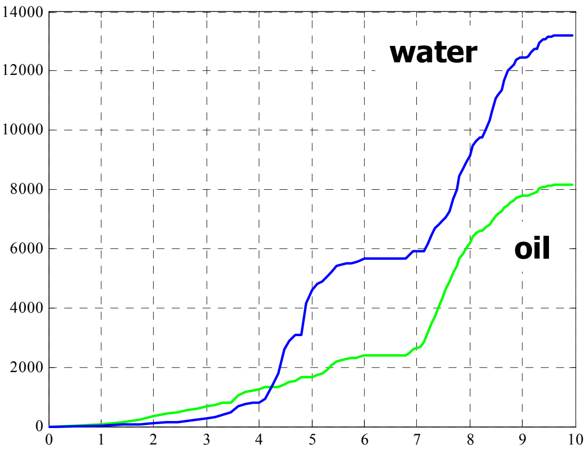

Figure 4 – Initially low water production during primary in a Lost Hills well dramatically increases after several months.

ROCK MACROSTRUCTURE

As a result of the cyclic depositional environment [12], the diatomite rocks are layered across width scales ranging from tens of meters to sub-millimeter. The inter-layer boundaries are weakly connected and ready to part when the fluid pressure changes. When a Lost Hills diatomite core dries somewhat, and shrinks, horizontal fractures appear at an almost uniform spacing of about 1 cm. Large-scale faults and fracture systems are also known to exist [13] in the diatomite fields. The large fracture systems will probably increase their size and connectivity when the pore pressure changes. For example, some of the infill wells in the Lost Hills waterflood patterns flow prior to hydrofracturing, and may produce some 10 barrels of oil per day. This observation provides clear evidence that the new vertical wells intersect a predominantly horizontal system of fractures, which are (1) initially filled with oil, and (2) pressurized by water from the adjacent injectors. As the micro-cracks created during field operations increase in number and connectivity, they will connect to the macrofracture system. Therefore, production and injection in the diatomite will result in the interactions of fractures at many scales.

An aqueous tracer test in Section 32 of Lost Hills, revealed [14] that the upper injection hydrofracture linked to four producers through the small flow channels or "tubes", that are about 100 times more permeable than the rock matrix, and have effective cross sections of the order 10-100 cm^2. The results of the tracer tests in near by patterns were similar. Therefore, macroscopic rock damage in the diatomite waterfloods seems to be the rule rather than exception.

HYDROFRACTURES

All wells in the diatomite are hydrofractured, and the vertical "fractures" are thought [15] to have tip-to-tip lengths of the order of 100-300 ft and heights of 50-300 ft. In reality, these "hydrofractures" are topologically complex volumes of pulverized soft rock with complex connectivity and geometry [6, 16-18]. The damaged rock volume around a hydrofracture may give an illusion of a vertical crack, but it is not.

Waterflood patterns in the diatomite are usually configured as staggered line drives, but these patterns not always follow the direction of maximum horizontal *in-situ* stress. Depending on the fracture orientation and flow direction, areal sweep by water may vary greatly [19]. Multiscale layering in the diatomite [12] and rock damage [20, 21] result in strong anisotropy and nonuniform vertical and areal sweep.

EVIDENCE OF RESERVOIR DAMAGE FROM INSAR IMAGES

As described elsewhere [9, 22], the Synthetic Aperture Radar interferograms (inSAR) from satellites can be used to detect the minute line-of-site displacements of ground surface that result from hydrocarbon production and water injection. Each interferogram consists of 20-by-20 m pixels that cover the entire field areas. The surface displacement can be integrated over the area of each field section or subsidence bowl, and the result is shown in **Figure 5** for the Lost Hills and South Belridge diatomites.

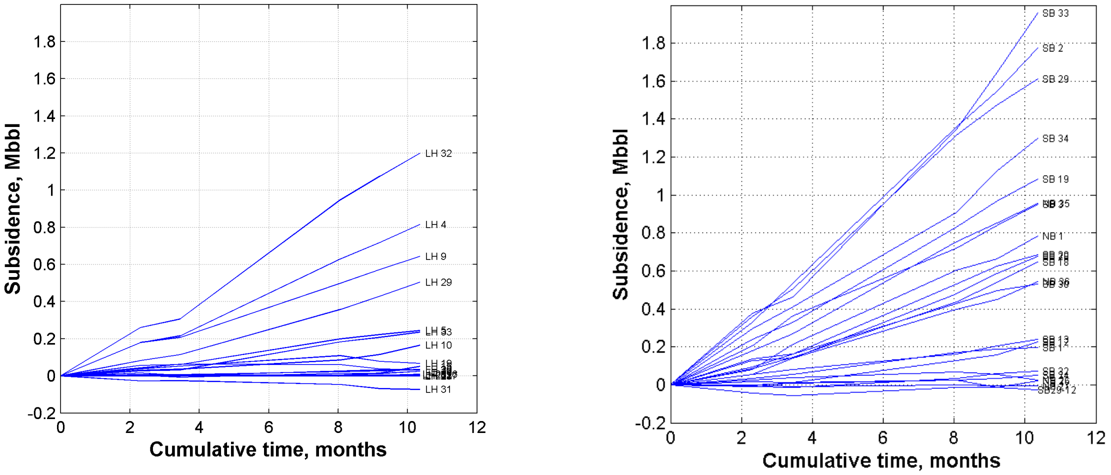

Figure 5 - Annual subsidence in the Lost Hills (left) and the South Belridge (right) diatomites in 1999. Each curve depicts cumulative subsidence per section in millions of barrels.

In 1999, four sections in Lost Hills experienced significant subsidence, whereas in South Belridge the number of such sections was thirteen. As the diatomite waterflood operators try hard to balance water injection with total withdrawals, the question arises, why does subsidence continue? An obvious answer to this question is provided by rock damage. The injected water enters discrete channels in some layers, but it does not enter all layers. Therefore, the injected water is recirculated through the channels in a few layers, while oil production by compaction continues elsewhere. Compaction remains the major production mechanism in the waterflooded diatomites.

Let’s now see what other field evidence do we have for these bold assertions. First we check, **Figure 6**, that in both fields the produced water is a constant fraction of the injected water, regardless of the operator or section location. The outliers in South Belridge are discussed in [9]. Somewhat more water is produced in Belridge reflecting the higher well density and more rock damage.

Second, we test the following hypothesis: In a waterflood that provides uniform pressure support across the entire reservoir column, more water injection results in less subsidence. **Figure 7** shows that this hypothesis is not true in Lost Hills, and it is also not true in the most advanced waterfloods in South Belridge. Section 32 in Lost Hills is an outlier because water is currently injected only across half of its area.

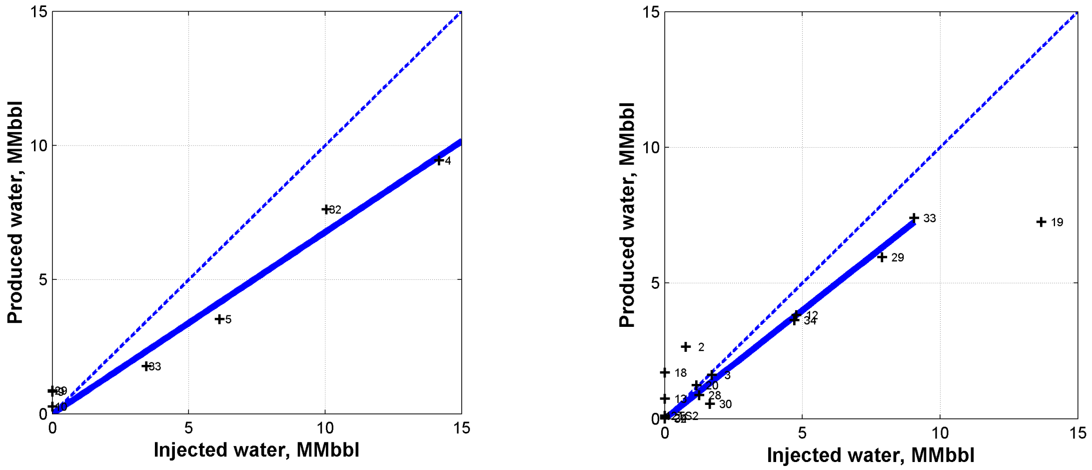

Figure 6 - Produced vs. injected water by section in the Lost Hills (left) and the South Belridge (right) diatomites. The correlation lines mean that 0.7 and 0.8, respectively, of the injected water was produced in most sections in 1999.

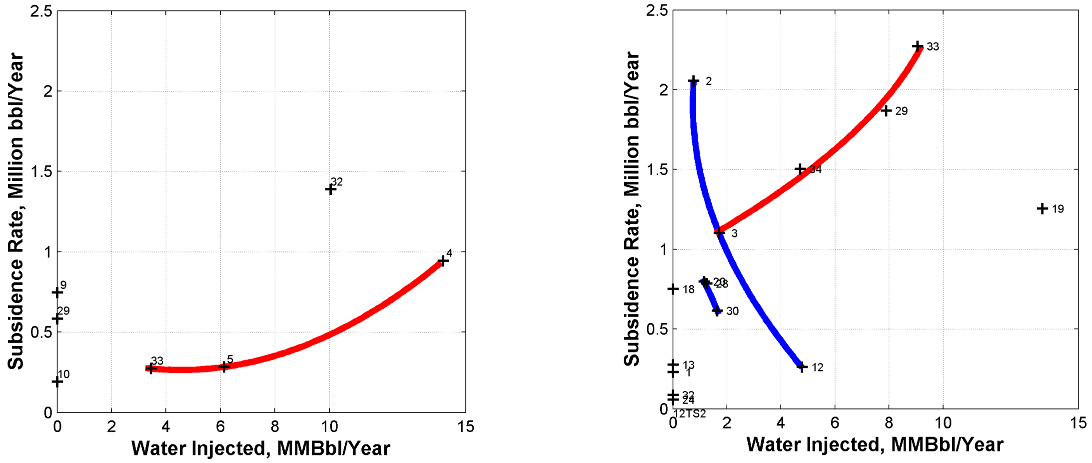

Figure 7 - The 1999 trends of subsidence vs. water injection by section in the Lost Hills (left) and the South Belridge (right) diatomites. The expected trend of less subsidence with more water injection is not observed in sections with higher water injection, indicating rock damage by the respective waterfloods.

Third, we plot the total hydrocarbon production by section versus subsidence, **Figure 8**. Here we see that more subsidence results in more production, but a plateau is reached. Section 33 in South Belridge is an outlier for two reasons: there are more wells in it and there is a waterflood response.

Fourth, we plot water production versus subsidence, **Figure 9**. The general trend here is that more subsidence causes more water to be produced, i.e., there is more water recirculation and less uniform pressure support.

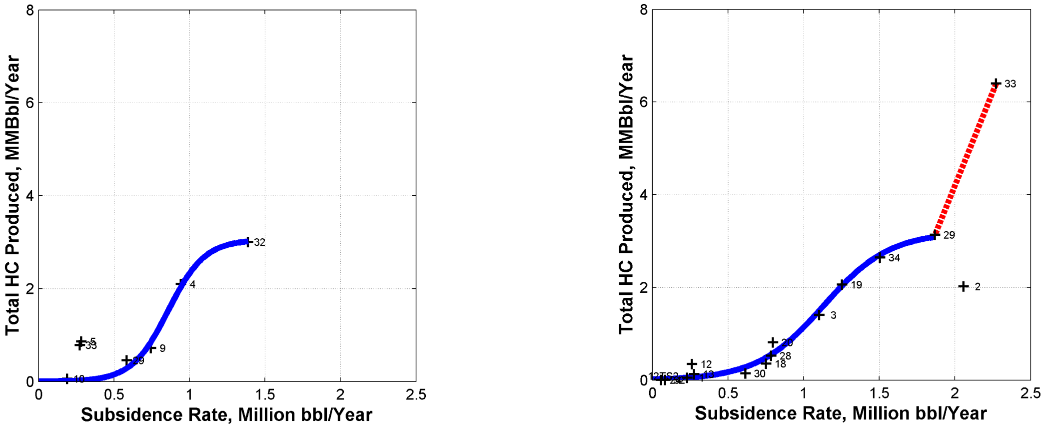

Figure 8 - The 1999 trends in total hydrocarbon production vs. subsidence in the Lost Hills (left) and the South Belridge diatomites (right). In general, more subsidence corresponds to more hydrocarbons produced, indicating that compaction is a major production mechanism. These plots are somewhat deceiving because they mask different well densities in different sections.

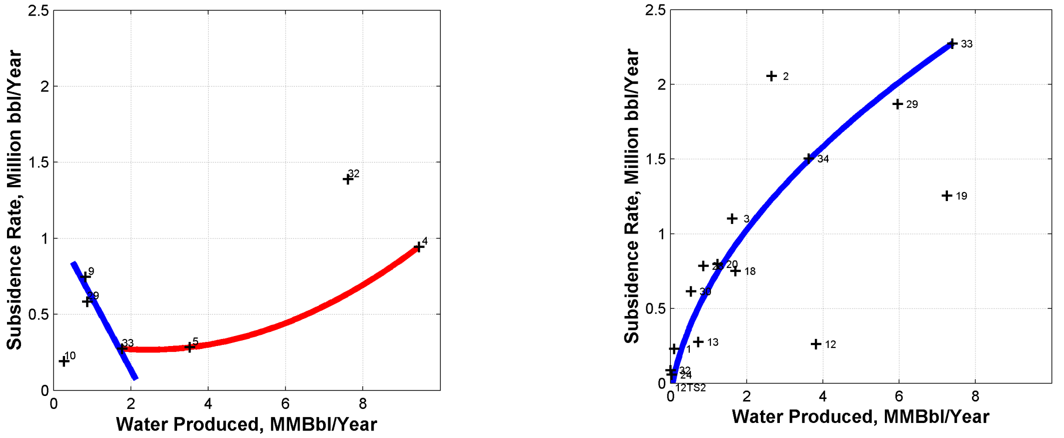

Figure 9 – The 1999 trends of subsidence vs. water produced in the Lost Hills (left) and the South Belridge (right) diatomites. In general, more water produced corresponds to more subsidence, indicating rock damage by waterflood. In Lost Hills still there are sections, mostly on primary recovery, that follow an opposite trend.

SUMMARY AND CONCLUSIONS

The current understanding of mechanisms of oil production in primary and waterflood is insufficient for the diatomites, and also for the chalks. Consequently there is little if any capability to predict the ultimate oil recovery and the rate of well loss caused by nonuniform subsidence. Given a reasonable injection policy, runaway damage of the rock can be reduced with the new injection controllers [23-25], but the injection profiles and areal sweep by water are currently uncontrollable.

Our motivation is to help produce oil from the practically impermeable California diatomites by improved oil recovery techniques that may involve water or methane injection. Because of the unusual nature of the rock, we have to reconsider completely the accepted concepts of oilfield development in the diatomite. In particular, we propose to:

1. Investigate the possibility of dry gas injection with subsequent recovery, recycling and reinjection.
2. Model the microstructure of the inhomogeneous and anisotropic rocks using discrete elements with the properties calibrated from tri-axial compaction tests with water flow.
3. Obtain from the micromechanical models the characteristic length scales of the microcracks.
4. Use these length scales to calibrate the macroscopic model of rock damage, similar to that developed by Barenblatt [7].
5. Predict large-scale damage of chalk and diatomite caused by water injection.
6. Use this knowledge to stabilize large waterflood projects and increase ultimate oil recovery.

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