FOSSIL ENERGY

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ADVANCED RESERVOIR CHARACTERIZATION IN THE ANTELOPE SHALE TO ESTABLISH THE VIABILITY OF CO_2 ENHANCED OIL RECOVERY IN CALIFORNIA'S MONTEREY FORMATION SILICEOUS SHALES

Quarterly Report
October 1, 1998-December 31, 1998

By
Michael F. Morea

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Work Performed Under Contract No. DE-FC22-95BC14938

Chevron USA Production Company
Bakersfield, California

National Petroleum Technology Office
U.S. DEPARTMENT OF ENERGY
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Advanced Reservoir Characterization in the Antelope Shale to Establish the Viability of CO_2 Enhanced Oil Recovery in California's Monterey Formation Siliceous Shales

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TITLE: **ADVANCED RESERVOIR CHARACTERIZATION IN THE ANTELOPE SHALE TO ESTABLISH THE VIABILITY OF CO2 ENHANCED OIL RECOVERY IN CALIFORNIA'S MONTEREY FORMATION SILICEOUS SHALES**

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Summary of Technical Progress

Based on our results, we will not proceed with a Phase II field trial in Buena Vista Hills. Although we had numerous technical successes (i.e., high resolution crosswell seismic, mineral model based saturation algorithm) and completed a detailed reservoir characterization, we could not overcome the siliceous shale's very low oil saturation, lithologic heterogeneity and lack of natural fractures at Buena Vista Hills. However, reservoir characterization work has demonstrated that under the right conditions, CO_2 is a viable enhanced recovery process for siliceous shales.

Therefore, we have decided to submit a detailed proposal and budget for a Phase II CO2 pilot in the Belridge Diatomite at Lost Hills Field, about 30 miles north of Buena Vista Hills. We plan to submit our Phase II Lost Hills proposal by January 31, 1999.

The target reservoir at Lost Hills is the Belridge Diatomite of the Monterey Formation. The Belridge Diatomite is a diatomaceous mudstone and is not present at Buena Vista Hills. This diatomaceous facies grades south from Lost Hills into the more clay rich upper Reef Ridge found at Buena Vista Hills.

In order to proceed with a pilot project we need to conduct an injectivity test in the Belridge Diatomite in Lost Hills. The objectives of the injectivity test are:

1. Inject CO2 in a new well without hydraulically propped fractures. Because the diatomite is a low permeability reservoir all wells must be hydraulically fractured. If we can successfully inject into wells that do not have to be hydraulically propped fractured, then we could save $250,000 per injection well - a potential cost savings of $1 MM on a 5/8's acre pilot installation. Therefore we will attempt to inject into a non-fractured well to see if CO2 can be injected at or near predicted simulation rates. Additional benefits of testing this well will be injection rate/pressure data by lithology.

The 12-8D was drilled in December 1998. This well will be used for the injectivity test of a non-fractured well. Plans call for the injectivity test to commence on March 1, 1999. This well will be completed as a producer after the injection test. After the well is on production we will be able to observe the stimulation/production benefits from a CO2 cyclic injection/soak/production period.

2. Inject CO2 into an existing hydraulically fractured water injection well. Data from this test will allow us to compare CO2 injection rates and pressures with a non-hydraulically fractured well (12-8D), and compare CO2 injection with water injection from a nearby water injection well (12-7W).

3. Gain experience in CO2 operations regarding injection profiling, corrosion monitoring, production surveillance, and breakthrough.

4. Utilize data to design CO2 pilot well completions.

Geologic Overview of Lost Hills Field

Lost Hills Field is located 40 miles northwest of Bakersfield, CA (Figure 1). The field was discovered in 1910. Productive intervals include Middle to Upper Miocene siliceous shales and diatomite, and Plio-Pleistocene sands.

The field is situated along a northwest-southeast trending series of structural highs that begins with the Coalinga Anticline to the northwest and culminates with the Lost Hills Anticline to the southeast. This series of highs roughly parallels folds of similar age on the westside of the San Joaquin Valley. These folds are oriented nearly parallel to the trend of the San Andreas Fault to the west and approximately perpendicular to the direction of regional compression.

Lost Hills oil is trapped at the crest and along the southeast plunge of the anticline (Figure 2). In this portion of the field where the pilot will be located (Figure 3), the structural plunge varies from 2 to 6 degrees toward the southeast. Dips along the northeast flank average around 30 degrees while those on the southwest flank average around 15 to 20 degrees. This asymmetry in dips in the NE_SW direction is consistent with a fault-bend folding model. This model predicts that structural growth of the Lost Hills Anticline was initiated during latest Miocene time and that the resulting anticline is perched above a ramp thrust that is located around 1300 feet below the surface. Numerous northeast-southwest trending normal faults with throws rarely exceeding 40 feet cut the Lost Hills structure. These faults do not appear to effect production.

The stratigraphy at Lost Hills is shown in Figures 4 and 5. The Monterey Formation is comprised of the Devilwater Shale, McLure Shale and Reef Ridge members. The Devilwater consists of shales and siliceous shales. It is slightly phosphatic. The McLure is subdivided into the McDonald Shale and the Antelope Shale. The McDonald consists of interbedded porcelanites and siliceous shales. It is also slightly phosphatic. The Antelope is comprised of finely laminated cherts and porcelanites. The uppermost member of the Monterey Formation is the Reef Ridge and it is subdivided into the Brown Shale and Belridge Diatomite. The Brown Shale is made up of interbedded siliceous shales, shales and silts. The Belridge Diatomite consists of interbedded diatomaceous mudstones, siltstones, and fine-grained sandstones.

Based on studies of late Miocene paleogeography and paleobathymetry, the rocks of the Monterey Formation were deposited in a deep marine environment. In the San Joaquin Basin, the late Miocene environment was such that: water depths were bathyal (between 600 and 3000 feet), cool water temperatures and upwelling in the upper 200 feet supported large diatom populations, and the deeper basin waters were oxygen poor. Two primary sedimentation processes were active in the basin at that time. First, hemipelagic sedimentation: the settling of diatom frustules and clay-sized particles onto the basin floor from the overlying water column. And second, turbidite sedimentation: the deposition of sand, silt, and clay-sized particles carried into the basin by density currents (usually originating along the basin margins).

This combination of environmental conditions and sedimentation processes led to the accumulation of thick deposits of organic-rich, laminated, diatomaceous sediments which occasionally are interrupted by thin-bedded, clastic-rich turbidite deposits. However, compared to the southwestern San Joaquin Basin, sandy turbidites at Lost Hills are not common. (The Monterey Formation in the San Joaquin Basin differs from the coastal and offshore Monterey in that it is much more clastic rich)

The composition of the Monterey rocks can be described in terms of three primary components: 1) biogenic silica, 2) clay, and 3) silt/sand. As shown in Table 1, there is a fair amount of vertical compositional variation within the stratigraphic column at Lost Hills. The Devilwater contains 27% biogenic silica, 50% clay, and 23% silt/sand. The McDonald is slightly richer in biogenic silica, roughly comparable in clay, and a bit lower in silt/sand. The Antelope is very rich in biogenic silica, poor in clay, and poor in silt/sand. The Brown Shale is clay rich. The Belridge Diatomite has roughly equal amounts of biogenic silica, clay and silt/sand. The overlying Etchegoin Formation is rich in silt/sand and clay, and almost totally lacking in silica.

Rock Unit	Average. % Biogenic Silica	Average % Clay	Average % Silt/Sand	Number of Samples
Etchegoin	4	38	58	8
Belridge Diatomite	33	36	31	19
Brown Shale	26	47	27	28
Antelope Shale	61	18	21	14
McDonald Shale	34	47	19	24
Devilwater Shale	27	50	23	8

Table 1. Average rock compositions from Well 166, Section 32, T26S/R21E.

As hemipelagic and turbidite deposits built up in the Lost Hills area and were further buried by Etchegoin and Tulare sediments, the diatomaceous sediments of the Monterey Formation gradually lithified into the highly porous (50-60% or more) but impermeable (0.1-10.0 millidarcy) rock termed diatomite. As discussed above, anywhere from 26% to 61% of this diatomite was composed of diatom frustules. Diatom frustules consist of a form of silica called Opal-A, which is an unstructured mineral (essentially a solidified gel) usually containing 3-10% water. As this diatomite is buried deeper and reaches greater temperatures (40-50 degrees C), the Opal-A material in the diatom frustule becomes unstable and undergoes a phase transition to Opal-CT (Figures 6-8). This form of silica is more structured than Opal-A and has released much of its water. Porosity is reduced to ~40%. At still greater depths and higher temperatures (80-90 degrees C), the Opal-CT undergoes a final phase transition to a form of quartz with only a trace of water left. The Monterey Formation at Lost Hills is presently comprised of Opal-A rocks at shallow depths ($\pm$ 2300 feet or shallower), Opal-CT rocks at intermediate depths ($\pm$2300 to $\pm$ 4300 feet), and quartz phase rocks below $\pm$ 4300 feet.

The exact temperatures at which the Opal-A to Opal-CT and Opal-CT to Quartz phase changes occur is governed by the amount of biogenic silica (diatoms) in the rock. Opal-A rocks rich in biogenic silica convert to Opal-CT at lower temperatures (and therefore shallower depths) than those poor in biogenic silica. Conversely, Opal-CT rocks rich in biogenic silica convert to Quartz phase at higher temperatures (and greater depths) than those poor in biogenic silica. For this reason, an interval of rocks whose laminations vary in their biogenic silica content create a transition zone of laminated phases near the phase transition temperature. The laminated phases in these transition zones (particularly where the laminae are thin) may be especially susceptible to natural fracturing, thereby enhancing system permeability. Also, volume reduction and water release associated with the phase changes probably adds to the fracturing in these zones. In general, hydrocarbons are found in all three (Opal-A, Opal-CT, and Quartz) phases. Also production is enhanced in the Opal-A to Opal-CT and, in particular, the Opal-CT to Quartz phase transition zones.

Geochemical analyses have demonstrated that Monterey Formation rocks in Lost Hills are typically composed of 1% to 6% total organics, making them fair to good hydrocarbon source rocks. Studies of kerogen maturation have shown that the Monterey rocks are immature (i.e. they have not been buried deep enough to generate oil) within the confines of the Lost Hills Field. However, studies of samples taken from down-flank wells indicate that these rocks are mostly mature in the syncline to the east of Lost Hills and possibly below the ramp thrust immediately beneath the Lost Hills Anticline. Because the Monterey Formation kerogens and the produced oils at Lost Hills have similar isotopic compositions, and because they contain similar concentrations of sulfur, it is believed that Lost Hills oil was sourced from the Monterey Formation itself.

Hydrocarbons migrated into the low permeability Monterey rocks at Lost Hills by way of faults, fractures and thin sands. Also the Opal-A to Opal-CT and Opal-CT to Quartz phase transition zones with their higher fracture density probably served as pathways for hydrocarbons to migrate from source beds down-structure to their ultimate resting place in the crest of the anticline.

In the McDonald Shale and Lower Brown Shale/Antelope Shale pools, hydrocarbons are confined fairly well within or immediately below the fractured Opal-CT to Quartz phase transition rocks. In the Upper Brown Shale, minor fracturing also helps to make it productive. Because the McDonald, Antelope, and Brown shales have such low matrix permeability, most of the oil produced from these rocks comes out of the fractures. In the Belridge Diatomite with its relatively higher matrix permeability, hydrocarbons have saturated the uppermost Opal-CT, the Opal-A to Opal-CT transition, and most of the Opal-A rocks. Most of the oil produced from the diatomite comes from the matrix. Lastly, some oil has even migrated into the overlying Etchegoin and Tulare Formations.

The target reservoir for the CO_2 pilot in Lost Hills is the Belridge Diatomite (Figure 9). In the pilot area, the diatomite is in Opal-A phase. The lower half of the Belridge Diatomite is comprised of approximately equal parts of biogenic silica (diatoms), silt/sand, and clay while the upper half is comprised mainly of silt/sand and clay. The diatomite is finely laminated. In general these laminations alternate between a more detritus rich lamina and a more diatomaceous rich lamina. The laminations reflect cyclic variations in yearly runoff (detritus rich) and upwelling (diatomaceous rich).

Superimposed on this depositional cycling are the changes in relative sea level that occurred in the Upper Miocene. As sea level rose, diatomaceous rich deposits were deposited further up on the slope. As sea level fell, sandy diatomite deposits prograded down the slope. These fluctuations in sea level caused the larger scale deposition of sedimentary packages of diatomite and sandy diatomite. The diatomites were deposited under oxygen poor to anoxic conditions that could sustain only a limited sediment-dwelling fauna. Thus laminations are preserved in the diatomites. Meanwhile sandy diatomites were deposited under oxygen poor to oxygenated conditions and are heavily bioturbated. Lastly, superimposed on the sea level changes was the overall progradation of the shelf, which resulted in the coarsening upward of the Belridge Diatomite, and the eventual filling in of the basin in the Pliocene.

As described above, the Belridge Diatomite is comprised of varying amounts of diatomaceous material, clay and silt/sand. In Lost Hills, the Belridge Diatomite ranges in depth from 800 to 3,000 feet. Oil gravity ranges from 28 to 18 degrees API. Although porosity is very high (40 - 65%), permeability is very low (<1 – 10 millidarcies). Oil saturation ranges from 40% to 65% in Opal-A and from 10% to 30% in Opal CT (Table

2). There are over 2 billion barrels of oil in place in the Belridge Diatomite in Lost Hills. To date only 120 million barrels have been produced.

Parameter	Lost Hills Pilot	Buena Vista Hills Pilot
Rock Unit	Belridge Diatomite	Upper Antelope Shale
Age	Uppermost Miocene	Upper Miocene
Depositional Environment	Hemipelagic-Turbidite; Slope-Basin	Hemipelagic-Turbidite; Basin
Rock Type	Diatomaceous Mudstone	Siliceous Shale
Silica Phase	Opal-A	Opal-CT
Percent Sand Beds	30%	5%
Sand Description	5-60 feet thick, fine-grained, argillaceous, bioturbated	<1 inch thick, fine-grained, non-bioturbated
Depth to Top of Unit	1,400 feet	4,200 feet
Thickness	700 feet	600 feet
Porosity	50%	29%
Permeability	0.1 – 10.0 millidarcies	<0.1 millidarcies
Oil Saturation	50%	14%

Table 2. Comparison of rock types at the newly proposed pilot location (Lost Hills) and the original location (Buena Vista Hills).

Development of the Lost Hills Field has evolved over the years. From 1910 to the late 1970's, slotted liner completions were used in the upper Belridge Diatomite. From the late 1970's to 1987, small volume hydrofrac completions were performed covering the entire Belridge Diatomite. From 1987 to the present, high volume hydrofrac completions have been performed across the entire Belridge Diatomite and the Upper Brown Shale. Since 1992 a portion of the diatomite has been under waterflood, and in 1998 a pilot steam-drive was started. The Lost Hills Field is developed on a 5 acre (siliceous shale) to 1.25 acre (diatomite) well spacing.

Technology Transfer

4^{th} Quarter:

Tang, R. W., Zhou, D., Beeson, D. Ulrich, R. L., and Morea, M. F., 1998, Immiscible CO2 Floods in Low Permeability Reservoirs,International Energy Agency, Collaborative Project on Enhanced Oil Recovery, 19th Workshop and Symposium, Carmel, CA.

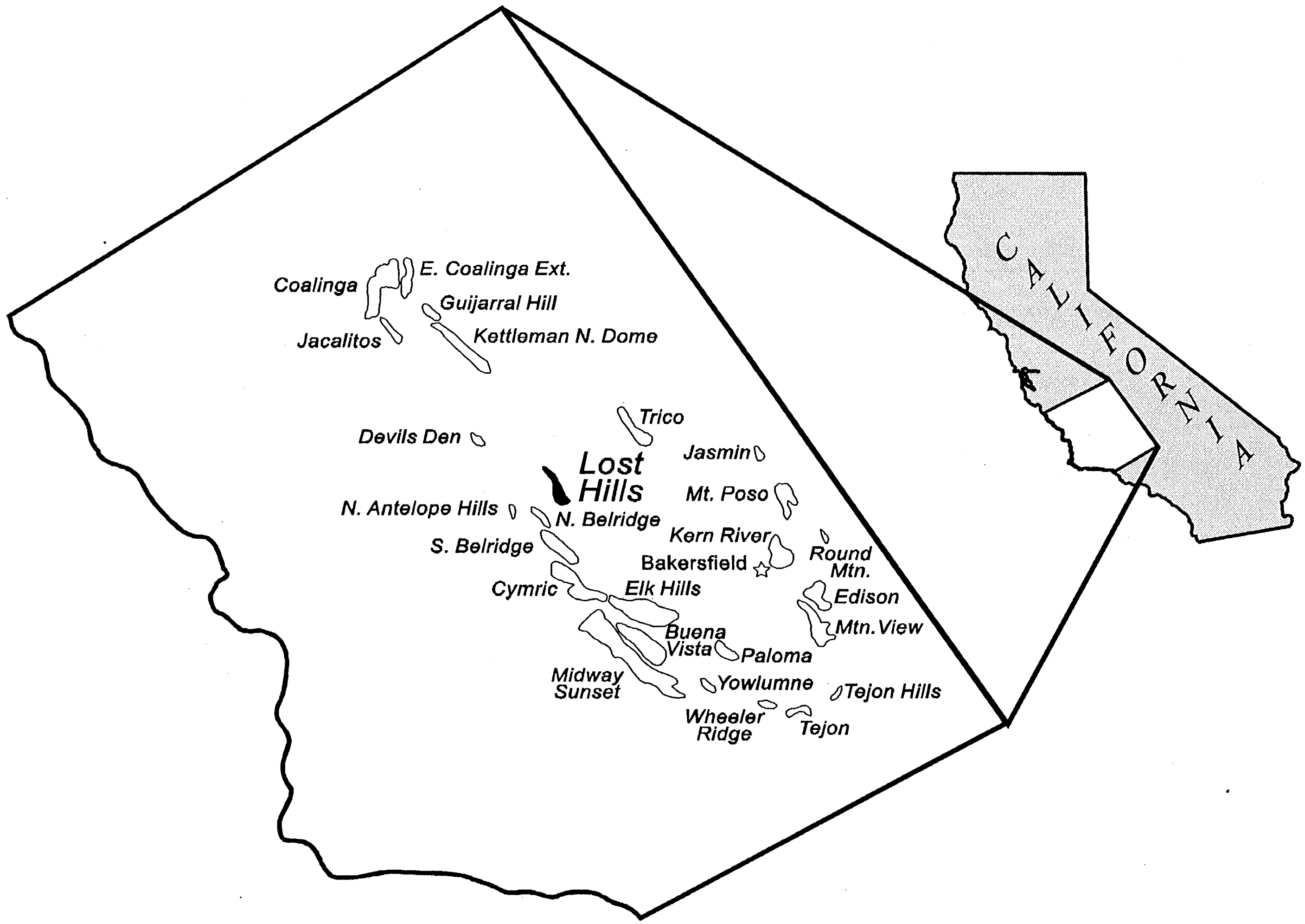

Figure 1. Location Map of major oil fields in the southern San Joaquin Valley. Lost Hills Field is highlighted.

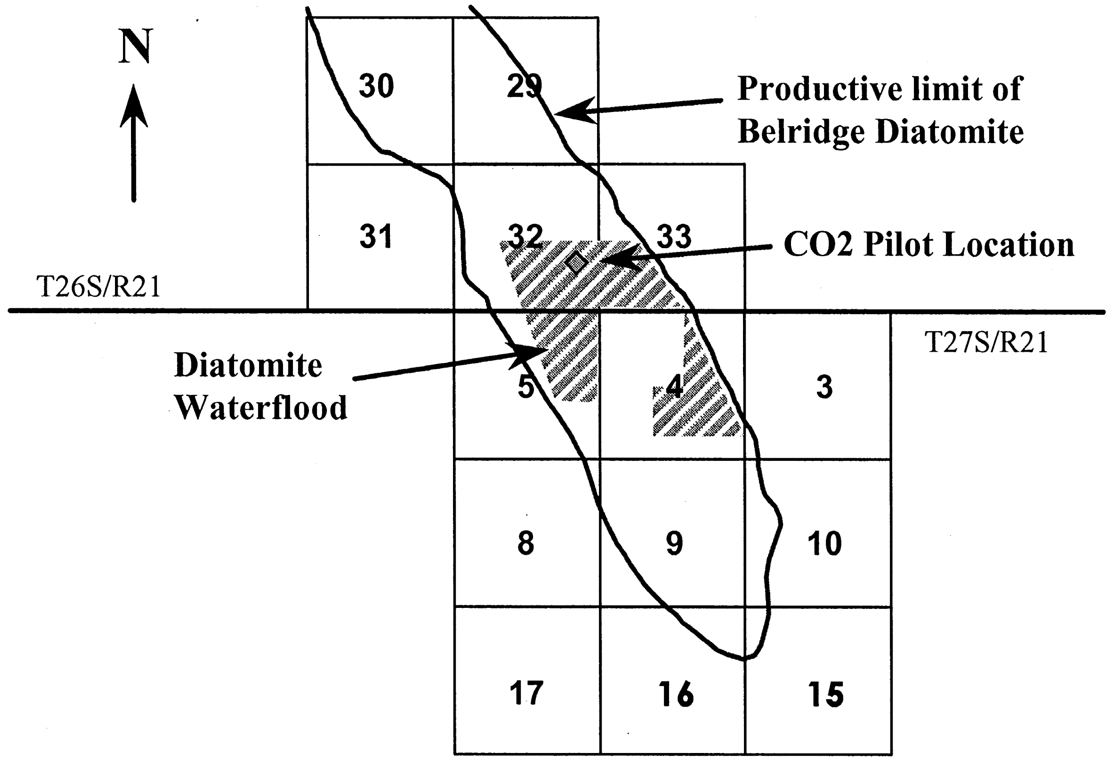

Figure 2. Productive limits of Belridge Diatomite follows trend of southeast plunge of the Lost Hills Anticline.

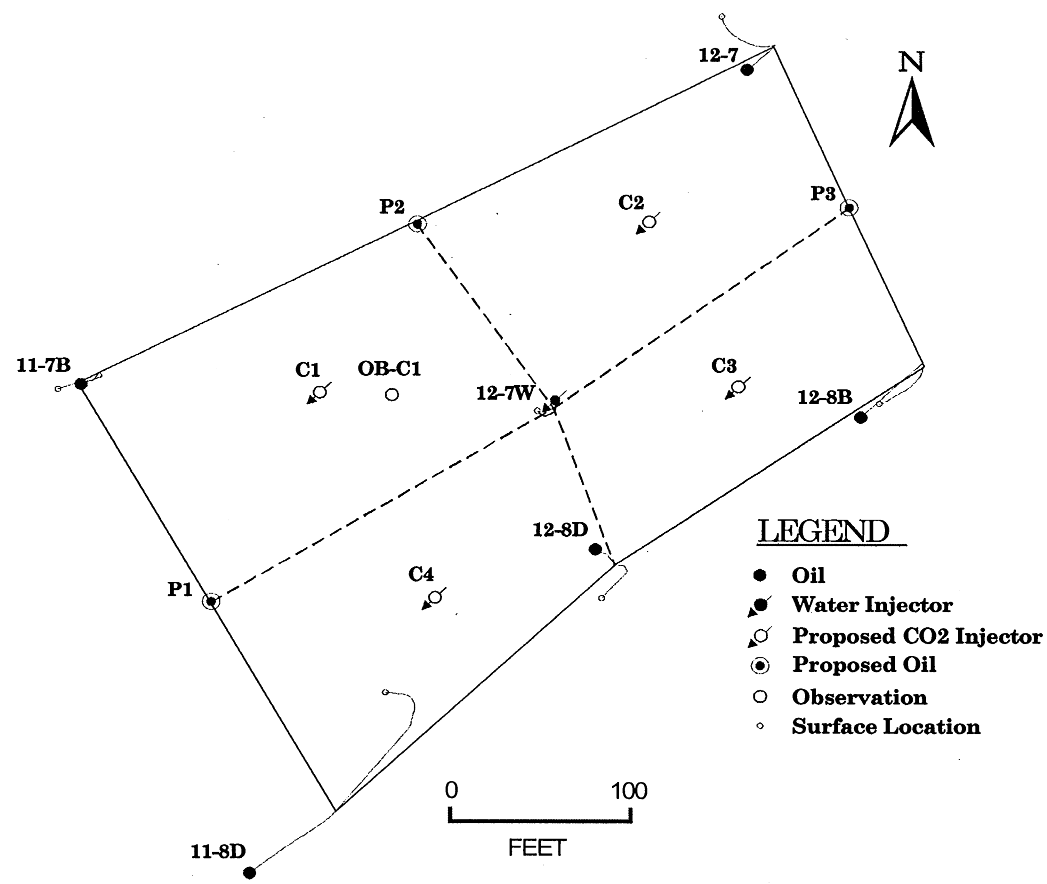

Figure 3. Lost Hills CO2 Pilot base map. The planned CO2 injectivity test on a non-hydraulically fractured well will be performed on well 12-8D. An injectivity test will also be performed on an existing hydraulically propped fractured well, 12-7W.

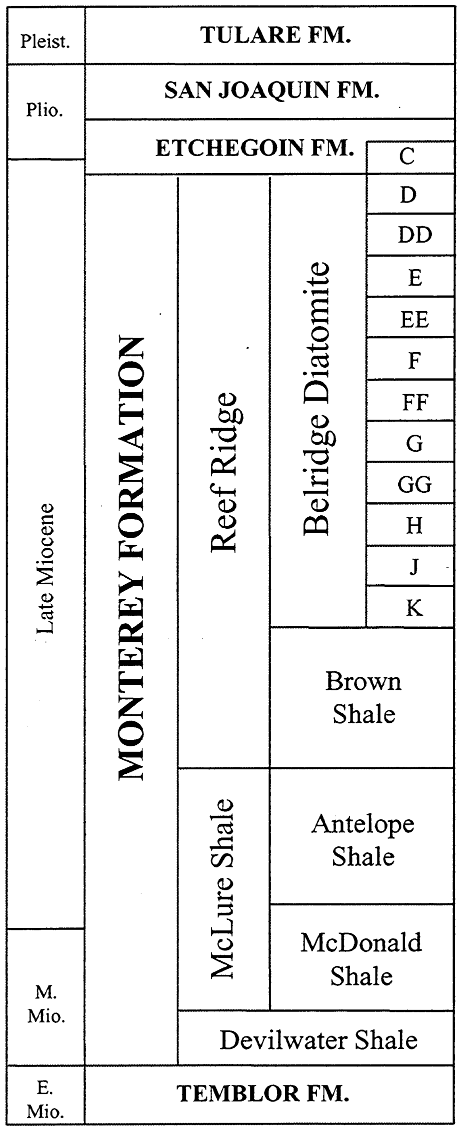

Figure 4. Lost Hills Stratigraphic Column.

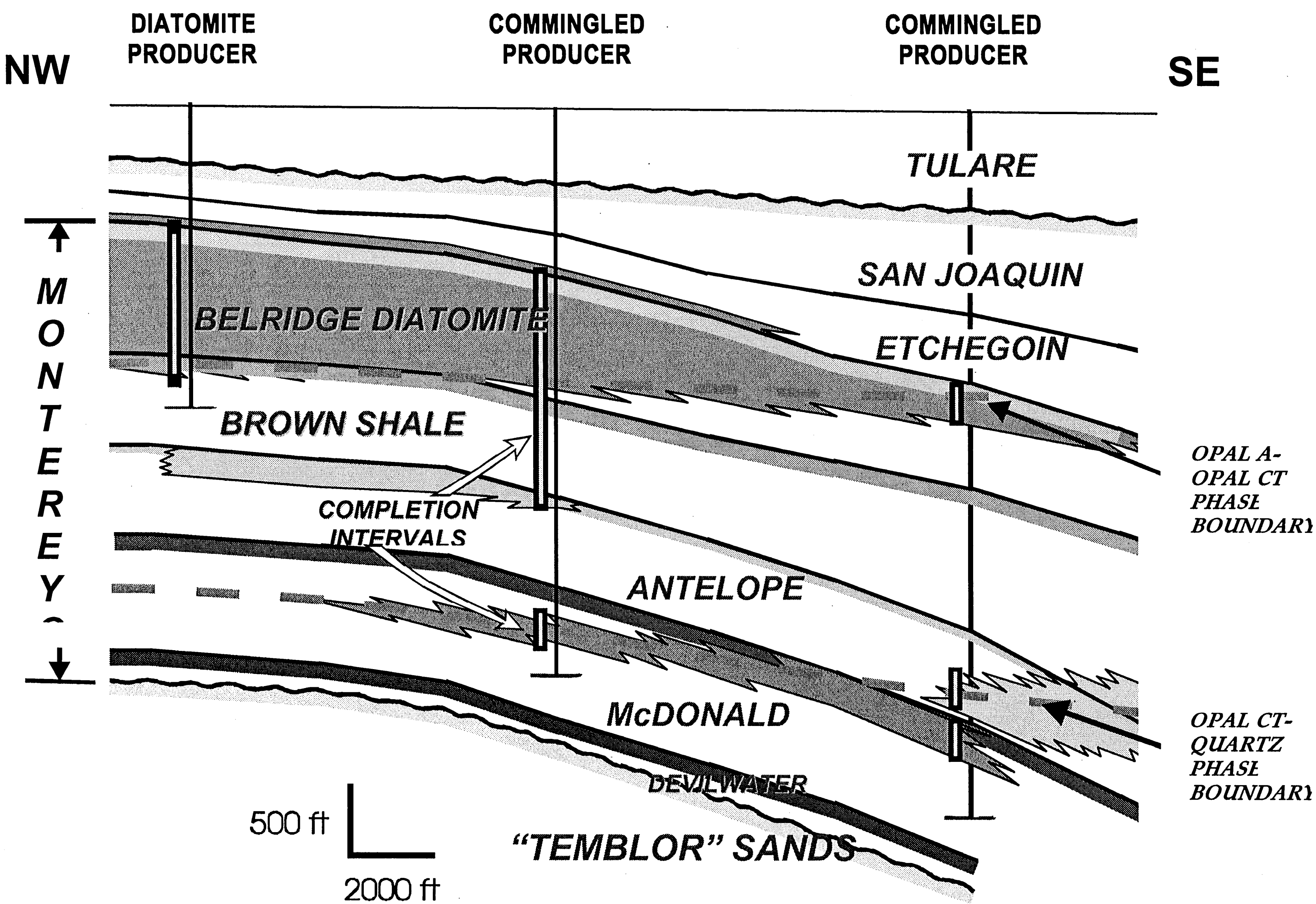

Figure 5. Generalized cross section along southeast plunge on Lost Hills. The Belridge Diatomite is the objective of the CO2 pilot project.

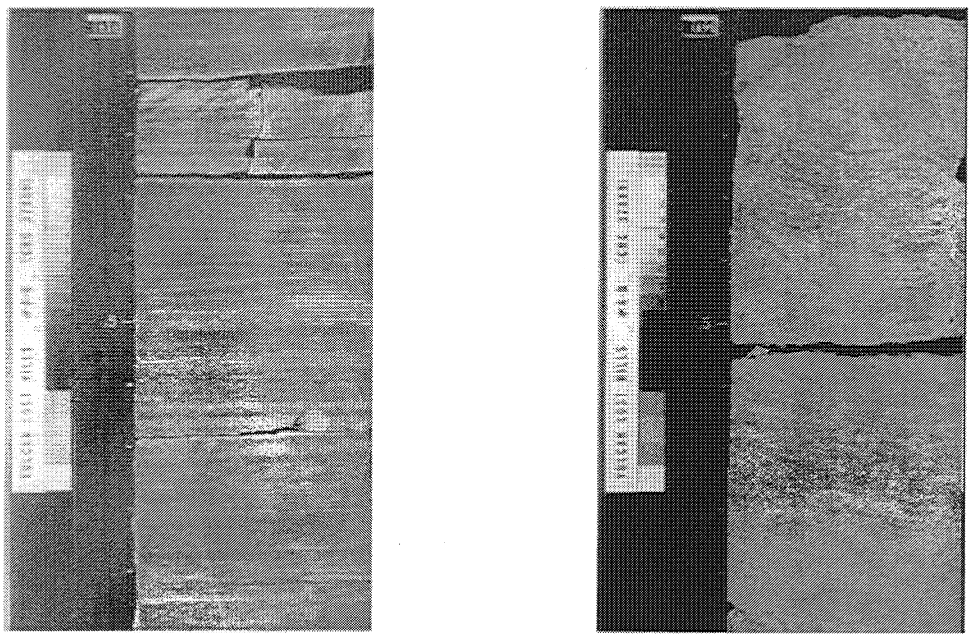

Figure 6. Slabbed core of laminated diatomite (left), and bioturbated sandy diatomite (right).

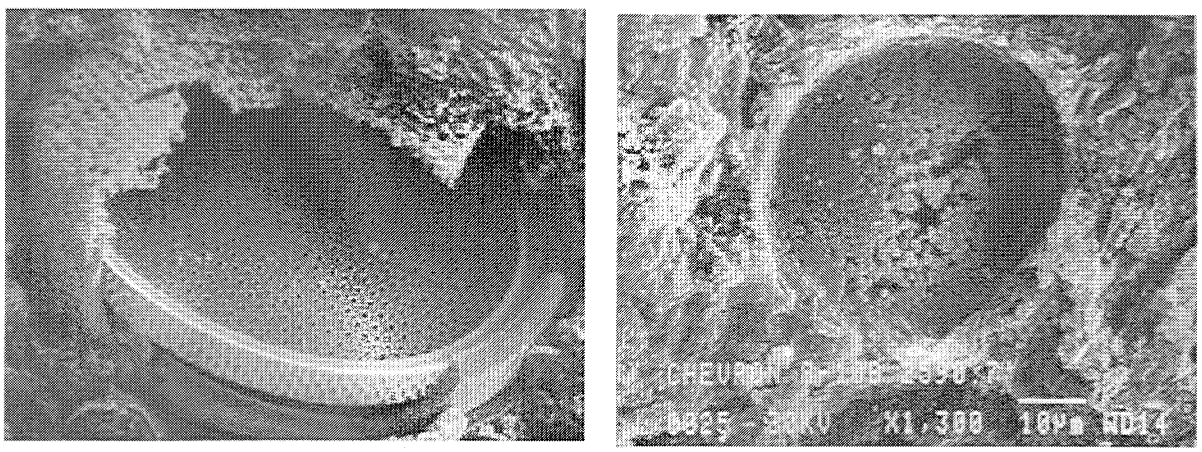

Figure 7. SEM photomicrographs of Opal-A frustule starting to convert to Opal-CT (left), and frustule converted to Opal-CT (right). 1,300X magnification.

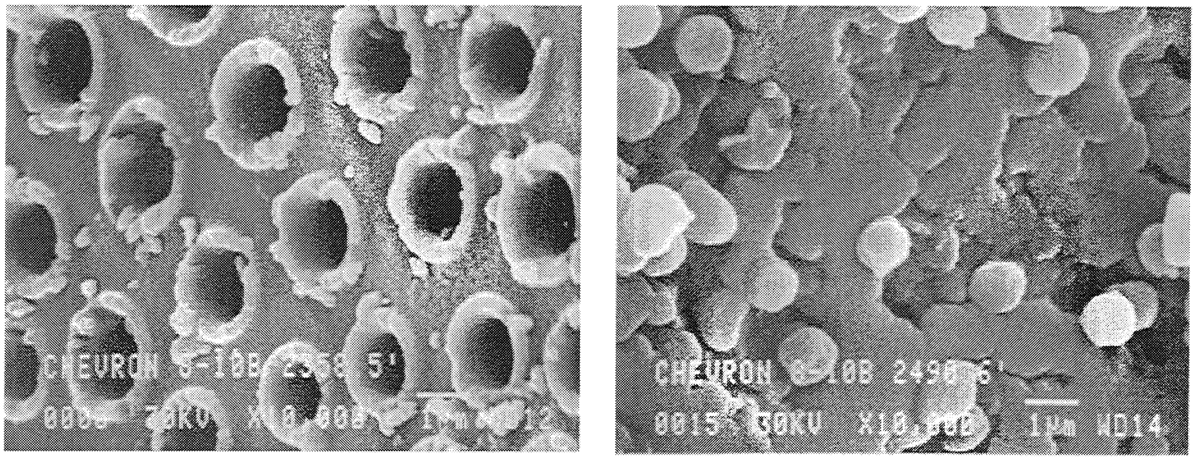

Figure 8. Opal-A frustule initiating conversion to Opal-CT (left), and a frustule after its conversion to Opal-CT. SEM photomicrographs, 10,000X magnification.

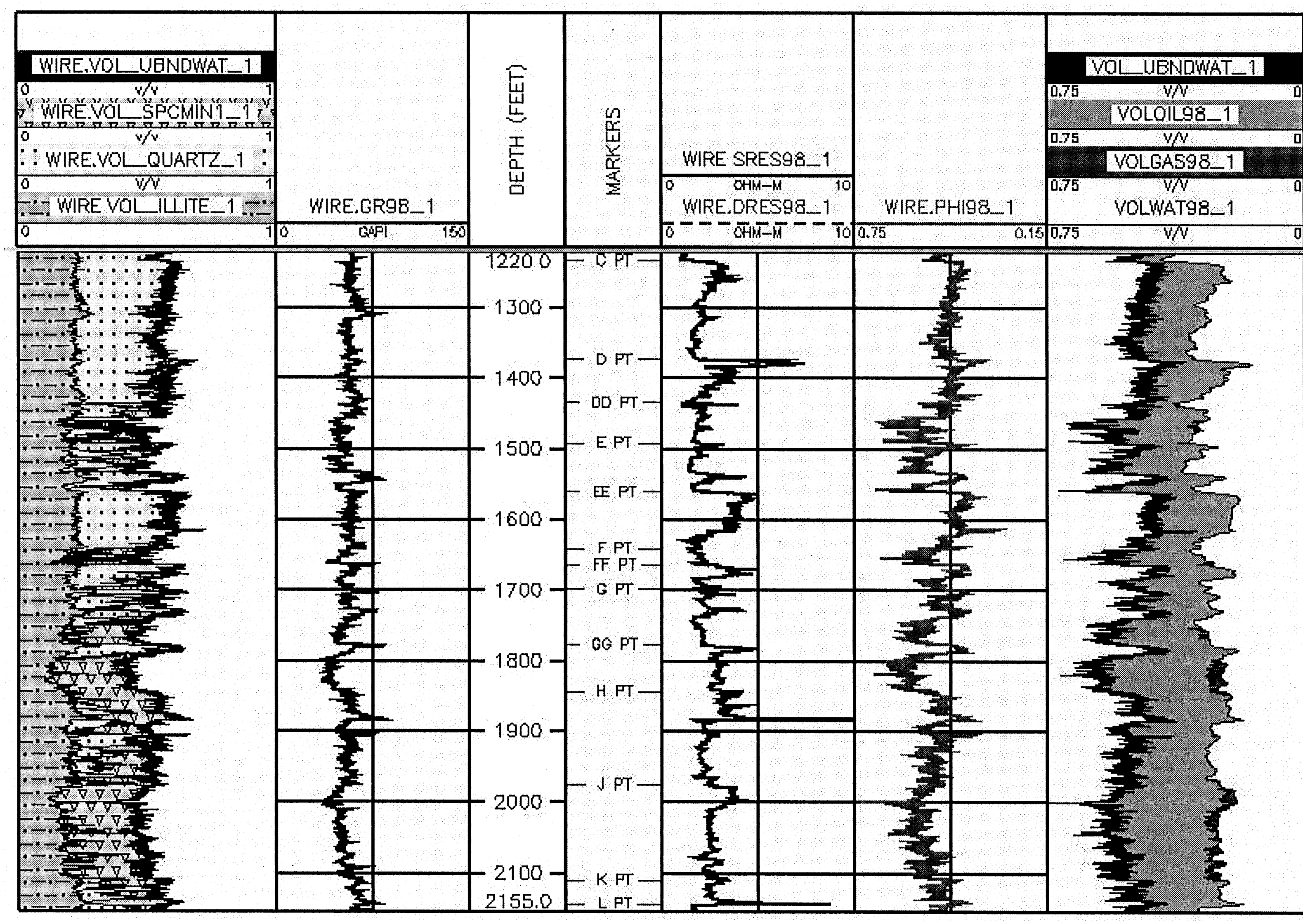

Figure 9. Type log (12-7W) of Belridge Diatomite in the Lost Hills pilot location.