

***QUANTITATIVE METHODS FOR RESERVOIR CHARACTERIZATION
AND IMPROVED RECOVERY: APPLICATION TO HEAVY OIL SANDS***

FINAL REPORT

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ABSTRACT

Improved prediction of interwell reservoir heterogeneity has the potential to increase productivity and to reduce recovery cost for California's heavy oil sands, which contain approximately 2.3 billion barrels of remaining reserves in the Temblor Formation and in other formations of the San Joaquin Valley. This investigation involves application of advanced analytical property-distribution methods conditioned to continuous outcrop control for improved reservoir characterization and simulation, particularly in heavy oil sands. The investigation was performed in collaboration with Chevron Production Company U.S.A. as an industrial partner, and incorporates data from the Temblor Formation in Chevron's West Coalinga Field.

Observations of lateral variability and vertical sequences observed in Temblor Formation outcrops has led to a better understanding of reservoir geology in West Coalinga Field. Based on the characteristics of stratigraphic bounding surfaces in the outcrops, these surfaces were identified in the subsurface using cores and logs. The bounding surfaces were mapped and then used as reference horizons in the reservoir modeling. Facies groups and facies tracts were recognized from outcrops and cores of the Temblor Formation and were applied to defining the stratigraphic framework and facies architecture for building 3D geological models. The following facies tracts were recognized: incised valley, estuarine, tide- to wave-dominated shoreline, diatomite, and subtidal.

A new minipermeameter probe, which has important advantages over previous methods of measuring outcrop permeability, was developed during this project. The device, which measures permeability at the distal end of a small drillhole, avoids surface weathering effects and provides a superior seal compared with previous methods for measuring outcrop permeability. The new probe was used successfully for obtaining a high-quality permeability data set from an outcrop in southern Utah.

Results obtained from analyzing the fractal structure of permeability data collected from the southern Utah outcrop and from core permeability data provided by Chevron from West Coalinga Field were used in distributing permeability values in 3D reservoir models. Spectral analyses and the Double Trace Moment method (Lavalley et al., 1991) were used to analyze the scaling and multifractality of permeability data from cores from West Coalinga Field.

T2VOC, which is a numerical flow simulator capable of modeling multiphase, multi-component, nonisothermal flow, was used to model steam injection and oil production for a portion of section 36D in West Coalinga Field. The layer structure and permeability distributions of different models, including facies group, facies tract, and fractal permeability models, were incorporated into the numerical flow simulator. The injection and production histories of wells in the study area were modeled, including shutdowns and the occasional conversion of production wells to steam injection wells. The framework provided by facies groups provides a more realistic representation of the reservoir conditions than facies tracts, which is revealed by a comparison of the history-matching for the oil production. Permeability distributions obtained using the fractal results predict the high degree of heterogeneity within the reservoir sands of West Coalinga Field. The modeling results indicate that predictions of oil production are strongly influenced by the geologic framework and by the boundary conditions.

The permeability data collected from the southern Utah outcrop, support a new concept for representing natural heterogeneity, which is called the fractal/facies concept. This hypothesis is one of the few potentially simplifying concepts to emerge from recent studies of geological heterogeneity. Further

investigation of this concept should be done to more fully apply fractal analysis to reservoir modeling and simulation. Additional outcrop permeability data sets and further analysis of the data from distinct facies will be needed in order to fully develop this new concept.

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RESULTS AND DISCUSSION

Geological Characterization of the Temblor Formation

Outcrops on the Coalinga Anticline

Detailed investigation of outcrop exposures of the Temblor Formation on the Coalinga Anticline was conducted in order to record vertical and lateral facies variations, identify correlative surfaces, and interpret depositional environments (Figures 1, 2). Twelve vertical sections were measured, and the sedimentary features were described in detail (Table 1). The majority of the exposures studied are located in close proximity within sections 20 and 21, T19S, R15E (Domengine Ranch 7.5' quadrangle). Approximately 700 m (2,300 feet) of vertical section were measured and described.

Sedimentological description of the exposures included logging of grain size, percent sand, biogenic features, and sedimentary structures. Complete gamma-ray profiles were recorded for each section using a hand-held scintillometer. Gamma-ray values were recorded at 15-cm intervals. All gamma-ray data have been loaded into a digital database. Digital photomosaics of the exposures were made.

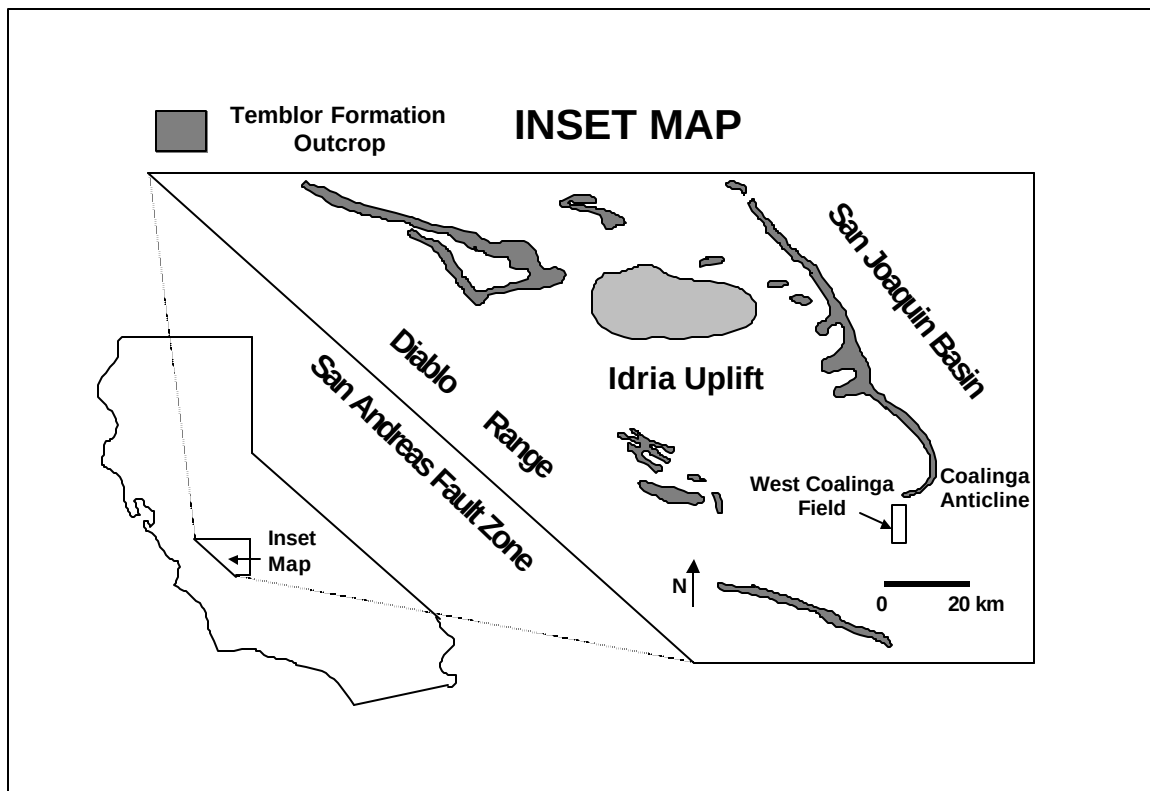


Figure 1. Location map of the Coalinga area, California.

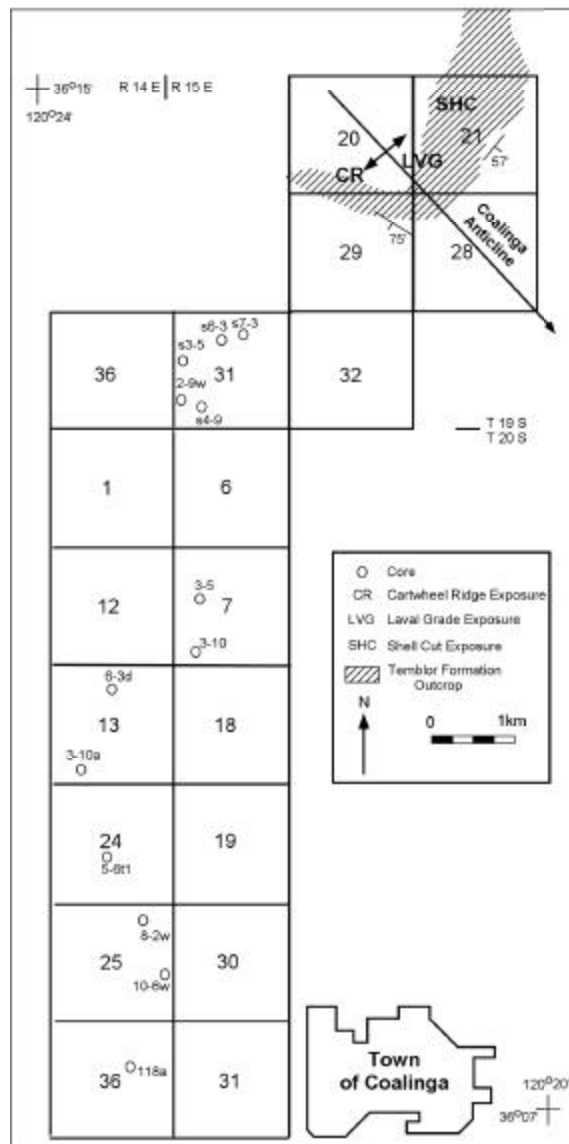


Table 1. Outcrop localities of the Temblor Formation studied near Coalinga Field.

Locality	Stratigraphic Interval	Location – UTM	Location – Section, Township, Range	Thickness Logged (m)
Cartwheel Ridge	Temblor	4015500mN/ 737500mE	SEC. 20, T19S, R15E	154
Razorback Ridge	lower Temblor	4015200mN/ 737550mE	SEC. 20, T19S, R15E	70
Side Cliff of Laval Grade	middle Temblor	4015250mN/ 737570mE	SEC. 20, T19S, R15E	12
Laval Grade 1 with middle Gully Cut	Temblor to Diatomite	4016000mN/ 738000mE	SEC. 21, T19S, R15E	119
Laval Grade 2 with Southmost Gully Cut	Temblor to Diatomite	4015900mN/ 738000mE	SEC. 21, T19S, R15E	118
Laval Grade 3	middle Temblor	4016100mN/ 738000mE	SEC. 21, T19S, R15E	22
Shell Cut 1	lower Temblor	4016200mN/ 738150mE	SEC. 21, T19S, R15E	15
Shell Cut 2	lower Temblor	4016200mN/ 738150mE	SEC. 21, T19S, R15E	31
Shell Cut 3	lower Temblor to C-sand	4016150mN/ 738300mE	SEC. 21, T19S, R15E	89
Shell Cut 4	lower Temblor	4016200mN/ 738000mE	SEC. 21, T19S, R15E	19
Big Tar Canyon	middle and upper Temblor	3980000mN/ 755890mE	SEC. 18, T23S, R17E	34
North Gully Cut	lower Temblor	4016000mN/ 737850mE	SEC. 21, T19S, R15E	23
			TOTAL	706

Cores from West Coalinga Field

The collection and loading of property data from Temblor reservoir sands in West Coalinga Field focused on two phases:

- 1) Detailed description of cores and comparison to geophysical logs; and
- 2) Quality control and loading of digital core-analysis data.

Both phases were completed in close collaboration with Chevron, with Chevron providing core-analysis data, core descriptions produced by their geologists, use of core photographs, facilities for core examination, and manpower support for core layout and preparation.

Approximately 1360 m (4,462 feet) of cores from 13 wells in Coalinga Field were described by Clemson University personnel (Table 2, Figure 2). Description included logging the same features and using the same format as followed for the outcrop work. Grain size, percent sand, biogenic features, and

sedimentary structures were logged. In addition, notations of Chevron's facies classification and degree of oil staining were recorded. In order to facilitate integration of outcrop results with subsurface information from Coalinga Field, five of the thirteen cores described are from the northern part of the oil field, which is nearest to the surface exposures. All of the cores were provided by Chevron, and the work was preformed at the Chevron Geologic Warehouse in Richmond, California.

Working collaboratively with Chevron personnel, core-analysis (i.e., porosity and permeability) data were loaded into a digital database (Excel spreadsheets). Prior to loading, data were examined for quality control, and depths were adjusted to match geophysical logs. Quality control work was done by Chevron personnel and by Clemson personnel working closely with Chevron. All wells with cores described and core-analysis data are listed in Table 3.

To develop predictions of flow barriers and subsurface geometries, geological and petrophysical characteristics were compared between outcrops and cores. Using porosity, permeability, and saturation data provided by Chevron, petrophysical data were compared to lithofacies and depositional environments of the Temblor Formation. Analysis included identification of statistical trends for individual depositional environments and within groups of lithofacies to integrate petrophysical properties with geometries of depositional bodies. Statistical analyses of the Coalinga core data were performed using SPSS (Statistical Package for the Social Sciences) software. Statistical methods include cluster analysis of fifteen lithofacies using permeability, porosity, sorting, grain size, and percent sand data. Dendrograms produced from the cluster analysis and frequency-distribution histograms were examined. Lithofacies determined to have similar characteristics were grouped into five sets (Table 4).

Table 2. Cores described from West Coalinga Field.

Well	Location (Section)	Meters
S6-3	31A	37
3-10A	13D	90
S3-5	31A	111
5-6T1	24D	98
3-5	7C	170
S7-3	31A	173
3-10	7C	174
118A	36D	56
6-3D	13D	128
S4-9	31A	79
10-6W	25D	58
2-9W	31A	70
8-2W	25D	117
	TOTAL	1,361

Table 3. Summary listing of core descriptions and core-analysis data from West Coalinga Field. The cores described by Clemson University personnel are listed in Table 2. Chevron personnel described the remaining cores.

Well	Location (Section)	Core Analysis Data	Core Description
6-6a	12D	X	
S10-7	31A	X	
12-4A	12D	X	
3-5	7C	X	X
S3-5	31A	X	X
118A	36D	X	X
2-9W	31A	X	X
3-10A	13D	X	X
S-6-3	31A	X	X
S4-9	31A	X	X
3-10	7C	X	X
5-5W	31A		
1-7T1	31A		
6-3D	13D	X	X
11-5A	13D		
S7-3	31A		X
10-6W	25D		X
5-6T1	24D		X
8-2W	25D	X	X
132A	36D	X	X
258A	36D	X	X
9-1A	36D	X	X
5-7T1	25D	X	X
4-15	24D	X	
9-4T1	13D	X	X
WD-8	18C	X	X
57	18C	X	X
65	18C	X	X
6-11A	6C	X	X
2-10	6C	X	X

Table 4. Lithofacies and lithofacies groups recognized in the Temblor Formation, West Coalinga Field.

LITHOFACIES DESCRIPTIONS			
Lithofacies	Descriptions	Group Number	Mean Permeability (darcies)
Pebbly Sand (PS)	Pebble conglomerate, coarse sand to cobbles, poorly sorted; trough cross-bedding, sand matrix with intraclasts; white to gray, to blue-gray color	1	3.35
Crossbedded Sand (XS)	Very fine to medium sand, moderate sorting; planar-tabular to trough crossbeds; white to gray color	1	3.2
Clean Sand (CS)	Fine to coarse sand, well sorted; structureless; white to gray color	1	2.9
Interlaminated Sand and Clay (ISC)	Very fine to fine sand with interlaminated to interbedded clay; poor to well sorted; lenticular, ripple-cross lamination; clay drapes and mud couplets; gray to green, brown color	2	2.85
Bioturbated Sand (BS)	Massive coarse to granular sand, poorly sorted high clay percent; bioturbation and burrow structures (e.g., <i>Skolithos</i> , <i>Diplocraterion</i>); orange, yellow to gray color	4	2.6
Burrowed Clayey Sand (BCLS)	Fine to coarse sand, moderately sorted; high clay percent; massive to laminated; generally structureless burrowed (e.g. <i>Glossifungitis</i> , <i>Teichichnus</i>); green to gray, tan color	3	2.28
Burrowed Interlaminated Sand and Clay (BISC)	Very fine to fine sand with interlaminated clay, moderate sorting; burrowed (e.g. <i>Ophiomorpha</i> , <i>Teichichnus</i>); green to brown, tan color	3	2.0
Burrowed Sandy Clay (BSCl)	Clay with lenses of fine to medium sand; structureless to laminated; burrows (e.g. <i>Ophiomorpha</i> , <i>Diplocraterion</i>); green to gray, tan to yellow color	3	2.1
Silt (Si)	Silt; structureless with minor lamination; diatom content varies; brown to tan, white,	2	1.6
Sandy Clay (ScI)	Fine to medium sand with clay, poorly sorted; massive to laminated, with sand lenses; yellow to gray color	2	1.5
Clay (C)	Massive to laminated clay; ripple-cross lamination; friable; dark brown to light gray color	2	1.4
Burrowed Clay (BC)	Massive to laminated clay; burrow structures (e.g. <i>Glossifungitis</i> , <i>Teichichnus</i>); dark brown to light gray to green color	3	1.0
Fossiliferous Sand (FS)	Medium to granular sand, poorly sorted; minor bioturbation, abundant complete to disarticulated shells, minor phosphate; rare bone; minor glauconite; dolomite cement; orange to yellow color	5	1.0
Carbonate Cemented Zone (Ccz)	Limestone zones; fossils; dolomite cement; orange to yellow color	4	0.89
Diatomaceous Clay (DC)	Clay, silt, and fine sand; massive to laminated; abundant to rare diatoms, forams, radiolarians (e.g. 5-85%); may contain macrofossils; light gray to white color	none assigned	0.5

Sedimentological Analysis

Five facies tracts are recognized in the Temblor Formation: incised valley, estuarine, tide- to wave-dominated shoreline, diatomite, and subtidal (Bridges et al., 1999; Bridges, 2001; Bridges and Castle, 2001, 2002). Sedimentological characteristics of the facies tracts are illustrated by the outcrop and core descriptions in Figures 3 and 4. The facies tracts are separated by laterally correlative bounding surfaces (Figures 3, 4, and 5).

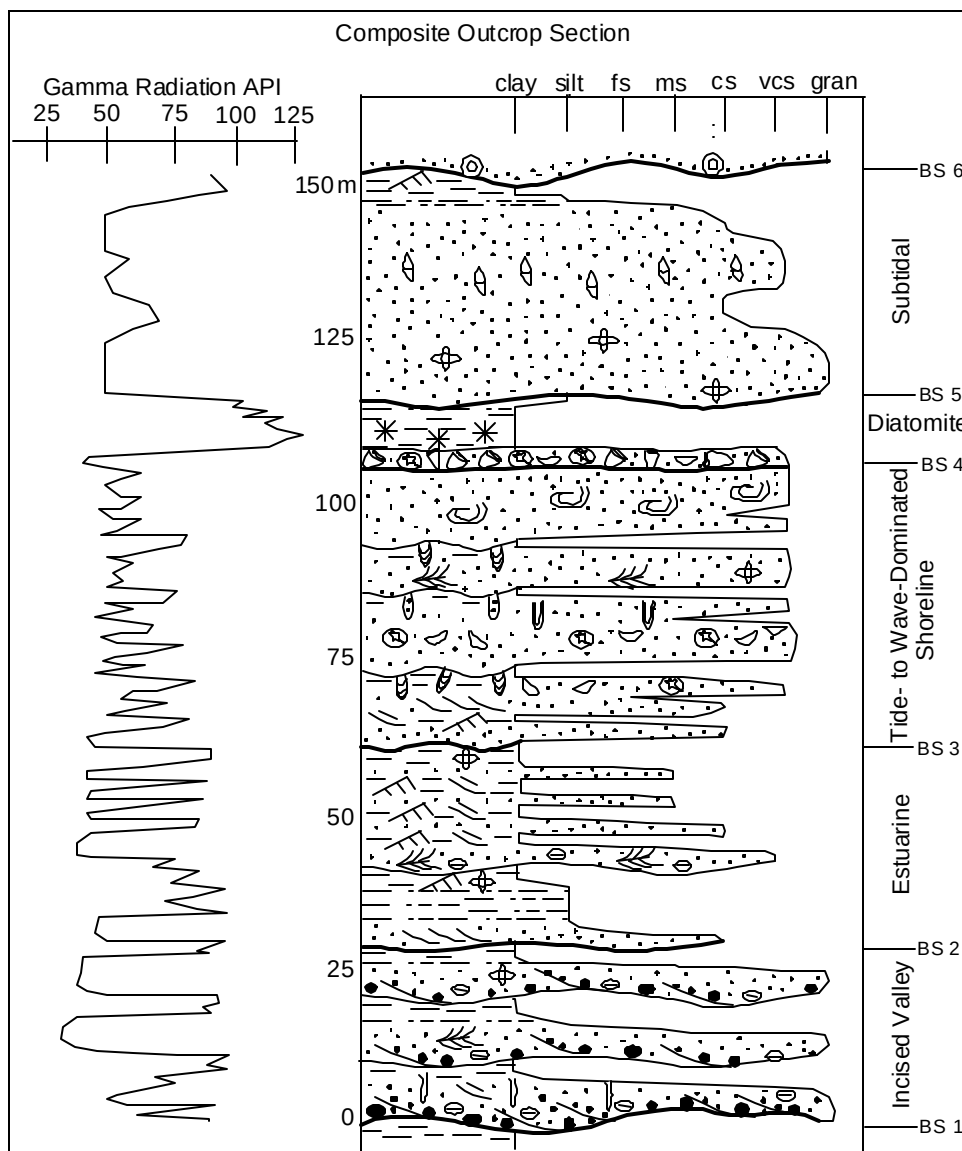


Figure 3. Outcrop description from Cartwheel Ridge to Laval Grade (see Figure 2 for location, Figure 5

for legend). The Temblor section is shown with Kreyenhagen Shale below 0 m and Santa Margarita Formation above 153 m. Symbols not to scale.

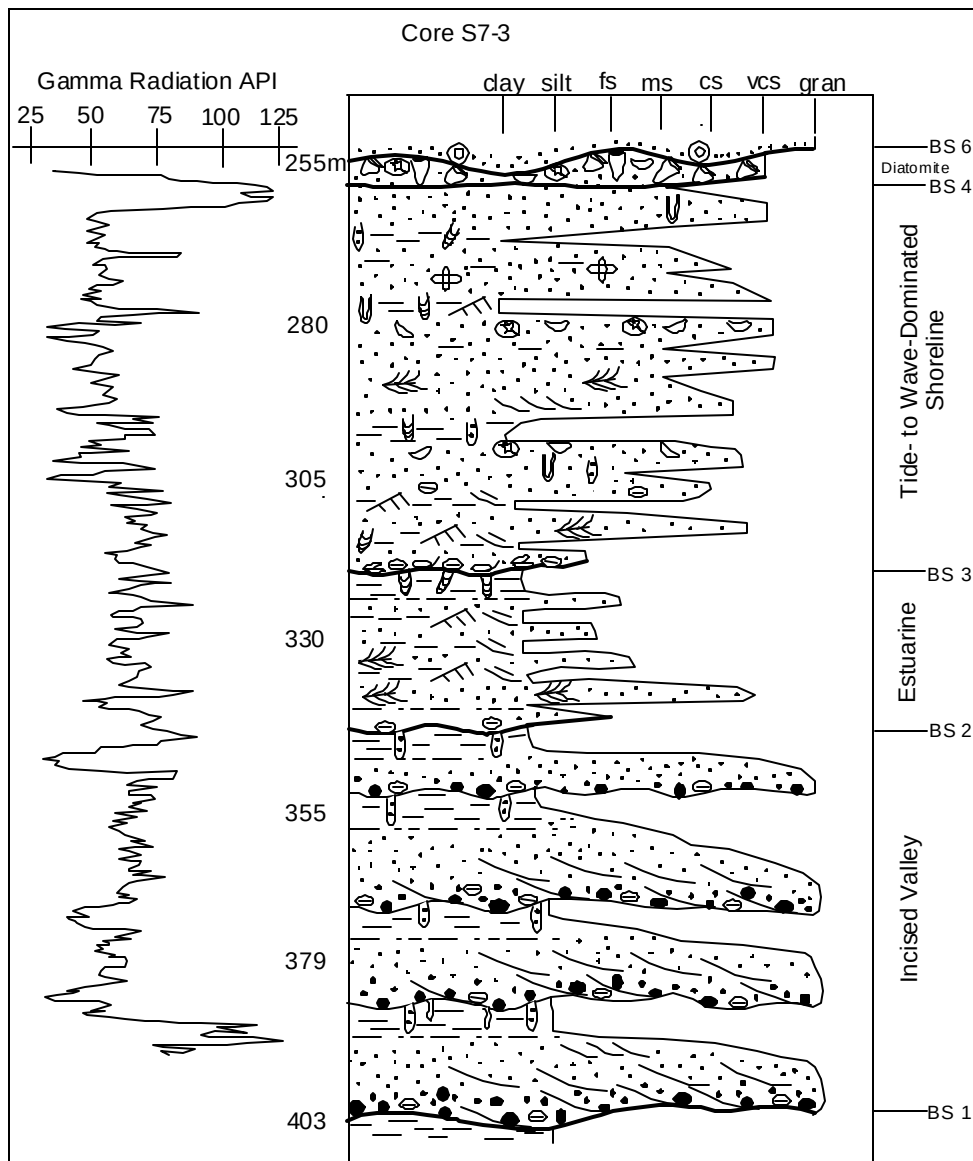


Figure 4. Core description from well S7-3 (see Figure 2 for location, Figure 5 for legend). The Temblor section is shown with Kreyenhagen Shale below 403 m and Santa Margarita Formation above 255 m. Symbols not to scale.

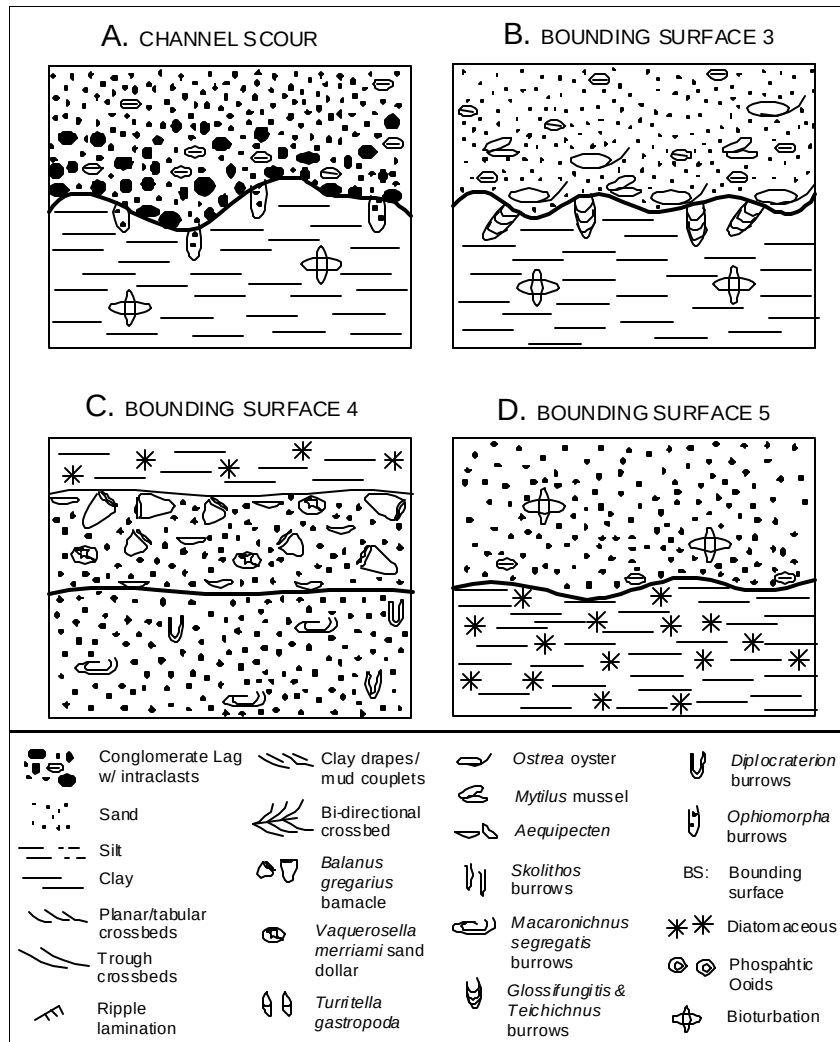


Figure 5. Bounding surfaces within the Temblor Formation. A) Typical channel scour within the incised-valley facies tract. These surfaces separate burrowed clay from 1 to 4 m of conglomerate to coarse sand. B) Bounding surface 3, which is the contact between the estuarine facies tract and the overlying tide- to wave-dominated shoreline facies tract. Note burrowed clay below and the *Ostrea* oyster bed above the bounding surface. C) Bounding surface 4, which separates the tide- to wave-dominated shoreline facies tract from the overlying diatomite facies tract. A barnacle bed, interpreted as a transgressive lag, occurs on the bounding surface. D) Bounding surface 5, which is the contact between the diatomite facies tract and the overlying subtidal facies tract.

Incised Valley

Description

The incised valley facies tract consists of predominantly poorly sorted sandstone and conglomerate above the lower unconformable contact of the Temblor Formation. Thickness of this facies tract reaches a maximum of 50 m and is highly variable due to irregularity of the lower contact, which displays up to 9 m of topographic relief in outcrop exposures. A 5- to 10-m thick interval of granule to cobble conglomerate commonly overlies the basal contact. Clasts in the conglomerate are composed of quartz, quartzite, serpentine, and volcanic rock, with quartz and feldspar dominant in medium- to coarse-grained sand matrix. Grains and clasts are angular to subrounded and poorly cemented. Lithology within the incised valley facies tract is laterally variable, and the facies tract was not recognized south of well S3-5.

Sandstone and conglomerate within this facies tract are commonly trough cross-bedded. Planar cross-beds become more common upward as grain size decreases to fine- and medium-grained sandstone. Current-ripple bedding is present in very fine grained sandstone, and common *Skolithos* and *Ophiomorpha* burrows occur in siltstone and claystone at the top of upward-fining intervals.

Interpretation

The vertical succession of grain size, occurrence of sedimentary structures, topographic incision, and lateral variability suggest that this facies tract represents deposition in incised valleys. Channel deposition is indicated by multiple, trough cross-bedded intervals that become finer grained upward above conglomeratic lag overlying a scoured base. Evidence of biological reworking or tidal processes is absent from the cross-bedded sandstones, suggesting predominantly non-marine (fluvial) channel deposition. Marine influence is recorded in siltstone and claystone at the top of each channel sequence by the occurrence of *Ophiomorpha* and *Skolithos* burrows.

Estuarine

Description

The incised valley facies tract is overlain by a 15- to 21-m thick interval of interlaminated to interbedded very fine to medium-grained sandstone, siltstone, and claystone that is interpreted as estuarine in origin. In outcrops the lower contact is recognized by interbedded fine-grained sandstone, siltstone, and burrowed claystone sharply overlying cross-bedded pebbly sandstone of the incised valley facies tract. South of well S3-5, where incised valley deposits are not present, the estuarine facies tract directly overlies the unconformable lower contact of the Temblor Formation (Figure 6). Maximum thickness of sandstone beds within the estuarine facies tract is approximately 3 m, and siltstone and claystone beds reach a thickness of 6 m. Both upward-fining intervals and upward coarsening intervals are present.

Sedimentary structures that occur commonly in sandstones of the estuarine facies tract include current-ripple cross lamination, flaser bedding, and tabular and bi-directional cross-beds. Common clay drapes and sand-mud couplets are present on cross-bed foresets. Beds of medium-

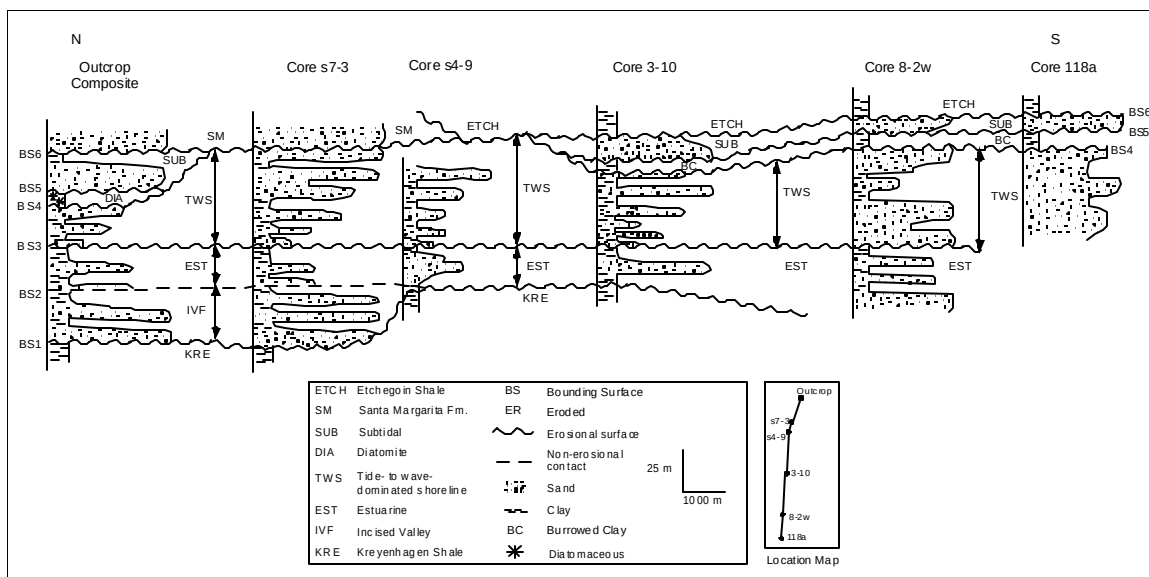


Figure 6. Cross-section showing lateral relationships of bounding surfaces and facies tracts. Datum is bounding surface 3.

grained sandstone with bi-directional cross-beds commonly alternate with intervals of fine- to medium-grained sandstone containing clay interlaminae, which commonly drape sand ripples. Minor desiccation cracks and minor root structures are present near the tops of claystone beds. Common lignite particles, wood fragments, and mud rip-up clasts are present in sandstone beds.

Interpretation

The presence of clay drapes and sand-mud couplets on foresets, along with bi-directional cross-bedding, suggests tidal influence. The occurrence of clay laminae with a systematic variation in vertical spacing from close together to farther apart suggests origin as tidal rhythmites. Similar features have been observed in modern tidal environments and in ancient strata interpreted as tidal in origin (e.g., Dalrymple et al., 1991; Nio and Yang, 1991). The combination of upward-fining sandstone and claystone sequences, basal scour surfaces, and tidal indicators suggests that deposition is likely to have occurred in estuarine channels, which is consistent with the previous studies of modern environments and ancient analogs.

Tide- to Wave-Dominated Shoreline

Description

Above a 0.5-m thick, oyster-bearing, fossiliferous sandstone bed directly overlying the estuarine facies tract, the proportion of sandstone beds to claystone beds gradually increases upward within the tide- to wave-dominated shoreline facies tract. Thickness of this facies tract ranges from 27 to 50 m. Sand grain size within the facies tract coarsens upward from very fine to coarse, and the grains are moderately to poorly sorted. Abundant mud rip-up clasts, rare glauconite grains, and rare to minor, dispersed quartzite granules and pebbles are present in the sandstone beds. Common sedimentary structures include planar and trough cross-bedding, clay drapes, sand-mud couplets on foresets, and current-ripple bedding. Bi-directional cross-bedding occurs commonly in the lower part of this facies tract and becomes rare upward. All of these structures become less common toward the southern part of the study area, while faint parallel bedding, low-angle cross-bedding, and hummocky cross-stratification become more common.

Argillaceous, bioturbated, medium- to coarse-grained sandstone beds, which are 0.5 to 6 m thick, occur commonly within the tide- to wave-dominated shoreline facies tract. Common *Ophiomorpha* and minor *Diplocraterion* are present in these beds. In addition, abundant *Macaronichnus segregatis* is present in coarse-grained sandstone beds, and minor *Teichichnus* occurs in claystone beds of the tide- to wave-dominated shoreline facies tract. Abundant *Skolithos* is present in clayey sandstone in the southern part of the study area. Common, fossiliferous sandstone beds and minor, arenaceous, fossiliferous limestone beds are present within the uppermost 30 m of the tide- to wave-dominated shoreline facies tract.

Interpretation

Based on the occurrence of sedimentary structures and biological features, along with an upward increase in grain size, this interval is interpreted as representing a prograding shoreline environment. In most of the study area, the common occurrence of tidal indicators, including bi-directional cross-bedding, clay drapes, and sand-mud couplets, suggests that tidal processes were dominant relative to wave processes. The distribution of primary structures and types of burrows indicate that the influence of wave processes relative to tidal processes becomes stronger to the south.

The occurrence of *Ophiomorpha* burrows in the tide- to wave-dominated shoreline facies tract suggests a shallow marine depositional setting, while *Teichichnus* burrows indicate brackish conditions (Seilacher, 1978; Pemberton et al., 1994). *Diplocraterion* burrows may occur in either brackish or marine environments (Seilacher, 1978). The organism that produced *Macaronichnus segregatis* has been interpreted previously as *Ophelia limacina*, which is a shrimp that lives in modern intertidal to shallow subtidal environments of Willapa Bay, Washington (Clifton and Thompson, 1978).

Diatomite

Description

A thick interval of diatomaceous claystone (diatomite) is present above the tide- to wave-dominated shoreline facies tract in the surface exposures studied. The diatomaceous claystone grades southward laterally to burrowed claystone and is not present south of well S7-3. This facies tract, which ranges in thickness from 2.7 to 9.3 m, contains variable amounts of clay, silt, sand, and carbonate cement. Microscopic examination of the diatomaceous claystone from outcrops revealed 1-85% diatoms, 5-75%

radiolarians and foraminifers (including *Quinqueloculina* sp), common volcanic rock fragments, and minor glass shards. Burrowed claystone within the diatomite facies tract contains common *Teichichnus* and common *Terebellina* burrows. Other internal features are not apparent within the diatomite facies tract. Because of distinctive light color and lateral continuity, the diatomaceous claystone serves as a useful marker bed in outcrop.

Interpretation

Diatomites form in depositional settings ranging from lacustrine to deep sea (e.g., Stoermer and Smol, 1999; Owen and Uthmaniyov, 1999; Bernoulli and Gunzenhauser, 2001). The occurrence of the foraminifer, *Quinqueloculina* sp., in diatomite of the Temblor Formation suggests very shallow marine deposition assuming that the foraminifers were not reworked (R.A. Christopher, written communication, 2000). Common *Teichichnus* and common *Terebellina* burrows in claystone beds of the diatomite facies tract indicate that some intervals may represent brackish water deposition. Previous interpretations for origin of Temblor Formation diatomite include deposition at shelfal to abyssal depths (Arnold and Anderson, 1910) and deposition caused by a diatomaceous bloom that occurred due to nutrient-rich upwelling (Bate, 1984).

Subtidal

Description

The stratigraphically highest facies tract of the Temblor Formation in the study area consists of a thick interval of bioturbated sandstone that is truncated at the top by a major regional unconformity. This facies tract, which is interpreted as subtidal in origin, reaches a maximum thickness of 40 m and comprises 3- to 20-m thick intervals of fine- to coarse-grained sandstone separated by thin interbeds of claystone and siltstone. A variable amount of carbonate cement is present, and minor, thin intervals of sandstone are tightly cemented.

Physical sedimentary structures, including bedding within the sandstone, are difficult to discern in this facies tract because of extensive burrowing. Sedimentary structures observed include faint, minor low-angle cross-bedding and planar-tabular cross-bedding. Minor *Skolithos* burrows can be recognized. The intensity of bioturbation decreases from north to south within the study area. Rare fragments of gastropods, sand dollars, and *Pecten* are present.

Interpretation

Faintly cross-bedded, bioturbated sandstones, similar to those of the uppermost facies tract in the Temblor Formation, are present in some modern subtidal environments. Dalrymple (1992) described modern subtidal sands as highly variable in their characteristics, including abundance of primary structures, degree of bioturbation, and amount of mud. The occurrence of *Skolithos* burrows in the subtidal facies tract is consistent with low to high current energy in a subtidal environment (Pemberton et al., 1994). The lack of abundant macrofossils in the subtidal facies tract may be due to unstable substrate caused by waves or tidal

currents.

Geological Characterization of Upper Cretaceous Outcrops, Southern Utah

Outcrop Location and Approach

The purpose of this phase of the investigation was to obtain information for developing a geologically realistic outcrop-conditioned model that could be applied to characterizing the variability of reservoir sands in West Coalinga Field. Fifteen stratigraphic sections in the informally named “B Sandstone” (middle portion of the John Henry Member of the Upper Cretaceous Straight Cliffs Formation, as recognized by Hettinger et al., 1993) were measured and described in the vicinity of Escalante, Utah (Figure 7). Eleven sections are approximately parallel to depositional strike, while the remaining four sections follow depositional dip. Seven closely spaced strike sections were described for the purpose of determining small-scale geological variability. Due to the long, continuous nature of the outcrops, it was possible to trace units between most of the logged sections.

A total of 350 m (1,148 feet) of section were studied in detail. Sedimentological description of the exposures included logging of grain size, percent sand, biogenic features, and sedimentary structures. Gamma-ray profiles of each section were recorded using a hand-held scintillometer. All gamma-ray data were loaded into a digital database.

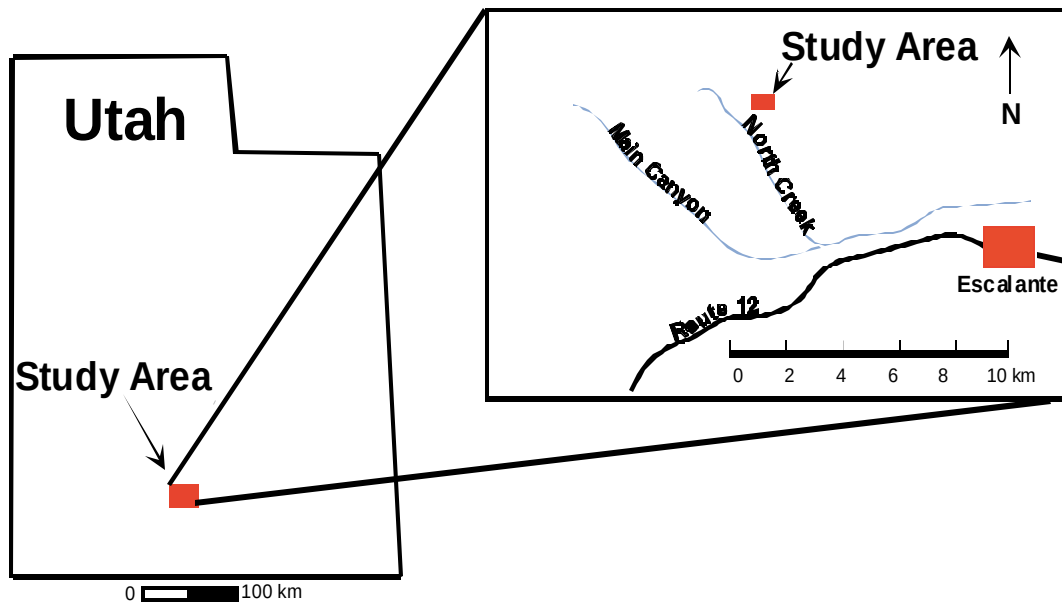


Figure 7. Location map for southern Utah study area. Permeability was measured from an outcrop near North Creek (indicated by “Study Area” on the detailed map).

Sedimentological Analysis

Offshore

Description

The lower 9-12 m of the interval studied consists of interlaminated to thinly interbedded shale, siltstone, and very fine grained sandstone (Figure 8). Because of the low resistance of this interval to weathering, it tends to form vegetated slopes and is poorly exposed in most of the study area. Common, small plant fragments and minor, small, horizontal and vertical burrows are present in areas of exposure. The sandstone beds contain minor ripple lamination and minor shell fragments. Bedding is flat to wavy.

At the base of this interval, a pebble-conglomerate lag directly overlies the A-sequence boundary of Hettinger et al. (1996). The pebble conglomerate, which ranges in thickness from 7 to 25 cm in the study area, contains poorly sorted pebbles in a fine-grained sandstone matrix. Rare to minor shell fragments and plant fragments are present in the sandstone.

Interpretation

Based on comparison with studies of modern sediments and ancient examples (e.g., Swift et al., 1991; Johnson and Baldwin, 1996), the lower interval of interlaminated to thinly interbedded shale, siltstone, and very fine grained sandstone in the B sandstone is interpreted as representing deposition in an offshore marine environment. Deposition is interpreted as having occurred predominantly below storm wave base because of the rarity of hummocky cross-stratified sandstone, shell lag beds, and other evidence for storm reworking. However, some of the thin sandstone beds may be analogous to laminated 'storm-sand layers' that have been described from modern shelf muds (Reineck and Singh, 1972).

Transition - Lower Shoreface

Description

Approximately 10-15 m of moderately to well sorted, very fine to fine-grained sandstone gradationally overlies the offshore facies of the interval studied. Massive-bedded, bioturbated intervals alternate with much thinner interbeds of hummocky cross-stratified sandstone. Overall, grain size gradually increases upward within this interval.

Abundant horizontal and vertical burrows are present within the bioturbated intervals, which contain minor clay. Diameter of the burrows, which are identified as *Ophiomorpha* and *Planolites*, ranges from approximately 0.5-1.5 cm, with length up to 15 cm. Most of the burrows are gently curving to sinuous, and some are lined with pellets. Similarly sized, branching burrows that occur in clusters near bedding contacts are identified as *Thalassinoides*.

Rare mud rip-up clasts, and minor fragments of plant and shell material are present within the bioturbated intervals. However, internal sedimentary structures are not apparent within most of the burrowed sand, probably because of destruction by burrowing. Rare ripple cross-lamination is present,

particularly near the top of beds.

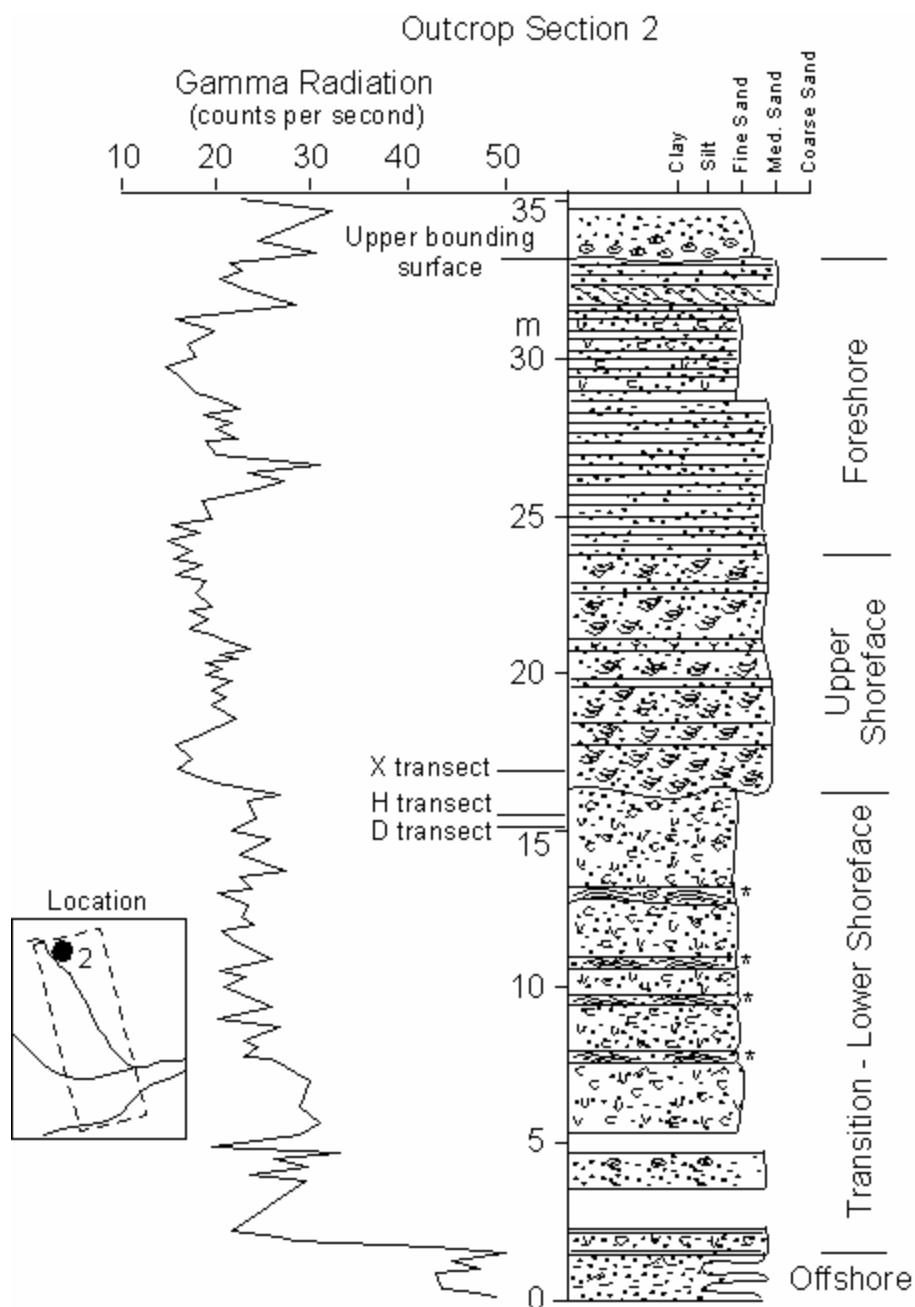


Figure 8. Description of Outcrop Section 2, where permeability was measured using the new small drill-hole minipermeameter. Positions of the horizontal transects along which permeability was measured are indicated (X, H, D). The A-sequence boundary, which is present at the base of the interval studied, is covered at this location. Location of the outcrop is along North Creek (see also Figure 7).

As many as eight stratified sandstone beds, each 15-80 cm in thickness, are present within this stratigraphic interval. These beds are clearly defined by sharp upper and lower contacts and by generally lighter color than the bioturbated sandstone, particularly on weathered surfaces. The lower contact is erosive into the underlying sandstone. The beds contain a very low content of clay and, because of carbonate cement, tend to be more resistant to weathering than the bioturbated sandstone. Internal stratification is horizontal to hummocky, with minor ripple cross-lamination. Minor to rare vertical and horizontal burrows, including *Ophiomorpha*, *Palaeophycus*, and *Skolithos* are present in the hummocky cross-stratified beds. Some of the hummocky cross-stratified beds can be traced laterally along the outcrop for more than 2,700 m, although they tend to pinch out and then reappear in the same stratigraphic position.

Interpretation

The presence of hummocky cross-stratification (HCS) suggests that deposition was most likely influenced by storm waves (e.g., Harms et al. 1975; Swift et al. 1983; Walker and Plint 1992). Ancient examples containing HCS have been interpreted previously as forming between storm and fair-weather wave base in the upper offshore to lower shoreface zone (e.g., Colquhoun, 1995; Castle, 2000). The upward increase in grain size in the interval that we studied suggests possible shoreline progradation.

Deposition in a lower shoreface setting is consistent with occurrence of the trace fossils *Ophiomorpha*, *Planolites*, and *Thalassinoides* (Frey and Pemberton, 1985; Pemberton et al., 1992; Pemberton and MacEachern, 1995). *Ophiomorpha*, *Palaeophycus*, and *Skolithos* have been reported in other hummocky cross-stratified Upper Cretaceous sandstones interpreted as storm deposits (Frey, 1990; Frey and Howard, 1990). Some of the interbedding between muds and sands and the internal sedimentary structures that were originally present in the sandstones may have been obliterated by bioturbation. In the lower shoreface and transition zone, the extent of bioturbation, and hence the preservation of storm-generated beds, depends on the magnitude and frequency of storms and the overall rate of sedimentation. The hummocky cross-stratified beds preserved between the massive bioturbated intervals in our study area probably record wave processes that were more intense than during deposition of the bioturbated beds.

Upper Shoreface

Description

Cross-bedded, moderately well sorted, fine- to medium-grained sandstone sharply overlies the lower shoreface interval. One- to 1.5-m thick intervals of trough cross-bedded sandstone alternate with 0.1-0.3 m thick beds of low-angle cross-bedded sandstone. Minor horizontal lamination, minor planar-tabular cross-bedding, and rare ripple cross-lamination are also present. Common shell debris and plant fragments occur on bedding planes, and rare horizontal to vertical burrows are present within the sandstone beds. Thickness of this interval ranges from 6-8 m in the outcrops studied.

The basal contact with the underlying shoreface interval is sharply defined and laterally continuous throughout the study area. The contact is erosive, showing approximately 1.5 m of relief among the outcrops studied. The contact is directly overlain by trough cross-bedded, horizontally laminated, or low-angle cross-bedded sandstone. Lag deposits were not observed on the contact.

Interpretation

This interval is interpreted as upper shoreface, with the abundant through cross-beds representing dune migration. Grain size and sedimentary structures are similar to those of modern, cross-stratified shoreface deposits (e.g., Howard and Reineck, 1981; Swift et al. 1991) and to ancient upper shoreface deposits (e.g., Swift et al. 1987; Walker and Plint, 1992; Colquhoun, 1995; Johnson and Baldwin, 1996). The previous studies demonstrated that sand deposition in this setting is controlled by a combination of storm and fair-weather processes.

The sharp basal contact of the upper shoreface facies is interpreted as forming by erosive scour in advance of upper shoreface deposition. This contact is interpreted as a regressive bounding surface that formed in response to relative sea-level fall. Similar surfaces have been described in ancient shoreface strata (e.g., Plint, 1988, Walker and Plint, 1992; Mellere and Steel, 1995; Castle, 2000).

Foreshore

Description

An interval of predominantly horizontally laminated, moderately well sorted fine- to medium-grained sandstone, approximately 9-14 m thick, overlies the upper shoreface interval. Minor low-angle cross-bedding and planar-tabular cross-bedding are present. Typically, 0.3-3.0 m thick beds of horizontally laminated and low-angle cross-bedded sandstone alternate with 0.15-0.3 m beds of planar tabular cross-bedded sandstone. A few beds within this interval contain a concentration of common to abundant shell fragments, and minor shell fragments are present on cross-bed foresets in other beds. Grain size exhibits a slight upward decrease in most of the outcrops studied; minor shale interbeds are present in the upper part of the interval in some of the outcrops.

Although burrows are rare in the horizontally laminated medium-grained sandstone of this interval, minor to common vertical and horizontal burrows are present in the upper, finer grained part of the interval. The burrows, which are identified as *Skolithos*, *Planolites*, and possibly *Psilonichnus*, are approximately 0.5-1.0 cm in diameter and up to 4 cm long.

The basal contact of this interval varies from sharp to gradational. The upper contact, which marks the top of the interval studied, is sharp and overlain by medium-grained sandstone containing abundant oyster shells and fragments and abundant mud rip-up clasts. This bed ranges from about 0.75-1.5 m in thickness.

Interpretation

The horizontally laminated and low-angle cross-bedded sandstone of this interval is interpreted as representing beach-face deposition in a foreshore setting. The occurrence of wave-produced sedimentary structures, shell fragments, upward fining, and burrows are consistent with descriptions of modern and ancient foreshore deposits (e.g., Clifton et al., 1971; Howard and Reineck, 1981; Clifton, 1988; Reading and Collinson, 1996).

Internal structures, finer grain size, and burrowing in the upper part of this interval indicate lower

energy deposition than represented by the underlying horizontally laminated foreshore deposits. From position in the overall succession and from comparison with other examples (e.g., Swift et al., 1991; Walker and Plint, 1992), the upper part of this interval may represent backshore deposition. Bioturbated sediments, similar to those in the upper part of the interval studied, have been described from modern backshore environments (e.g., Frey et al., 1984; Frey and Pemberton, 1987). Based on comparison with similar contacts and associated lithologies from other ancient successions (e.g., Bergman and Walker 1987; Pattison and Walker, 1992; Arnott et al. 1995), the sharp upper contact is interpreted as a wave-cut surface overlain by a lag bed.

Small Drill-Hole Minipermeameter Probe for Outcrop Permeability Measurement

A new small drill-hole minipermeameter probe (Figure 9) was developed to make permeability measurements on outcrops at the Escalante field site. This technology has been refined to be a truly reliable field method. Small cylindrical holes are created in an outcrop with a masonry drill, followed by drill-hole vacuuming, probe insertion, seal expansion and *in situ* calculation of the intrinsic permeability via measurement of the injection pressure, flow rate, and knowledge of the system geometry. Advantages of this approach are elimination of the use of questionable permeability measurements from weathered outcrop surfaces, provision of a superior sealing mechanism around the air injection zone, and its potential for making measurements at multiple depths below the outcrop surface.

The theory for analyzing radial gas flow from a cylindrical hole has been developed for the new drill-hole minipermeameter probe. Use of the new probe prescribes a change in the system geometry from that of the more conventional surface-sealing probe. The mathematical theory for this new probe type was derived in a way that is analogous to the derivation by Goggin et al. (1988) for the conventional probe. There is a geometrical factor for the new probe, which accounts for the system geometry and diverging flow through the domain. In order to determine the geometrical factor for the new probe, finite-difference computer simulations were developed to model the pressure-distribution throughout the system. This was begun by verifying the finite-difference solutions of Goggin et al. (1988) for the conventional probe, which applies flow to an exposed rock surface. The work proceeded by modifying the boundary conditions of the simulation to reflect the new drill-hole system geometry, and as a result, the geometrical factor for the new system was obtained.

The theory for analyzing radial gas flow from a cylindrical drill-hole into the surrounding medium was expanded to include possible variations in system geometry. The variations tested include thickness of the packer (or seal), depth of the drill-hole into the outcrop, and radius of the drill-hole. There is a geometrical factor for each variation of the probe/rock system, which accounts for the system geometry and the diverging flow through the porous media domain. To determine the geometrical factor for different system geometries, finite-difference computer simulations were developed to model the pressure-distribution throughout each system. The development of the new drill-hole probe is discussed by Dinwiddie (2001) and Dinwiddie et al. (1999, 2000a, 2000b, 2001). A patent application for the probe has been approved (Molz et al., 2002a).

The physical basis for the spatial weighting function of the instrument was developed utilizing streamline coordinates (Molz et al., 2000, 2002b). Application of the spatial weighting function for the new drill-hole probe is presented in Figure 10. Spatial weighting function distributions indicate that with diverging

flow-field instruments (such as the gas minipermeameter probe) in any configuration, porous medium volumes in the inlet vicinity are heavily weighted, with volumes near the seal boundaries shown to be extremely important (Molz et al., 2000, 2002b). The technique described allows one to quantify the size and shape of the averaging volume that contributes to an effective permeability measurement.

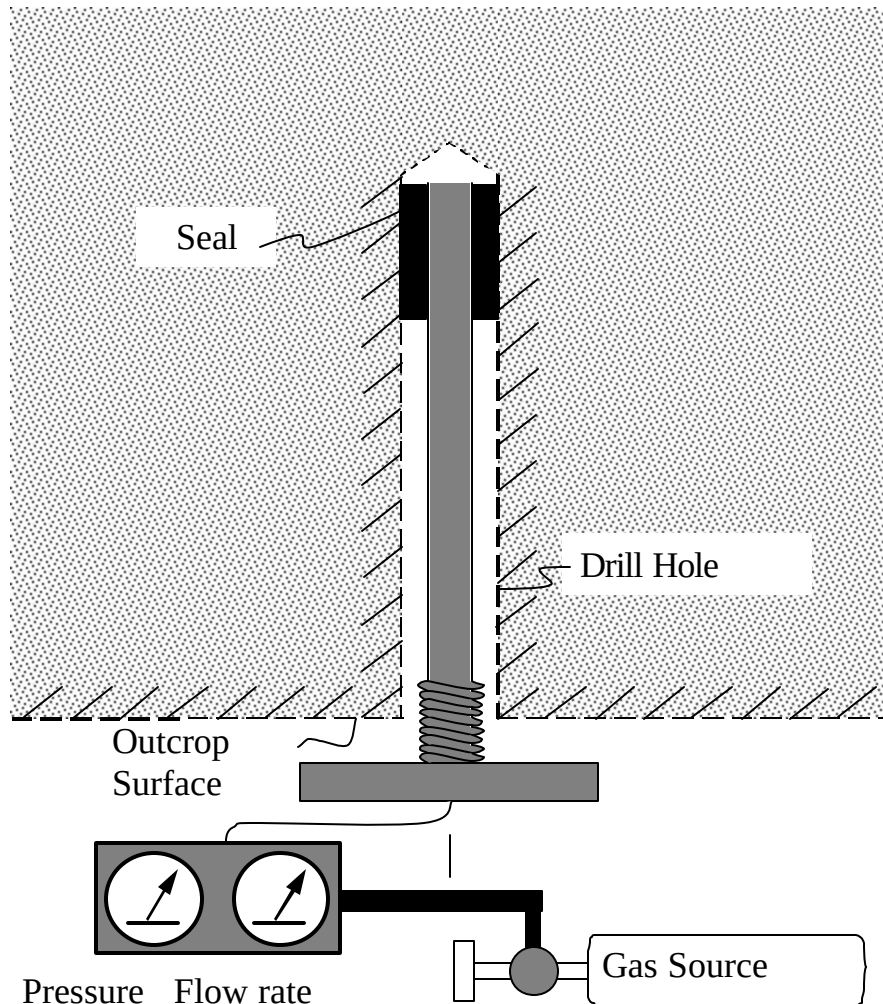


Figure 9. Schematic of the new drill-hole mini-permeameter designed for steady-state *in situ* field measurements.

Laboratory analyses using the small drill-hole minipermeameter probe were performed to assess the

results obtained. The following tasks were completed: 1) thin section analysis of the rock zone in the immediate vicinity of the drill-hole for the purpose of appraising any damage due to drilling; 2) operator familiarization with achieving the optimal normal force between the seal and the drill-hole wall; 3) determination of the minimum distance needed between drill-holes to eliminate the possibility of short circuiting gas flow through adjacent holes; and 4) pseudo-calibration of drillhole minipermeameter data with Hassler-sleeve permeability data to verify order-of-magnitude accuracy. These laboratory analyses were performed on several sandstone boulders, which were transported from the Escalante, Utah field site to Clemson University for testing of the prototype probe. Laboratory testing of the new probe in sandstone obtained from the field-site facilitated the move to *in situ* field measurements near Escalante, Utah. Additionally, the laboratory work indicated general guidelines for field use, such as appropriate pressure and flow rate ranges, expected life of seal material, and the efficacy of obtaining measurements at multiple depths within a drill-hole.

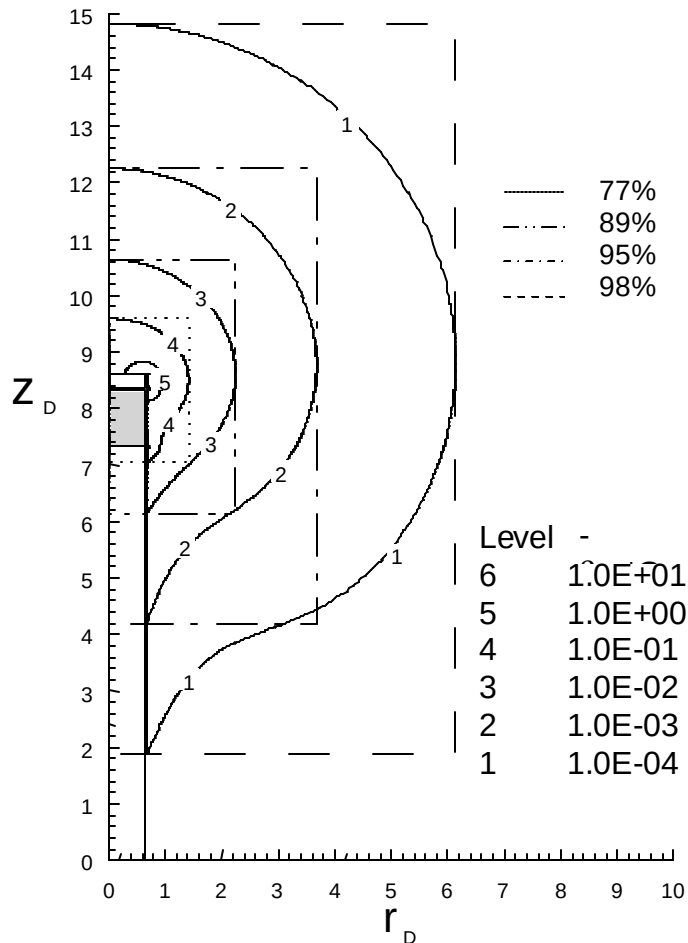


Figure 10. Lines of equal pseudo-potential gradient squared, which are proportional to the dimensionless spatial weighting function, are displayed as curvilinear contours. When integrated, the spatial weighting

function over the entire flow domain must sum to 1. By numerically integrating the spatial weighting function over smaller volumes in the vicinity of the inlet, the averaging volume of the instrument becomes apparent. This is illustrated by the concentric cylinders, indicated by variously dashed lines, which increasingly encompass greater percentages of the spatial weighting function. The drillhole geometry for this numerical model was assumed to be flattened at the distal end.

Permeability Data from Upper Cretaceous Outcrop, Southern Utah

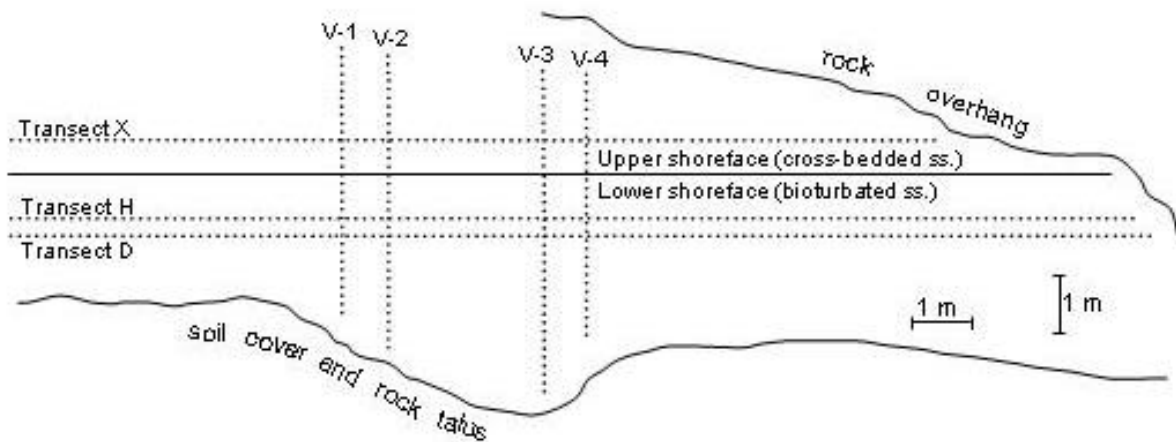
One of the outcrops of the Upper Cretaceous Straight Cliffs Formation in the southern Utah study area was selected for testing of small-scale variation in permeability using the new small drill-hole minipermeameter (Figures 7, 8). This outcrop has a near-vertical face measuring approximately 21 m across and 6 m high. Consistent with the accumulation of talus at the base and a well-defined overhang at the top, this outcrop appeared less weathered than others. Approximately 500 locations were tested for permeability within two sandstone facies. Location spacings for measurements were every 15 cm along three horizontal transects and four vertical profiles (Figure 11). Measurements were made in triplicate at each location, and the results were arithmetically averaged. Lithologic information, including grain size and sedimentary structures, was recorded for every measurement location. To obtain an approximation of the mineralogy and fabric in each of the two sandstone facies tested for permeability, thin sections were prepared and examined from 32 measurement points exhibiting representative permeability values. Sodium cobaltinitrite was applied to each thin section as a stain to aid in the petrographic identification of potassium feldspar. Each thin section was point-counted (300 points each) for detrital mineral content, matrix, cements, and porosity. Secondary porosity was identified following the criteria proposed by Schmidt and McDonald (1979). Grain size was estimated by measuring the maximum length of grains of approximately average size in each thin-section. Sorting was estimated following methods of Beard and Weyl (1973) and Longiaru (1987).

Permeability Variation

Permeability was measured in two facies: the lower shoreface bioturbated sandstone and the upper shoreface cross-bedded sandstone. In the bioturbated sandstone, approximately 340 locations were tested for permeability along two horizontal transects and in the lower portion of four vertical profiles (Figures 12, 13). Approximately 170 locations in the cross-bedded facies were tested for permeability along one horizontal transect and in the upper portion of the four vertical profiles. The arithmetic average of permeability measurements for all sample locations were reported by Dinwiddie (2001) and Current (2001).

Permeability values range between 41 and 1,675 millidarcies (md) in the bioturbated sandstone facies. The arithmetic mean of all permeability measurements in this facies is 276 md, and the geometric mean is 253 md. Permeability in the bioturbated sandstone facies shows very little variability over a scale of several m (e.g., $125 \text{ md} < k < 275 \text{ md}$ over a distance of 6 m within Transect D), which is attributed to homogenization caused by burrowing. The range of permeability variation for both the horizontal transects and the vertical profiles is generally less than one order of magnitude. Grain size in the bioturbated facies also shows little variation laterally and vertically.

Permeability in the cross-bedded facies ranges between 336 and 5,531 md, with an arithmetic mean of all permeability measurements equal to 1,746 md and a geometric mean of 1,395 md. Grain size and permeability show a higher degree of variability in the cross-bedded facies, both vertically and horizontally, than is present in the bioturbated facies. Permeability variation exceeding 1,000 md is not uncommon among nearby sample locations. At a vertical position of 5 to 6 sample locations above the contact between the bioturbated facies and the cross-bedded facies, a high permeability peak can be correlated among the



vertical profiles. Permeability at this position ranges from 1,924 md in profile V-2 to 5,126 md in profile V-3.

Figure 11. Locations of vertical profiles and horizontal transects along which permeability was measured on the outcrop face, section 2 (Figure 8). Approximate positions of rock overhang and soil cover are shown.

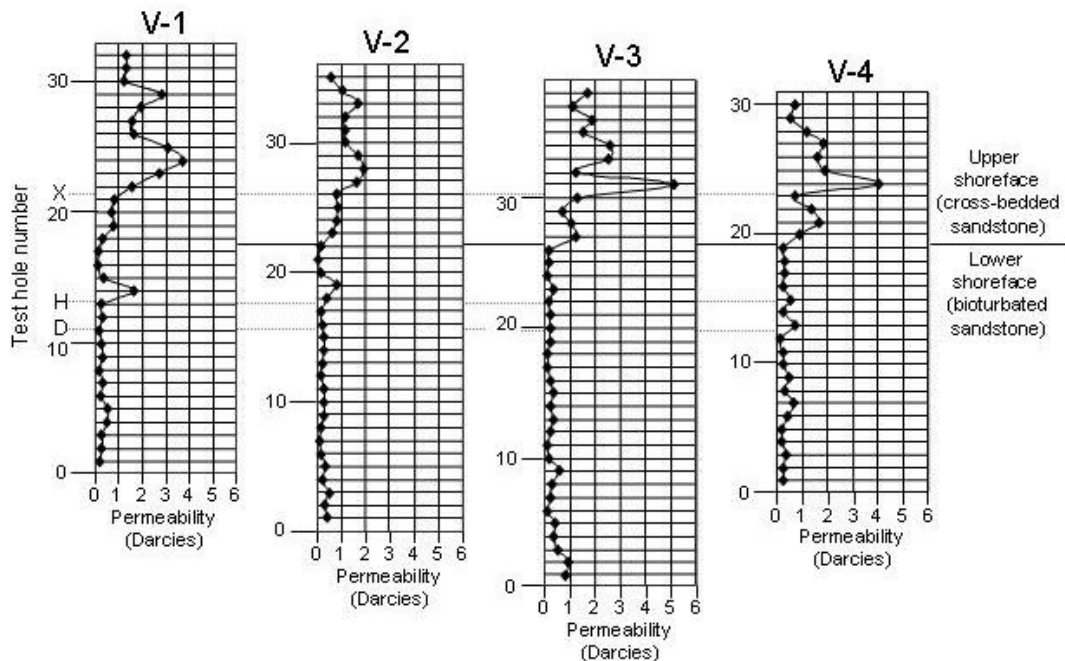


Figure 12. Vertical permeability profiles. Permeability values in the cross-bedded sandstone are higher and show greater variability than in the bioturbated sandstone. Intersections of horizontal transects D, H, and X are shown. Hole location and profile numbers have been reassigned, with location 1 as the lowest position

in each profile, and therefore may differ from Dinwiddie (2001) and Current (2001).

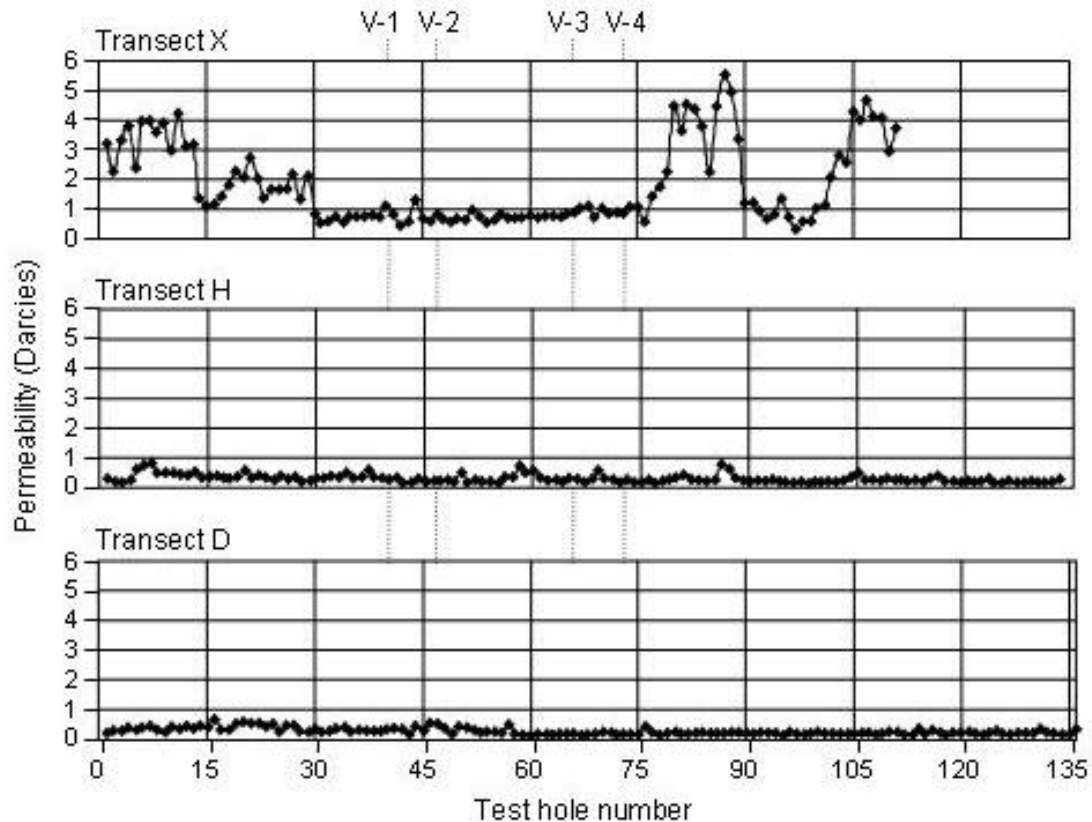


Figure 13. Horizontal permeability transects. Permeability values vary over a much greater range in the cross-bedded sandstone (transect X) than in the bioturbated sandstone (transects H and D). Intersections of vertical profiles V1, V2, V3, and V4 are shown. Hole location numbers have been reassigned, with location 1 as the left-most position in each transect, and therefore may differ from those used by Dinwiddie (2001) and Current (2001).

Geologic Controls

There are similarities in lithology between facies in the Temblor Formation and facies in the Straight Cliffs Formation (Table 5). In both cases, permeability values are related to lithologic properties produced by the depositional processes.

Table 5. Comparison of lithologies between southern Utah field site and Coalinga site.

Escalante, Utah	Coalinga, California
Straight Cliffs Formation	Temblor Formation
Late Cretaceous (Turonian)	Early to Middle Miocene (Saucesian, Relizian, Luisian)
<u>Lithology</u> : cross-bedded medium-grained sandstone; bioturbated fine-grained sandstone; interlaminated to interbedded shale and very fine to fine-grained sandstone; shell and pebble lags; mud rip-up clasts	<u>Lithology</u> : cross-bedded fine- to medium-grained sand; bioturbated coarse-grained sand; interlaminated to interbedded clay and fine-grained sand; fossiliferous sand; diatomaceous silt and clay; quartz and lithic pebble lags; mud rip-up clasts
<u>Sedimentary Structures</u> : trough and planar-tabular cross-bedding; horizontal lamination; ripple cross-lamination; hummocky cross-stratification	<u>Sedimentary Structures</u> : trough and planar-tabular cross-bedding; clay drapes on foresets; ripple cross-lamination; bi-directional cross-bedding; mottled bedding
<u>Biological Features</u> : ¼" to ½" diameter vertical and horizontal burrows, filled with sand; wood and plant fragments	<u>Biological Features</u> : ¼" to 1" diameter vertical and horizontal burrows, clay lined and some sand filled; meniscus burrows present on some erosional surfaces; wood fragments

Permeability values tend to be greater in the cross-bedded facies than in the bioturbated facies in the southern Utah data sets because of coarser grain size, greater primary porosity, and smaller percentages of clay matrix and cement (Table 6). Based on petrographic observation, primary pores are larger and better connected in the cross-bedded facies than in the bioturbated sandstone, which is related to coarser grain size in the cross-bedded facies (Lorinovich et al., 2000). Small amounts of grain-moldic secondary porosity have formed by dissolution of feldspar grains in both sandstone facies. Although the percentage of moldic porosity is greater in the bioturbated facies than in the cross-bedded facies, its contribution to permeability is small because of low connectivity among grain-moldic pores. The growth of minor pore-lining chlorite cement has resulted in a reduction of permeability in both sandstone facies. Based on qualitative petrographic observations from both facies, the individual samples with the highest permeability values contain the largest amount of porosity and the least amount of matrix and cement.

Table 6. Texture, composition, and fabric of facies tested for permeability in the B Sandstone unit of the John Henry Member. Data are averaged from petrographic counting of 300 points per sample.

Facies	Number of Samples	Mean Grain Size (mm)	*Mean Sorting	**Ratio of Detrital Framework Grains (%)			Ratio of Fabric Components (%)					
				Quartz	Feldspar	Lithic Fragments	Framework Grains	Clay Matrix	Calcite Cement	Chlorite Cement	Primary Porosity	Secondary Porosity
Lower Shoreface (Bioturbated SS)	20	0.11	4.8	80.	3.5	16.	65.	2.9	5.2	2.5	21.	3.3
Upper Shoreface (Cross-bedded SS)	12	0.23	3.4	65.	2.4	32.	67.	1.0	3.0	2.3	25.	1.8

*Mean sorting estimated using the method of Beard and Weyl (1973): 1=very poor; 2=poor; 3=moderate; 4=moderately well; 5=well; 6=very well.

** Feldspar mineralogy is orthoclase. Lithic grains are predominantly chert, with minor sedimentary and volcanic rock fragments. The higher proportion of detrital quartz to lithic grains in the bioturbated sandstone than in the cross-bedded sandstone is probably related to grain size difference between the two facies.

Field permeability measurements from lower shoreface bioturbated sandstone and upper shoreface cross-bedded sandstone demonstrate facies-dependent variations in permeability. Because of lithologic homogenization by extensive burrowing, the bioturbated sandstone exhibits a low degree of permeability variation over a scale of several m. In contrast, permeability in the cross-bedded facies varies by more than an order of magnitude over a scale of a few cm. This high degree of variability is caused by small-scale variations in grain size and structure related to the depositional processes. In contrast to the bioturbated facies, the primary textural properties have been preserved rather than modified by burrowing.

Fractal Analysis

Utah Data Set

Fractal scaling properties of the data were analyzed with the intent to predict permeability distributions. Analysis of two permeability (k) data sets, collected along two horizontal transects in the bioturbated sandstone facies at the Escalante field site, indicates that horizontal $\log(k)$ increment distributions are highly Gaussian (Figure 14, 15). Fractal scaling of $\log(k)$ is also observed with a Hurst coefficient of 0.33 (Figure 16), indicating negative correlation of $\log(k)$. The plot of $\log(k)$ increments versus distance appeared stationary. Results from vertical transects, which included measurements from the two different facies, are more variable, but still display Gaussian behavior (Figure 17, 18) to a good approximation with a Hurst coefficient of 0.68 (Figure 19). These results suggest that the fractional Brownian motion (fBm) model may be appropriate for $\log(k)$ simulations within a facies.

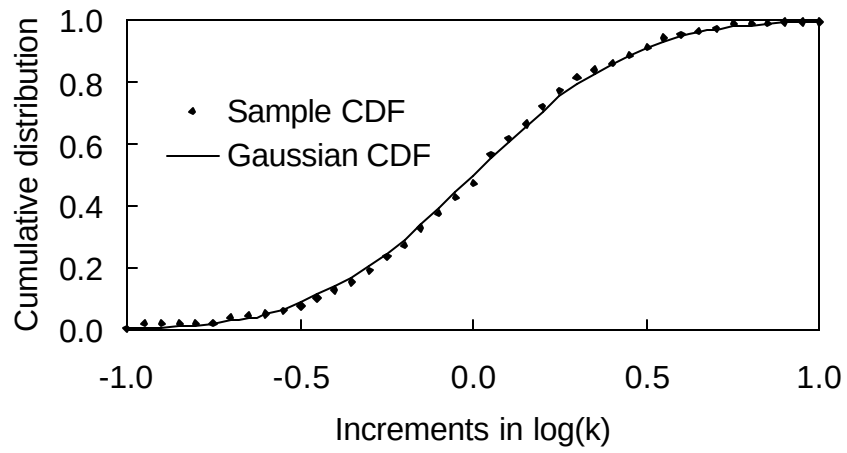


Figure 14. Probability distribution of $\log(k)$ increments in the horizontal direction

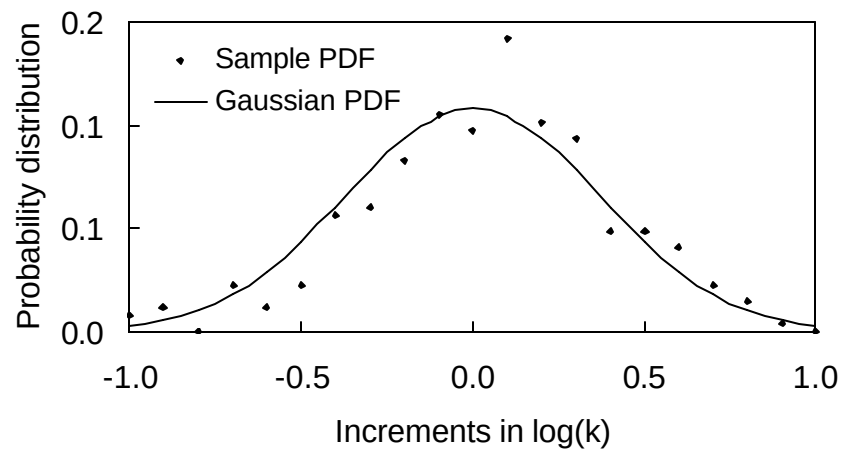


Figure 15. Cumulative distribution of $\log(k)$ increments in the horizontal direction

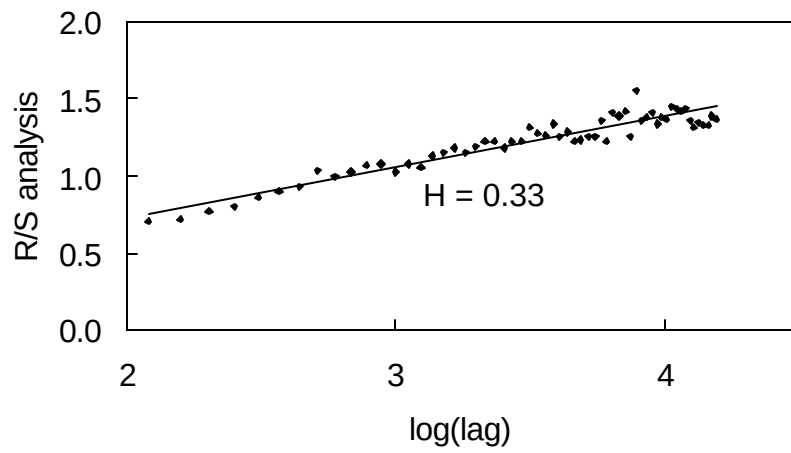


Figure 16. Rescaled range (R/S) analysis of $\log(k)$ in the horizontal direction

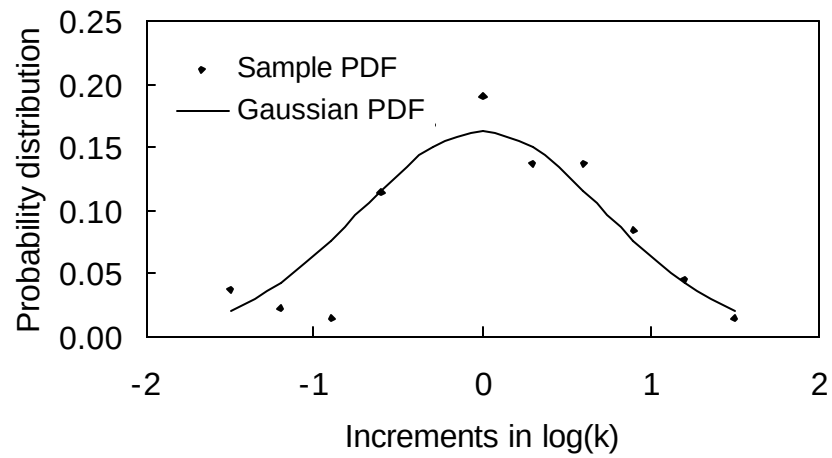


Figure 17. Probability distribution of $\log(k)$ increments in the vertical direction

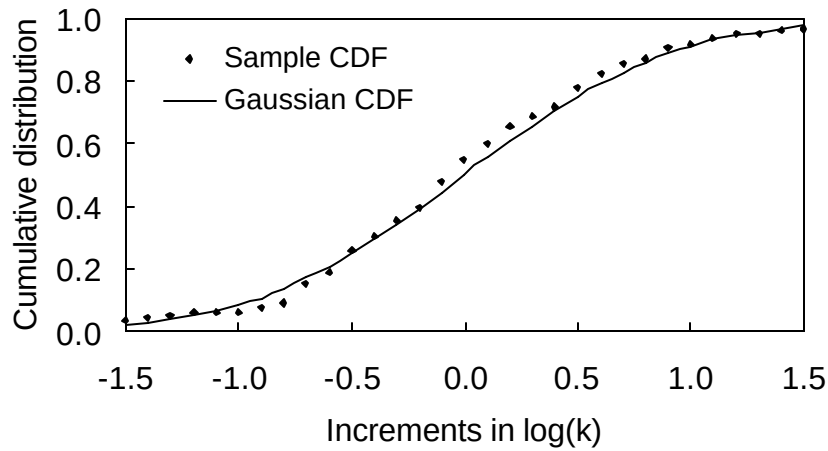


Figure 18. Cumulative distribution of $\log(k)$ increments in the vertical direction

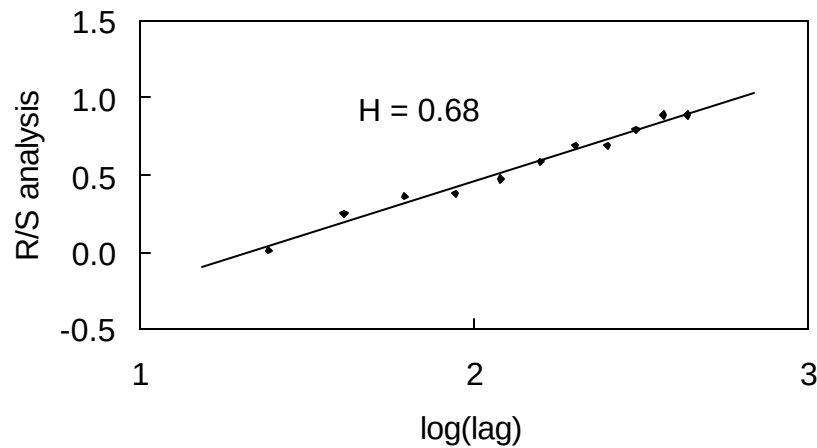


Figure 19. Rescaled range (R/S) analysis of $\log(k)$ in the vertical direction

Coalinga Data Set

Spectral analyses and the Double Trace Moment (DTM) method (Lavalée et al., 1991) were used to analyze the permeability data from West Coalinga Field, assuming that the data displayed scaling properties of Levy multifractals. This was done by estimating the parameters of the Universal Multifractal (UM) model (Schertzer and Lovejoy, 1987). The UM model has been reasonably successful in representing, among other geophysical fields, spatial distribution of rain (Schertzer and Lovejoy, 1987), ice

core formation structures (Schmitt et al., 1995), and topography (Lavalley et al., 1993). Papers by Gupta and Waymire (1993) and Veneziano (1999) provide additional useful information regarding multifractal models.

The fractal analysis of data from West Coalinga Field was a difficult task initially because of the lack of data continuity. Variance scaling is definitely present in the data, but the associated Hurst (H) coefficient was difficult to calculate. Using spectral techniques, a value in the vicinity of 0.3 was estimated. Further analysis of the core data, which included a series of facies tracts, yielded sets of $\text{Log}(k)$ increments that were not Gaussian. This differed from our Utah data, which were obtained within what we call pure facies. However, we were able to show that data from the West Coalinga Oil Field, as well as data obtained by others in the laboratory using the conventional minipermeameter, displayed multifractal scaling over a significant range of scales (Boufadel et al., 2000).

Permeability data from five wells were used for the analysis. The vertical spacing of measurements was generally about 0.3048 m (one foot). Due to missing measurements, only portions of the data could be used (246 values out of about 1,000 values). Two disjoint data sets were obtained from Well 4: 4A and 4B. Figure 20 shows plots of the intrinsic permeability as a function of depth for all wells. Figure 21 shows that scaling exists in the permeability field. The slope T ranged generally from about -1.05 to about -1.35 , with an arithmetic average of about -1.2 . This is not too far from the limiting stationary value of -1 .

Although the double trace moment (DTM) method has been restricted previously to stationary data sets, the plots in Figure 21 show that such a limitation is not necessary. One can transform the non-stationary data to stationary data by performing a fractional differentiation (which can be easily done in the Fourier space by multiplication by f raised to a positive power) to bring the slope T between -1 and $+1$. Consider for example Well 3, the slope T is equal to -1.17 , hence it suffices to multiply (in Fourier space) the Fourier transforms of the measured k values by $f^{0.085}$ (f = spectral frequency variable) to obtain a new slope $T = -1$ (because the spectrum is the square of the Fourier transform magnitude). Alternatively, one can obtain stationary data by taking the increments of the data in the real space, which corresponds to a multiplication by f in the Fourier space (Lavalley et al., 1993). This is the approach followed in our work.

The major parameters characterizing multifractals derive from the underlying Levy distribution that is assumed to govern the logs of the data, not the increments in the multifractal case. These are the Levy index, α , and the width parameter, σ . We now proceed to estimating the parameters α and σ using the DTM method applied on the field F . (The analysis procedure will not be described in detail herein since it is quite technical. Details may be found in Boufadel et al. (2000).)

We computed DTM_q , (q = order of the statistical moment.) using equations representative of the scaling of the double trace moments. The plots in Figures 22 and 23 show the DTM_q for $q=0.5$ and $q=2$ for Wells 4B (first part) and Well 5. Notice that the linear fit is generally good in all graphs, indicating that multiscaling (or multifractal behavior) is demonstrated. A break in scaling occurred for Well 5 at low scaling ratio values (Fig. 23). This was probably because of the combined effect of limited data length and intermittency (Fig. 20F), which resulted in spatial averages (using the equations representing the scaling of the double trace moments) being poor estimates of ensemble averages at low scaling ratios. This occurred to a lesser extent for other wells probably because of their lower degree of intermittency in comparison to Well 5 (Fig. 20).

Figure 24 shows plots of the log of the moment scaling exponent ($\text{Log}|M(q, \eta)|$) versus η , the order of the double trace moment variable used in the DTM analysis, and the best-fit linear curve for Wells

4B (first part) and Well 5. The break in the linear behavior at high η values is expected because of the divergence of the dressed moments (Schertzer and Lovejoy, 1991).

Table 7 lists the estimated α and σ values from various data sets. The parameter α varied between 1.57 and 1.93 while σ varied between 0.042 and 0.43. The arithmetic averages of α and σ (obtained by averaging within each data set and then averaging between sets) were about 1.78 and 0.17, respectively.

From the observed spectral slopes (Fig. 21) and the values of α and σ for each data set (Table 7), we computed values of H_m , the multifractal Hurst coefficient, varying between 0.19 and 0.32, with an average value of about 0.25.

Table 7. Values of α and σ Estimated by the DTM method.

The average values are $\alpha=1.78$ and $\sigma=0.17$

		q=0.5		q=2.0		
		α	σ	α	σ	Comment
Well 1	1 st Part	1.80	0.137	1.81	0.159	16 out of 26 data points
	2 nd Part	1.83	0.4323	1.75	0.4157	16 out of 26 data points
Well 2	1 st Part	1.74	0.048	1.71	0.055	32 out of 55 data points
	2 nd Part	1.72	0.146	1.61	0.132	32 out of 55 data points
Well 3	1 st Part	1.93	0.047	1.84	0.042	16 out of 27 data points
	2 nd Part	1.70	0.185	1.57	0.163	16 out of 27 data points
Well 4A	One Set	1.79	0.155	1.70	0.151	20 data points
Well 4B	1 st Part	1.82	0.168	1.78	0.175	32 out of 49 data points
	2 nd Part	1.90	0.172	1.90	0.186	32 out of 49 data points
Well 5	One Set	1.88	0.234	1.76	0.194	64 out of 67 data points

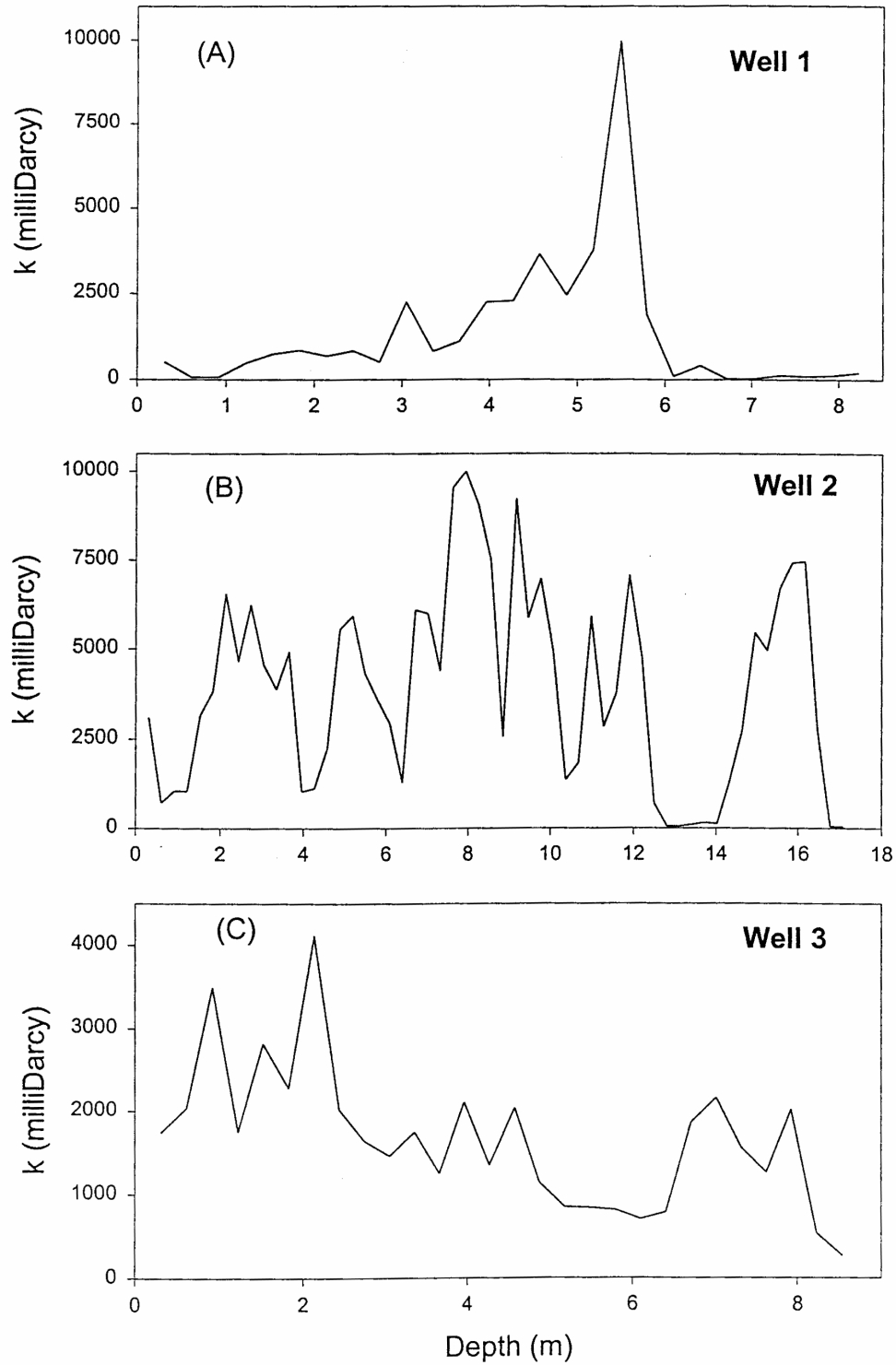


Figure 20. Observed core permeability data from West Coalinga Field, California.

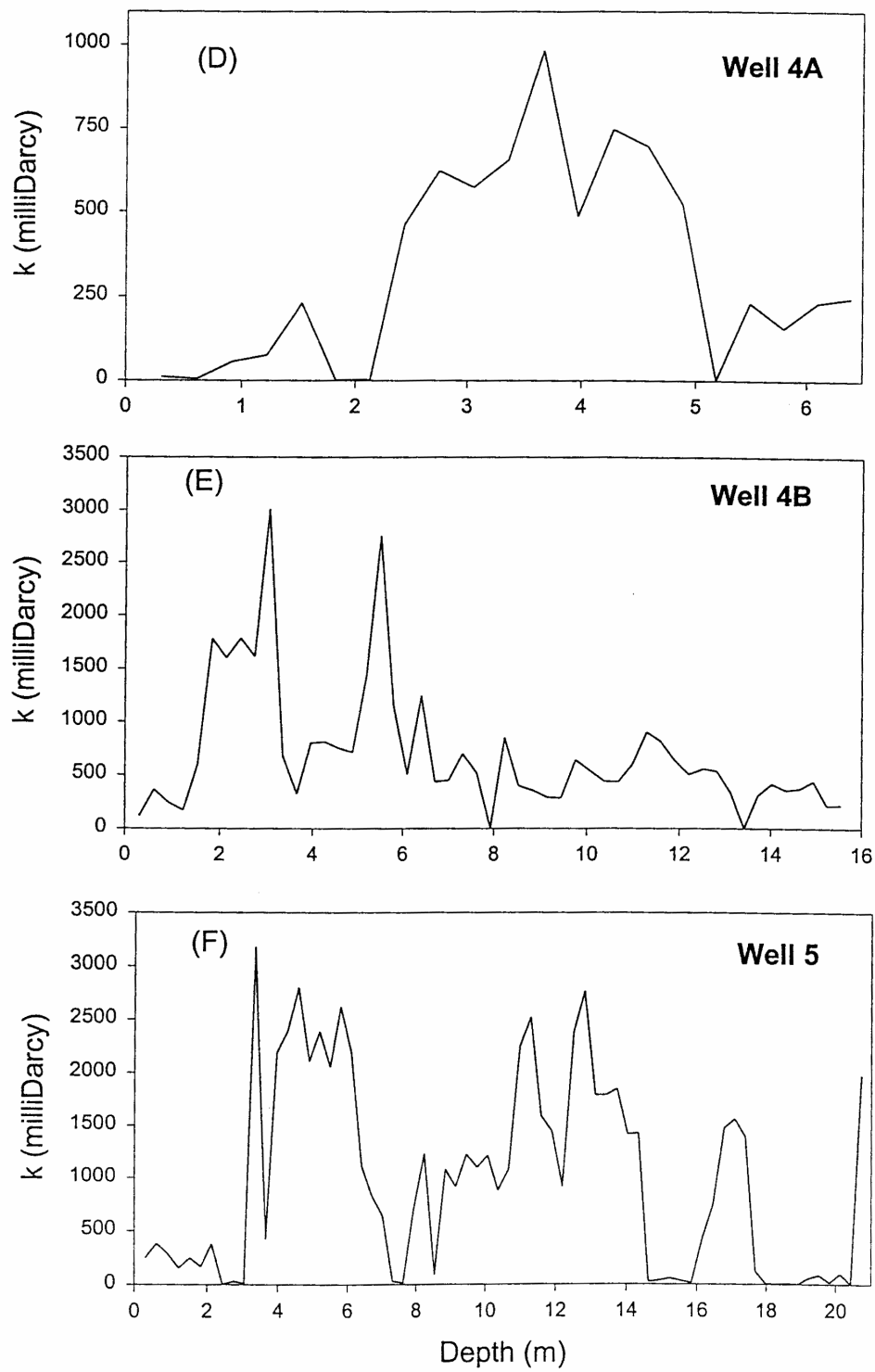


Figure 20. Continued

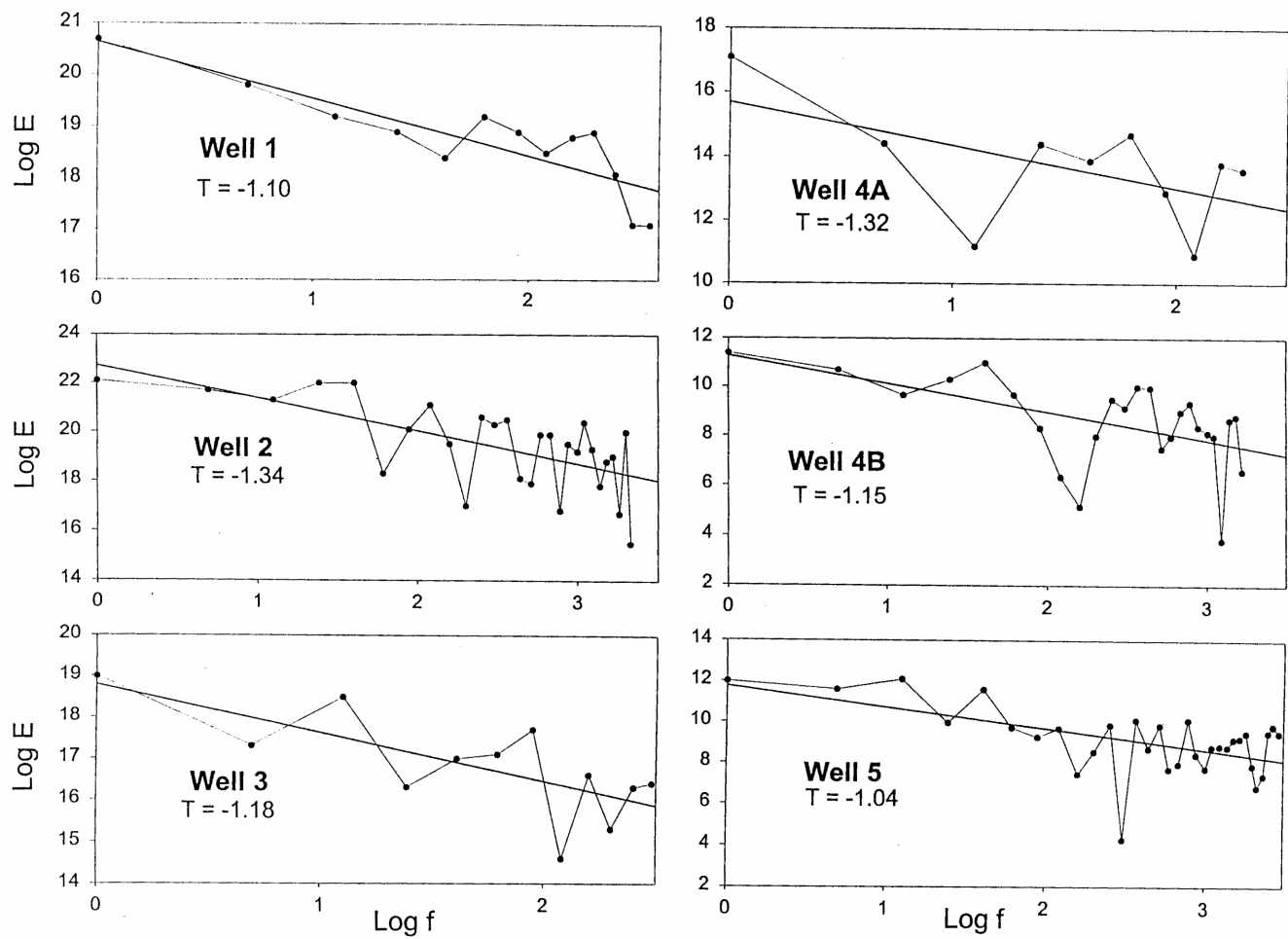


Figure 21. Observed spectral slopes, T , of the permeability data reported in Figure 20.

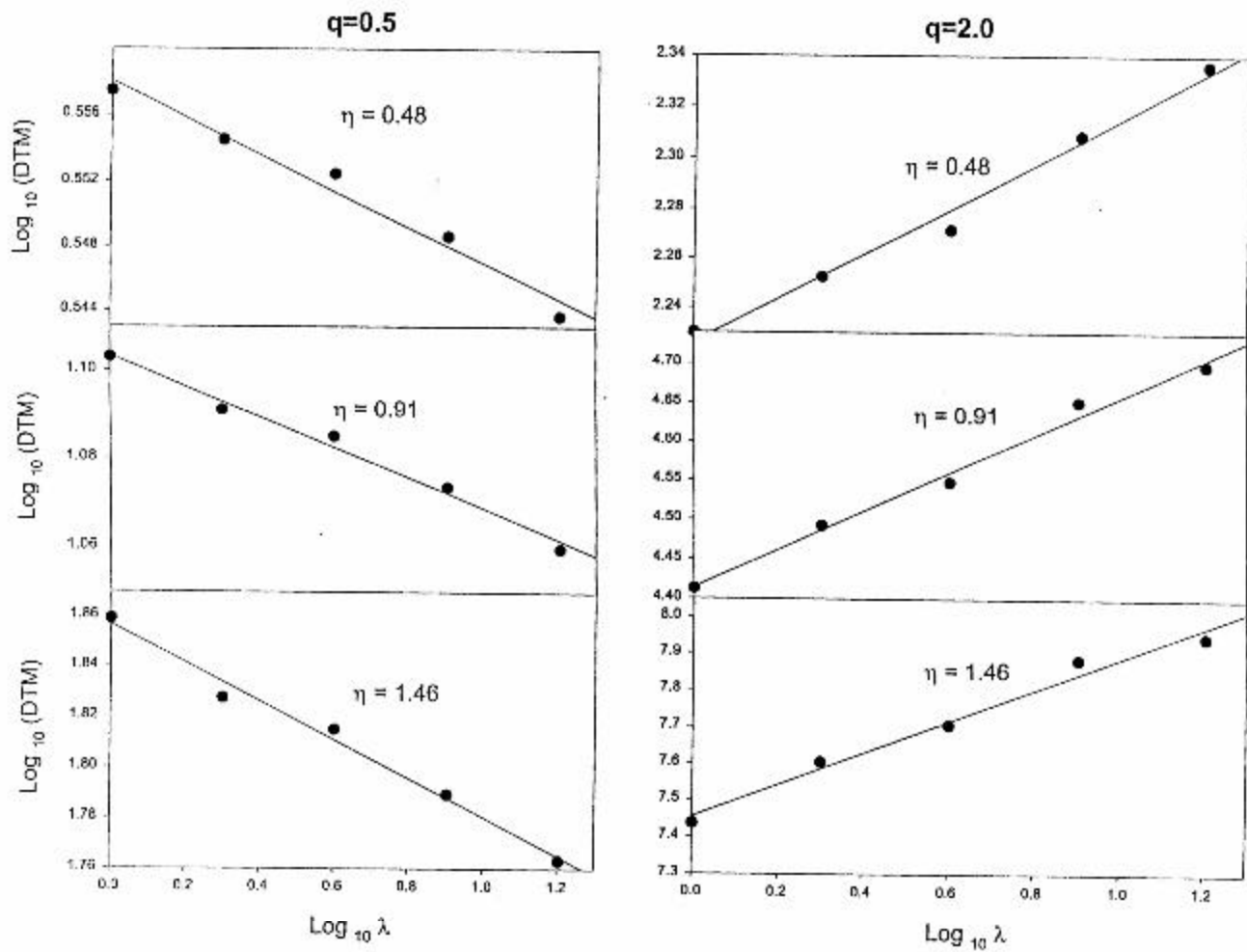


Figure 22. DTM (from equations representing the scaling of the double trace moments) for Well 4B (First Part). λ is the scale ratio, which is greater than or equal to unity, and η is the double trace moment value.

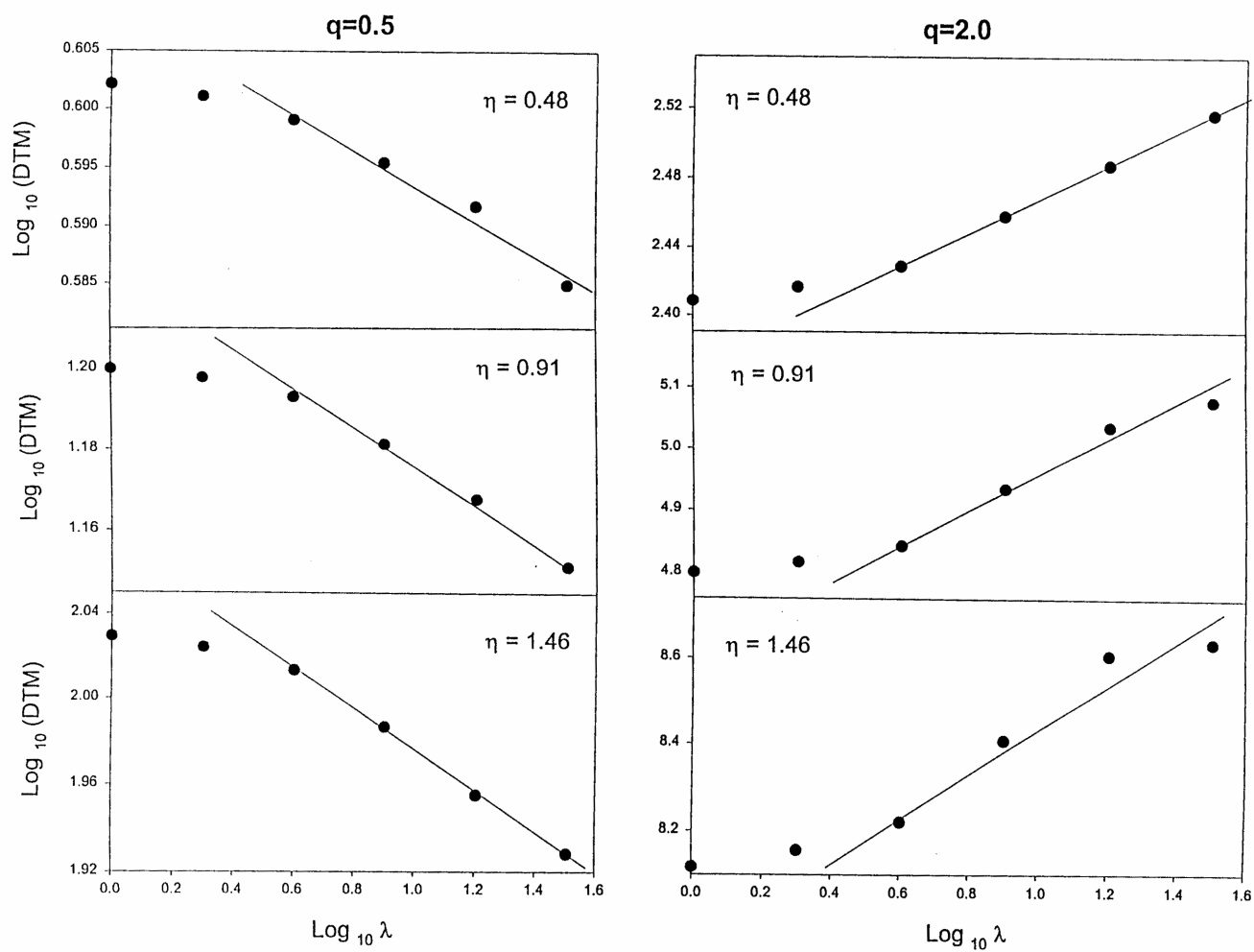


Figure 23. DTM (from equations representing the scaling of the double trace moments) for Well 5. λ is the scale ratio, which is greater than or equal to unity, and η is the double trace moment value.

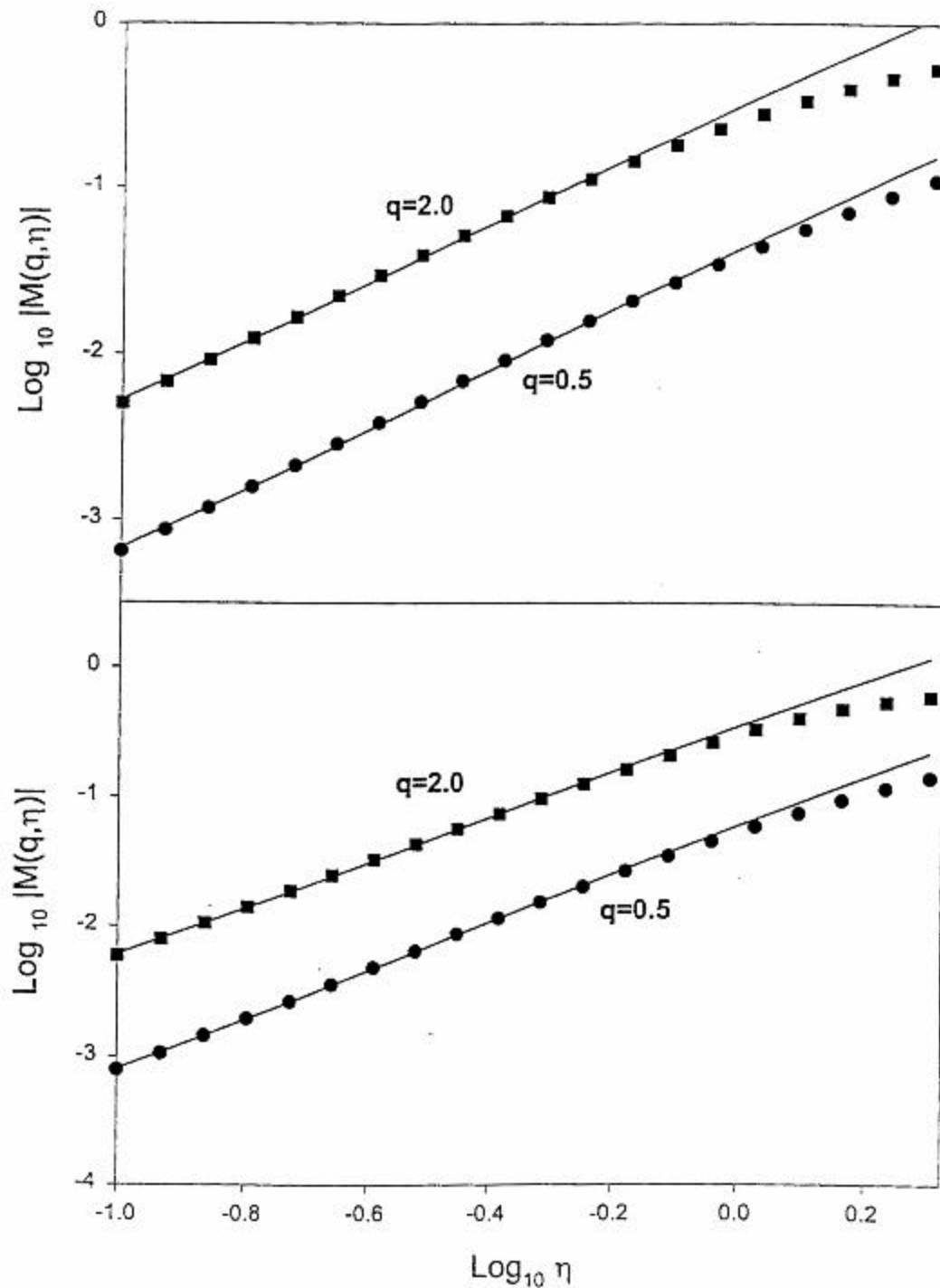


Figure 24. $\text{Log} |M(q, \eta)|$ as a function of $\text{Log} \eta$ for A) Well 4B (First part) and B) Well 5. Note the goodness of fit at low η values. M is the moment scaling exponent, q is the statistical moment to which M applies, and η is the double trace moment value. Linear plots are consistent with the applicability of multifractal theory.

Fractal/Facies Concept

A new concept for representing natural heterogeneity, which is called the *fractal/facies* concept (Lu et al., 2002), was developed based on results of this project and from related work. Motivation for the concept is given below.

Permeability may be conceived as exhibiting two components of variation: a "structure" or "systematic" component and a "random" or "noise" component. If the facies concept is introduced, then the "structure" may be associated with the facies, and the "random" component associated with the permeability variation within facies.

Previous studies have presented evidence that $\log(k)$ increments (k = intrinsic permeability) within pure facies often follow a Gaussian distribution. For example, a k data set from a vertical Berea sandstone core was obtained in the laboratory using a surface gas minipermeameter. It consists of 2,884 consecutive k measurements with 1.27-cm spacings. Recently, Lu et al. (2002) concluded that both the k increments and $\log(K)$ increments have non-Gaussian distributions with heavy, non-Gaussian tails when the entire data set is used for the analysis. However, under the assumption that permeability is related to at least three of the primary facies types found in eolian sequences (that is, grain-flow, wind-ripple, and inter-dune), Goggin (1988) provided evidence that k in each facies is log-normally distributed. Therefore, the $\log(k)$ increments for each stratification should be approximately normally distributed. We checked for this behavior using Goggin's (1988) data. Shown in Figure 25 are results for the inter-dune data, indicating that the cumulative distribution of $\log(k)$ increments are well approximated by a Gaussian cumulative distribution function. Rescaled range (R/S) analysis of $\log(k)$ also shows that long range correlated $\log(k)$ structure is found with a Hurst coefficient $H = 0.39$ (Fig. 26). Similar results were obtained for the grain-flow and wind-ripple facies.

Fractal scaling properties of the outcrop data from southern Utah provide further support of the fractal/facies concept. For the two horizontal transects with 269 measurements in the bioturbated, shallow-marine sandstone studied at the Escalante field site, the $\log(k)$ increments have a Hurst coefficient of 0.34 and are highly Gaussian as documented in Figure 27. These properties are specifically for the bioturbated sandstone, which is considered as a single, pure facies. We conclude, therefore, that there is further field evidence for Gaussian behavior of $\log(k)$ or $\log(K)$ increments within pure facies. This is one of the main motivations for proposing what is called the fractal/facies concept (Lu et al., 2002). This approach, along with the results from fractal analysis of the permeability data, was applied to distributing permeability for reservoir simulation of a portion of West Coalinga Field.

The fractal/facies approach offers a potentially simplifying concept and a method for predicting property distributions consistent with sedimentologically controlled facies architecture in reservoirs. However, to fully develop this approach, further investigation of additional permeability data sets is needed.

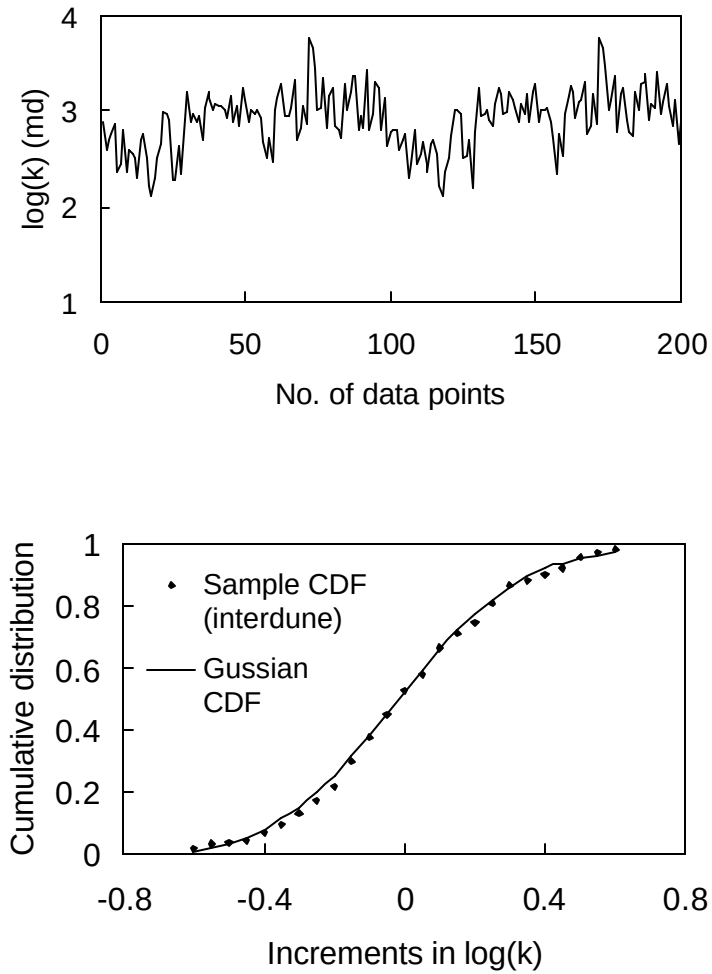


Figure 25. *Top:* Permeability data collected from the inter-dune facies in eolian sandstone by Goggin (1988). *Bottom:* The cumulative distribution of the increments of $\log(k)$ showing that the $\log(k)$ increment distribution is highly Gaussian (from Lu et al., 2002).

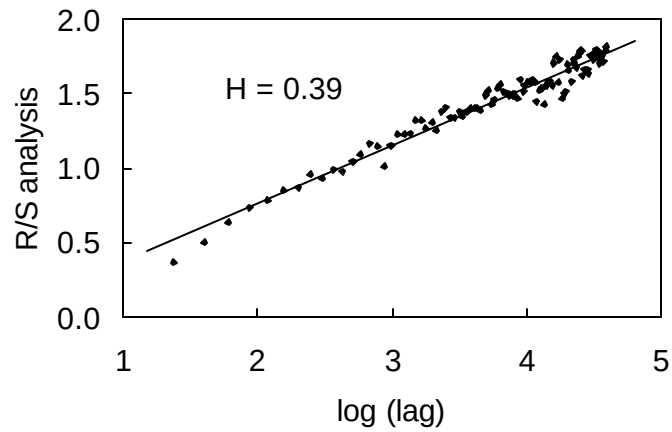


Figure 26. Rescaled range analysis of $\log(k)$ collected from the inter-dune facies in eolian sandstone by Goggin (1988). The Hurst coefficient, H , is given by the slope of the best fitting straight line.

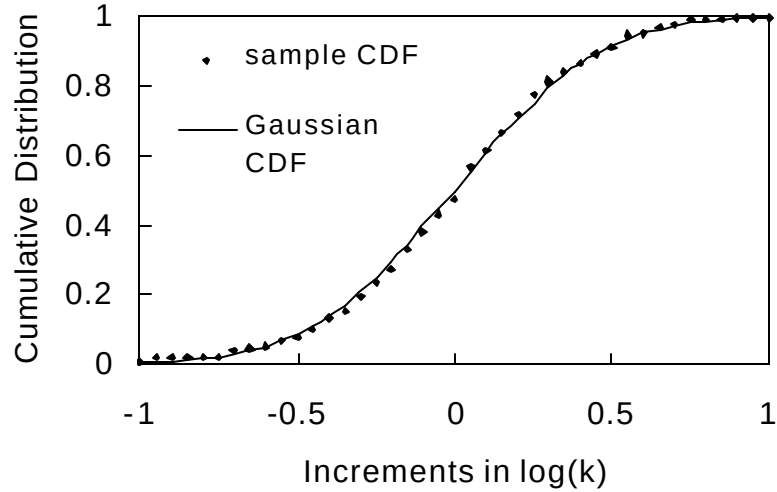


Figure 27. The cumulative distribution function for the $\log(k)$ increments of the bioturbated sandstone from the Southern Utah field site. The distribution function is highly Gaussian.

Construction of Geological Models, West Coalinga Field

Object-based, three-dimensional geologic models were constructed for parts of section 31A in the northern part of West Coalinga Field and section 36D in the southern part of the field (Fig. 2). The models for section 36D were used for the incorporation of permeability distributions for application to steam-flood simulation. The models incorporate geophysical logs as well as lithologic data and depositional interpretations from our core and outcrop investigation of the Temblor Formation in the Coalinga area. Specific geologic models produced include facies tract and lithofacies group models (Figures 28 and 29). Multiple realizations of models were generated to represent the geometry of reservoir zones. In addition, a statistical analysis involving approximately 2000 data points from 13 cored wells in West Coalinga Field was conducted to identify groupings of lithofacies and to evaluate permeability trends in both lithofacies and facies tracts. A cluster analysis was performed to group lithofacies based on permeability, porosity, sorting, grain size, and percent sand. GOCAD three-dimensional modeling and visualization software is being used for this investigation.

The major steps followed for constructing three-dimensional geologic models of facies tracts and lithofacies groups were:

- 1) Loaded bounding surface horizons to provide structural constraints;
- 2) Loaded continuous and discrete geophysical log, lithofacies group, and facies tract data;
- 3) Developed model architecture and geologic regions to define the facies tract and lithofacies group stratigraphic grids;
- 4) Applied sequential indicator simulations to develop a representative and geologically reasonable lithofacies group model; and
- 5) Examined the facies tract and lithofacies group models for geological validity and compared modeling results with cores and geophysical logs.

For the facies tract models, reference horizons were defined based on the regional sedimentological and sequence-stratigraphic relationships, as interpreted in the previous tasks of the project. These horizons were identified in cores and outcrops as stratigraphic bounding surfaces that separate the five major facies tracts: incised valley, estuarine, tide- to wave-dominated shoreline, diatomite, and subtidal (Bridges, 2001; Bridges and Castle, 2002). This approach provides a structural constraint by forcing the model grid to conform to the surfaces, including honoring truncation of stratigraphic intervals by unconformities (Figure 30). In section 31A, six bounding surfaces with a region between each surface were created in GOCAD to represent the five facies tracts present in the northern part of West Coalinga Field. In Section 36D, four bounding surfaces and three regions are present. The facies tracts present in the southern part of the field are estuarine, tide- to wave-dominated shoreline, and subtidal.

In GOCAD, each corner node of the grid is assigned the facies group and facies tract value of the surface. The output from the model lists the x, y, and z location, facies tract value, facies group value and oil saturation percentage for that node. Additionally, thick intervals of a single facies group or facies tract were broken up into smaller intervals (layers) for the purpose of reservoir simulation.

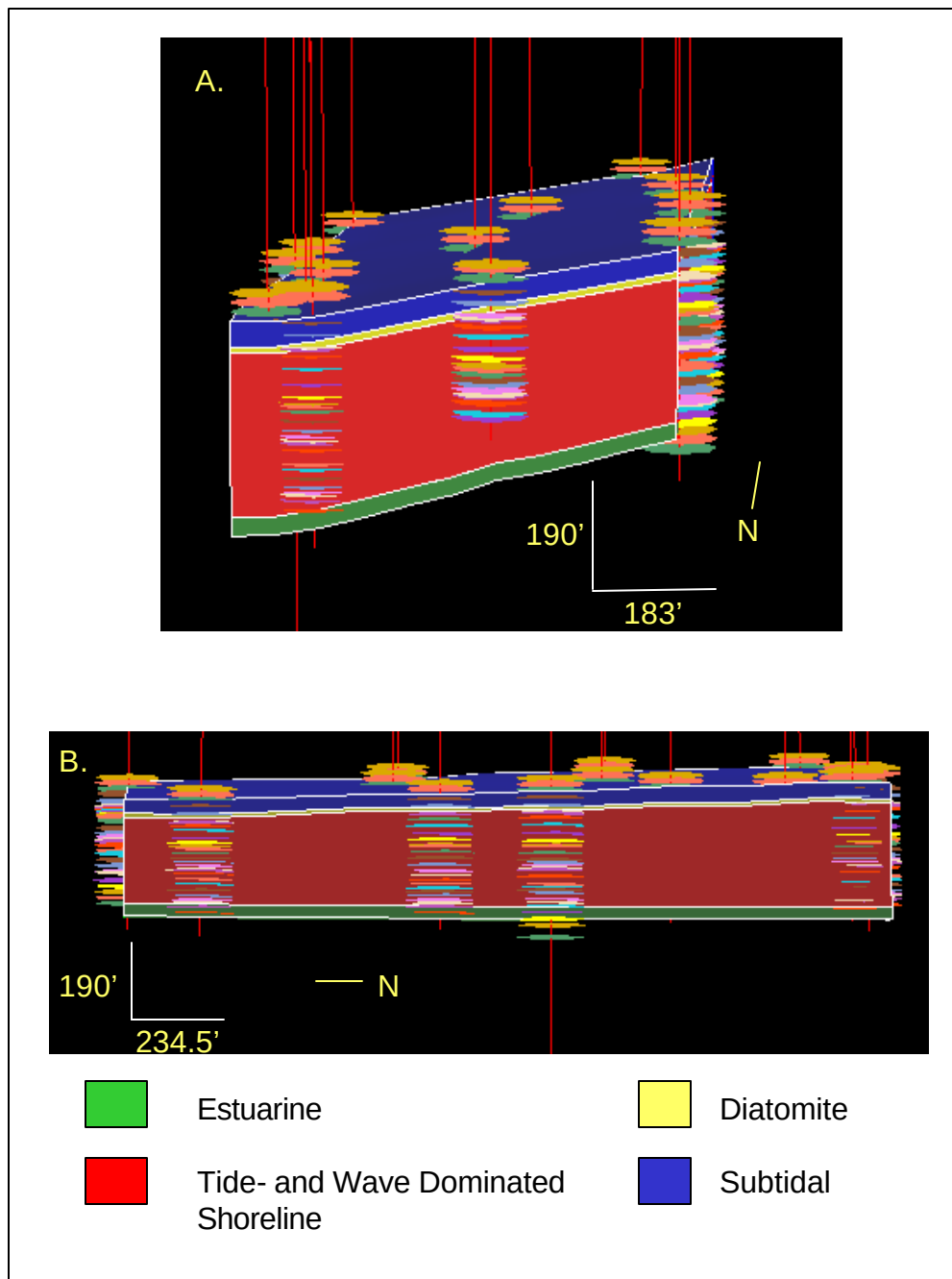


Figure 28. Facies tract model for the simulation area shown in Figures 30 and 31. Laterally correlative bounding surfaces separate the facies tracts. A) View of the northern face of the model. B) View looking at the east side of the model. Well paths are shown. From Current (2001).

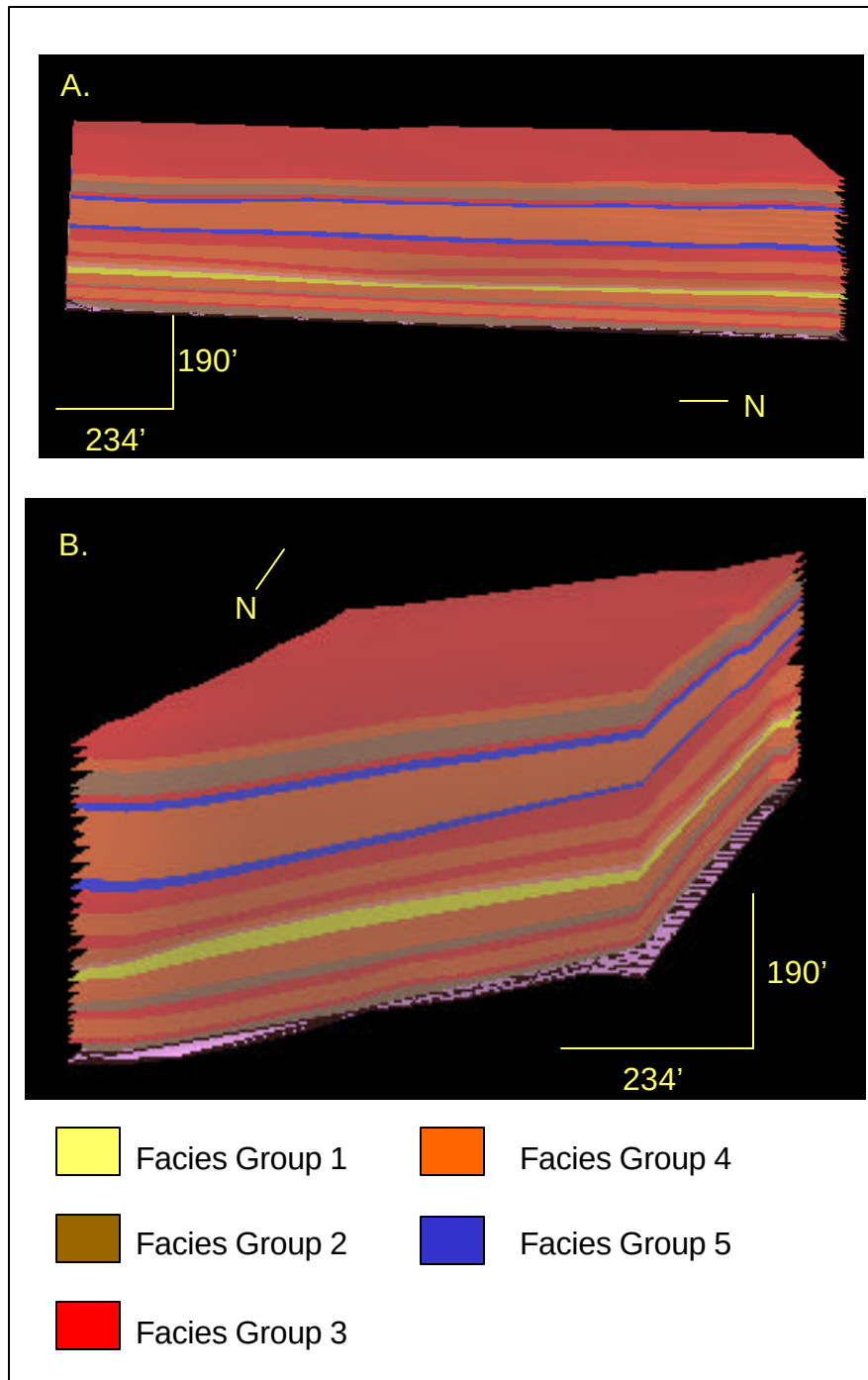


Figure 29. Facies group model for the simulation area shown in Figures 30 and 31. The individual lithofacies and their groups are listed in Table 4. A) View looking at the east side of the model. B) View of the northern face of the model. From Current (2001).

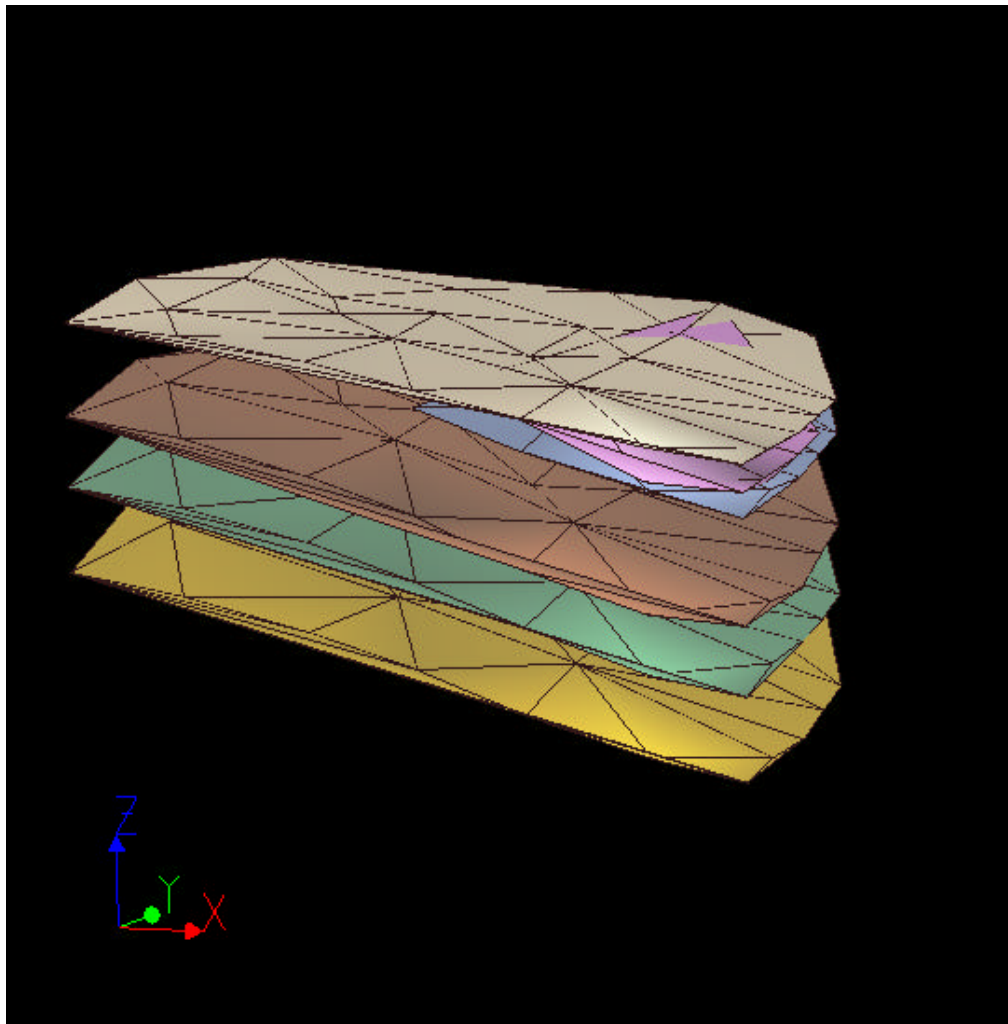


Figure 30. Bounding Surface horizons created from connecting input points within GOCAD. The bottom and top horizons (Bounding Surfaces 1 and 6, respectively), correspond with the base and top of the Temblor Formation. The other horizons correspond with contacts between the facies tracts. Bounding Surfaces 4 and 5 (the blue and purple horizons) are truncated by erosion at the top of the Temblor Formation. The Y axis points in the direction of north. Section 31A. From Bridges (2001).

Reservoir Simulation, West Coalinga Field

Background and Approach

Geological modeling software, as described above, was used to merge the petrophysical properties (e.g., the fractal permeability structure) of the wells in the simulation area with the stratigraphy. The geologic model grid provided the framework for the flow simulation mesh, and petrophysical properties were assigned to all cells of the mesh. Numerical simulations of steam injection into three adjacent 5-spot well configurations in West Coalinga Field were performed (Fawumi, 2002) to examine the responses of the geologic models (Figure 31). This is an area with an ongoing steam flood being conducted by ChevronTexaco for recovery of heavy oil. In this area, 5-spot well configurations are centered around the central producing wells of 127, 128, and 22 (Figure 32).

Steam injection operations in this area commenced in 1995. A five year period (October 1995 to October 2000) was selected for the flow simulations. The starting date corresponded to the commencement of the steam flood. After October 2000, the production/injection scheme was changed, and a horizontal production well was installed through the study area, altering the overall flow regime. During the simulation period, the injection and extraction histories for the wells in the study area varied greatly. The steam volume of the injection wells changed monthly, and many of the injection wells did not come online until 1997 or later. The production wells were regularly shut down for maintenance, or were converted into steam injection wells for a few months before being turned back into production wells. All of these changes in production and injection were honored in the input of the flow simulator.

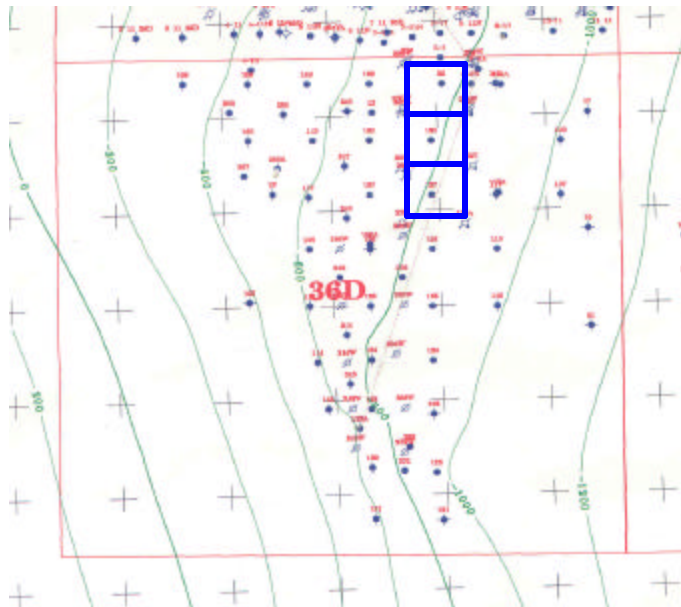


Figure 31. Location of simulated area in Section 36D, West Coalinga Field. The blue lines show the

approximate outline of three adjacent 5-spot injection-production well configurations.

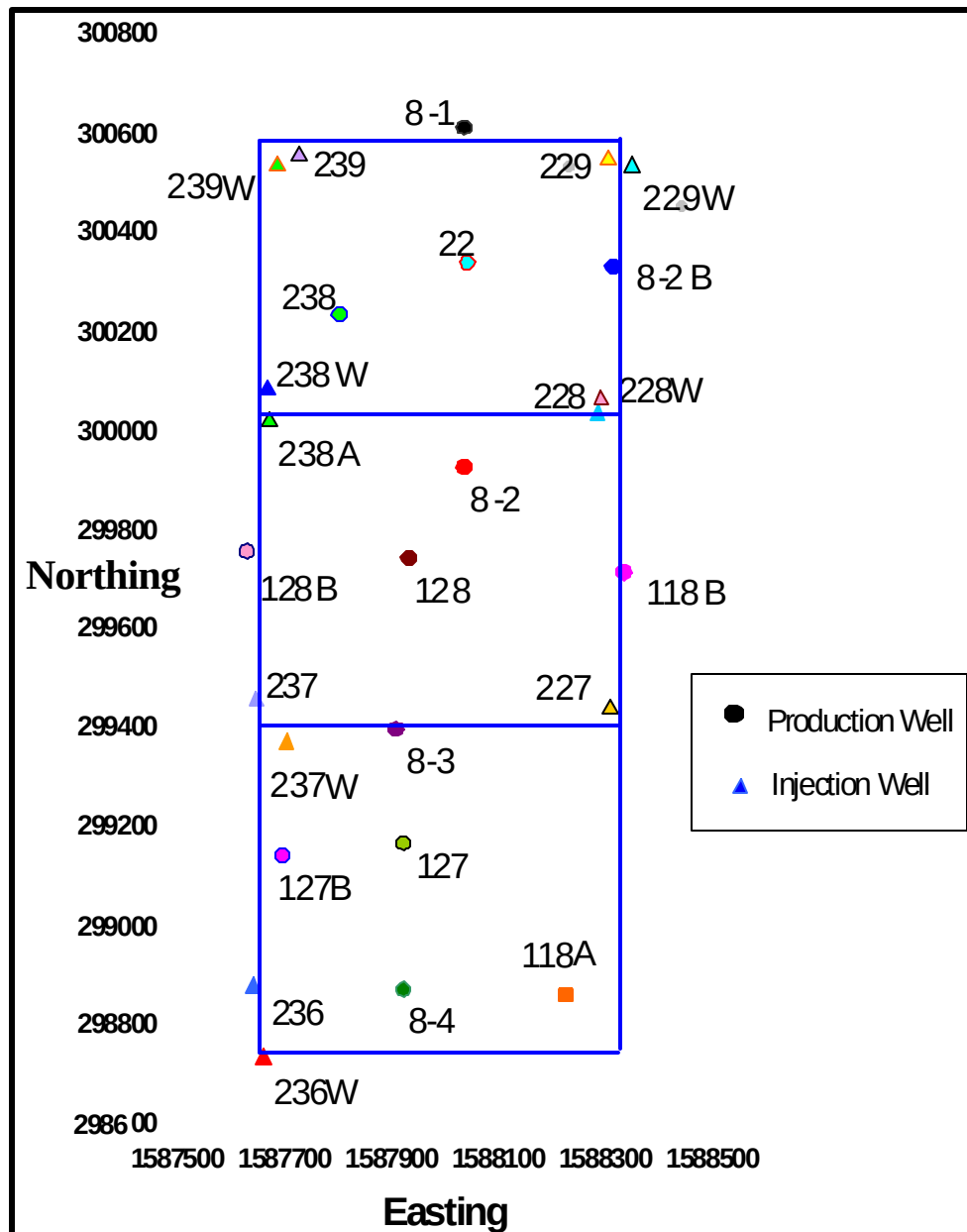


Figure 32. Location of the producing and injection wells for the three 5-spot configurations used in the numerical flow simulations.

For performing the simulation at West Coalinga, a numerical steam flood simulator capable of modeling multiphase, multicomponent, nonisothermal flow was required that could provide (at the minimum):

- (1) a mass balance on water and oil,
- (2) an energy balance,
- (3) three-phase flow of gas, water, and oil phases,
- (4) heat transfer by convection and conduction with phase change effects,
- (5) the capability for three-dimensional flow in anisotropic heterogeneous media.

T2VOC (Falta et al., 1995) possesses the capabilities noted above and has been used extensively by government agencies and private corporations to model the flow of water, air (steam) and oil in multi-dimensional, heterogeneous porous media. This simulator, which is publicly available (at a cost), was developed over a 20 year period at the Lawrence Berkeley Laboratories in California, and was originally designed for geothermal reservoir modeling. The model and source codes are distributed by the DOE Energy Science and Technology Software Center (web: <http://www.osti.gov/estsc/>; email: estsc@adonis.osti.gov).

The governing partial differential equations (PDEs) for the transport of water and a non-aqueous component (oil) are presented along with the energy balance used to account for non-isothermal flow. The details of these equations can be found in Falta et al. (1995). A general finite difference formulation is used to solve the multiphase, multicomponent mass and energy balance equations.

$$\begin{aligned} \frac{\partial}{\partial t} \left(f \left[S_g C_g^w + S_w C_w^w \right] \right) = \nabla \cdot \left(\frac{C_g^w k_{rg} k_o^o}{m_g} (\nabla P_g + r_g g \nabla z) \right) \\ + \nabla \cdot \left(\frac{C_w^w k_{rw} k_o^o}{m_w} (\nabla (P_g - P_{cgw}) + r_w g \nabla z) \right) + q^w \end{aligned}$$

Equation 1. The PDE for the water component.

$$\begin{aligned} \frac{\partial}{\partial t} \left(f \left[S_g C_g^o + S_o C_o^o \right] \right) = \nabla \cdot \left(\frac{C_g^o k_{rg} k_o^o}{m_g} (\nabla P_g + r_g g \nabla z) \right) \\ + \nabla \cdot \left(\frac{C_o^o k_{ro} k_o^o}{m_o} (\nabla (P_g - P_{cgw} + P_{cow}) + r_o g \nabla z) \right) + q^o \end{aligned}$$

Equation 2. The PDE for the oil component (pseudo component)

$$\begin{aligned} \frac{\partial}{\partial t} \left(f \left[S_g r_g u_g + S_w r_w u_w + S_o r_o u_o \right] + (1-f) r_R C_R T \right) = & \nabla \cdot \left(\frac{h_g r_g k_{rg} k_o^\circ}{m_g} (\nabla P_g + r_g g \nabla z) \right) \\ & + \nabla \cdot \left(\frac{h_w r_w k_{rw} k_o^\circ}{m_w} (\nabla (P_g - P_{cgw}) + r_w g \nabla z) \right) + \nabla \cdot \left(\frac{h_o r_o k_{ro} k_o^\circ}{m_o} (\nabla (P_g - P_{cgw} + P_{cow}) + r_o g \nabla z) \right) \\ & + l_T \nabla^2 T + \sum_{j=1,n} q_j^h \end{aligned}$$

Equation 3. The PDE for multiphase heat transfer

In the flow simulator, the production wells were modeled using a productivity index (PI), where production occurs against a prescribed flowing wellbore pressure. This condition implies that minimal oil production will occur until the pressure gradient generated by the steam injection is conveyed to the producing wells. The PI is a function of the permeability of the layer the well is perforated in, the well radius, and the effective radius of the cell. This is calculated using the following relation:

$$PI = [2 * \pi * k * \Delta z] / [\ln (r_e/r_w) + s - 0.5]$$

Equation 4. The productivity index (PI) for the producing wells.

where k = permeability of the layer, Δz = layer thickness, r_e = grid block radius, r_w = well radius, and s = skin factor.

In addition to the PI, production occurs against a prescribed flowing wellbore pressure (P_{wb}). Discussions with Chevron production engineers revealed that the fluid level in the well is kept at the level of the pump, and that the pump is typically located at the halfway point of the perforations. Thus a P_{wb} of atmospheric pressure was assigned to the top element of the producing wells.

While the injection rates were specified by Chevron, the enthalpy of the injected fluid had to be calculated. The enthalpy is a function of the steam quality and temperature. At the Coalinga field, the steam quality is 60%, which means that the injectate is 60% steam and 40% hot water. The equation used to calculate the enthalpy of the mixture is:

$$h_{\text{mix}} = \chi_w * h_w + \chi_s * h_s$$

Equation 5. The enthalpy of the injected fluid

where h_{mix} = enthalpy of the mixture, h_w = enthalpy of the water, h_s = enthalpy of the steam, χ_w = fraction of water, and χ_s = fraction of steam. The enthalpies are referenced to 500°F, which is the temperature of the injected gas/fluid mixture.

Five-Spot Configuration and Boundary Conditions

The 5-spot configuration is based on the principle of a central production with an injection well at each of the four corners (Figure 33). When the 5-spots being modeled are adjacent, the corner injection wells of adjacent 5-spots are shared. Ideally, this configuration produces a no flow boundary at the edges of the 5-spot. In the flow simulations, the edge of each 5-spot configuration is modeled as a no-flow boundary. This means that a no-flow boundary was applied around the sides of the entire model. The bottom layer of the model is designated as a very low permeable layer with a no flow boundary below it. The top two layers of the model also have very low permeabilities, with a no flow boundary above them.

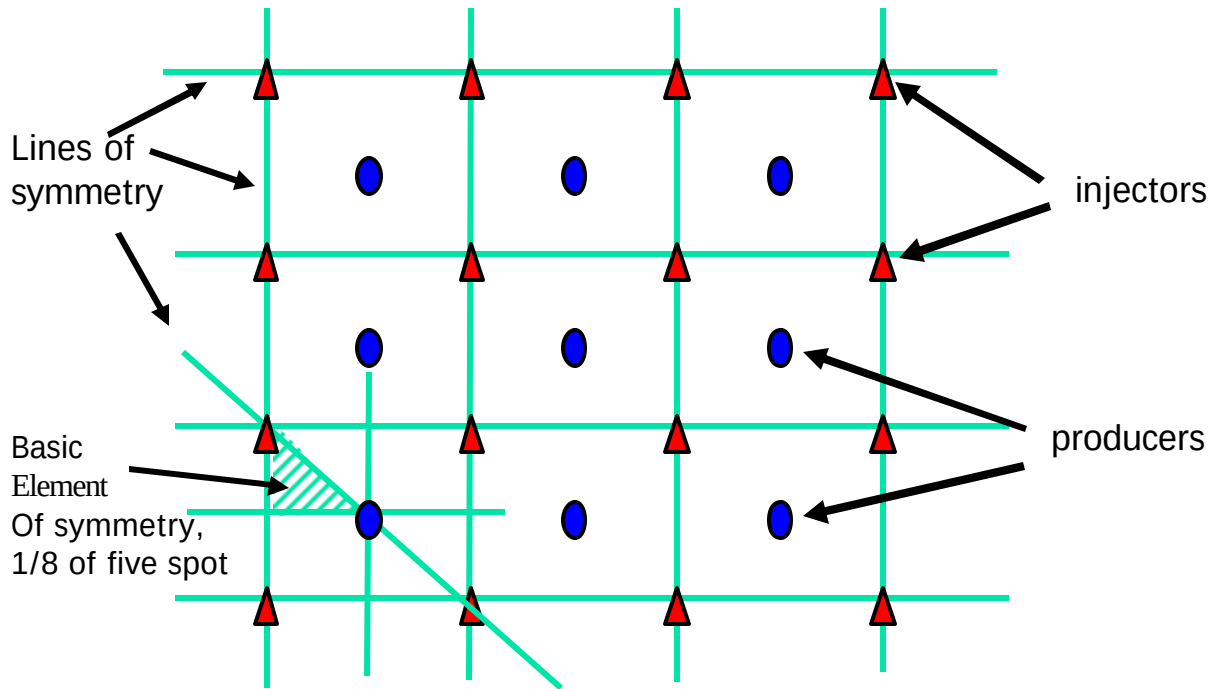


Figure 33. Standard repeated 5-spot pattern. The production wells are shown as circles and the injection wells are shown as triangles.

Steam Flooding in Heavy Oil Reservoirs

Heavy oil is an important energy resource with large worldwide reserves, but its extremely high viscosity at reservoir temperatures limits its removal from the subsurface using traditional pumping techniques. Steam injection can reduce the oil viscosity to the point where it will readily flow due to the effect of heat (Figure 34). Large pressure gradients generated by the steam front also help to mobilize the heavy oil. Lower interfacial tension and solvent bank effects may also help, but are secondary. The viscosity of West Coalinga heavy oil is about 900 centipoise at a reservoir temperature of 40 degrees centigrade (or 104 degrees Fahrenheit).

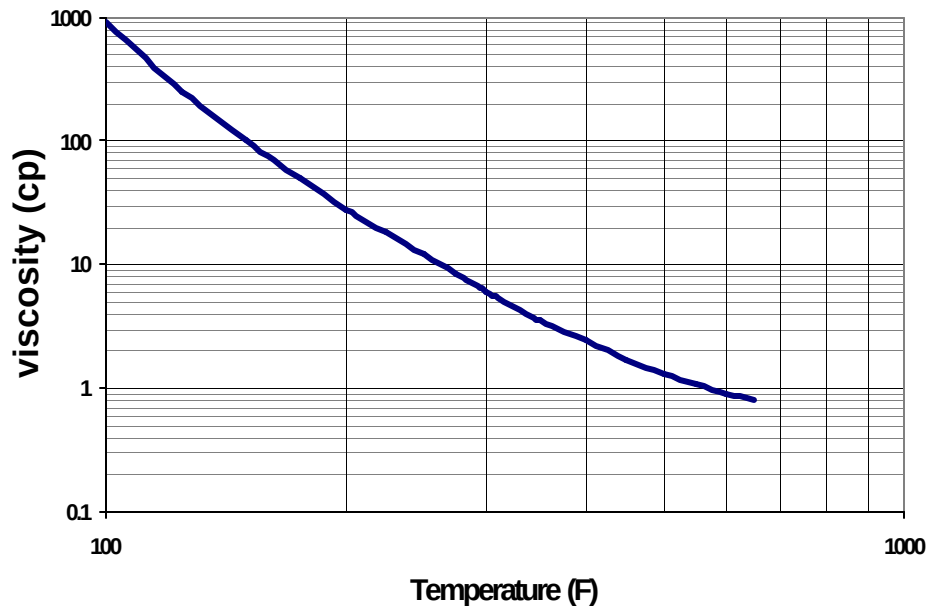


Figure 34. Viscosity of West Coalinga Crude Oil (provided by Chevron).

Grid Framework of the Numerical Flow Simulator

GOCAD, which was used for the geological modeling, bases its grid architecture on the connections between vertices, while T2VOC uses a node-centered approach to calculate the flow of fluid and heat between cells. As no grid conversion program was commercially available, a conversion program was written to handle the process. The conversion program computed the cell geometry for T2VOC and assigned all the required cell properties, as follows:

- (1) Grid cells were defined by 8 corner points (vertices) from the GOCAD output,
- (2) A cell ID number was assigned to each element,
- (3) The coordinate of the center node of each element was calculated,
- (4) The distance between the center nodes of adjacent elements was calculated,
- (5) Oil saturations were calculated for each cell as the mean of the oil saturations from the GOCAD vertices,
- (6) Water and gas saturation were calculated for each element,
- (7) The center and area of the interface between grid cells were calculated,
- (8) The angle between the gravitational vector and the line connecting adjacent grid was determined,
- (9) The volume for each grid cell was calculated,
- (10) The productivity index was assigned for each cell penetrated by the producing wells,
- (11) The mesh and reservoir parameters were formatted in the appropriate T2VOC input format.

The resulting grid contained 32 vertical layers, 10 cells in the x direction and 30 cells in the y direction, yielding a total of 9600 cells. The grid framework is shown in Figure 35.

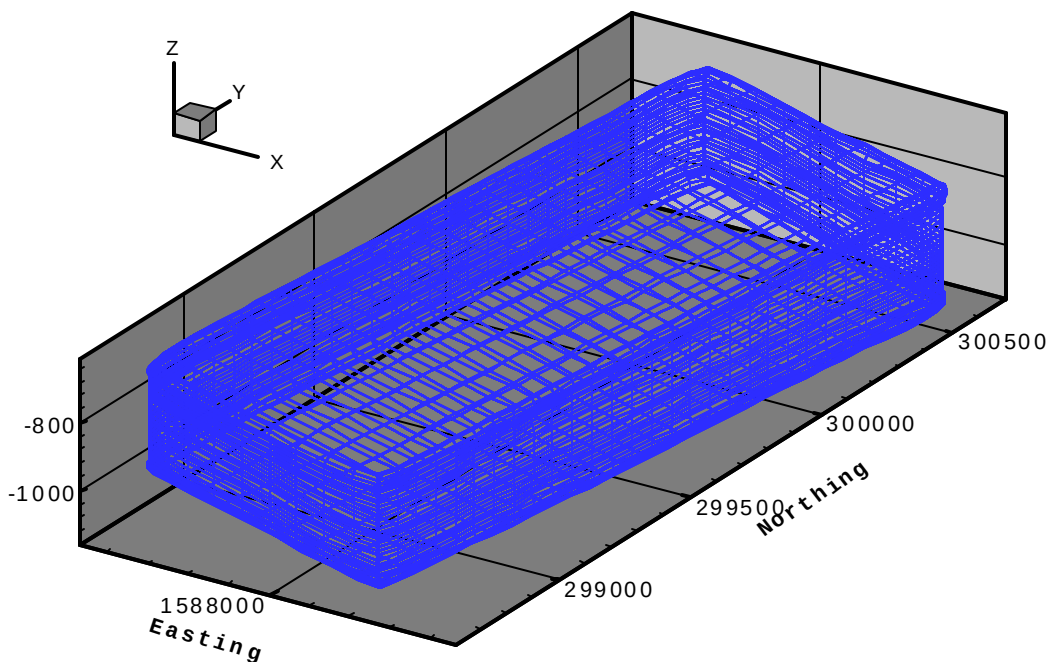


Figure 35. Grid framework used for permeability distributions in the numerical flow simulator.

Permeability Distributions for Simulation Input

Facies Tract Model

Three alternative approaches (facies tract, facies group, and fractal) for distributing permeability were taken, and the results compared by using the distributions for simulation input. The permeability distribution was the only variable among between the three approaches.

In the facies tract model, each facies tract within the stratigraphic architecture was assigned a single value of mean permeability (Table 8). The permeability distribution is dominated by a relatively homogenous distribution in the lower layers (Figures 36 and 37).

Table 8. Permeability of each element of the stratigraphic architecture in the facies tract model.

Facies Tract	Mean Permeability (mD)
Tract 1	562
Tract 2	316
Tract 3	316
Tract 4	22
Tract 5	224

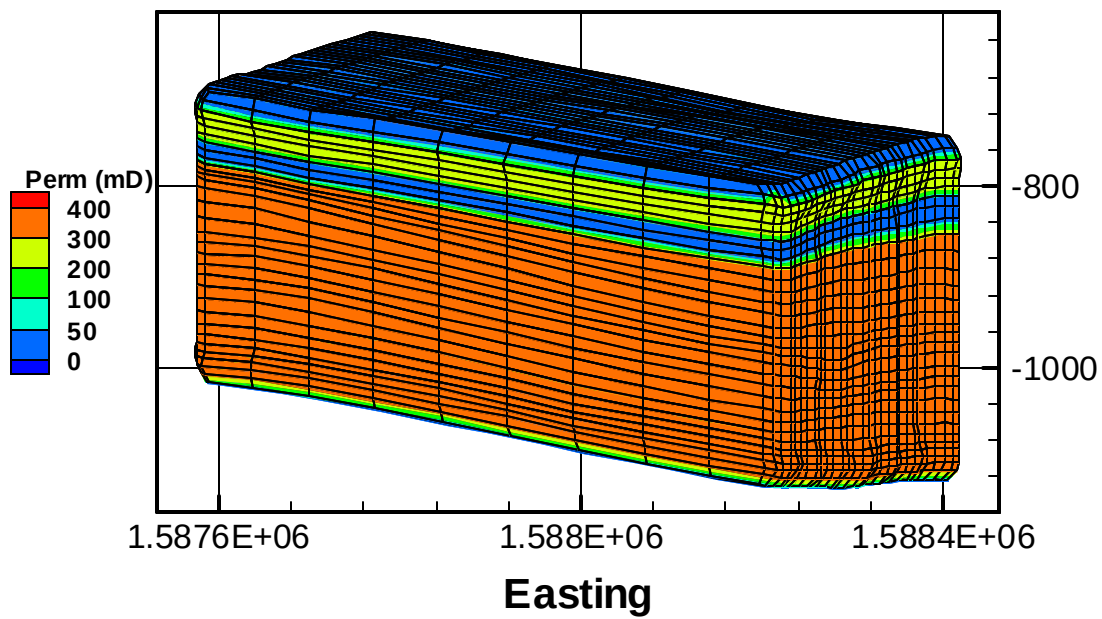


Figure 36. Facies tract permeability distribution in the Easting direction (South end).

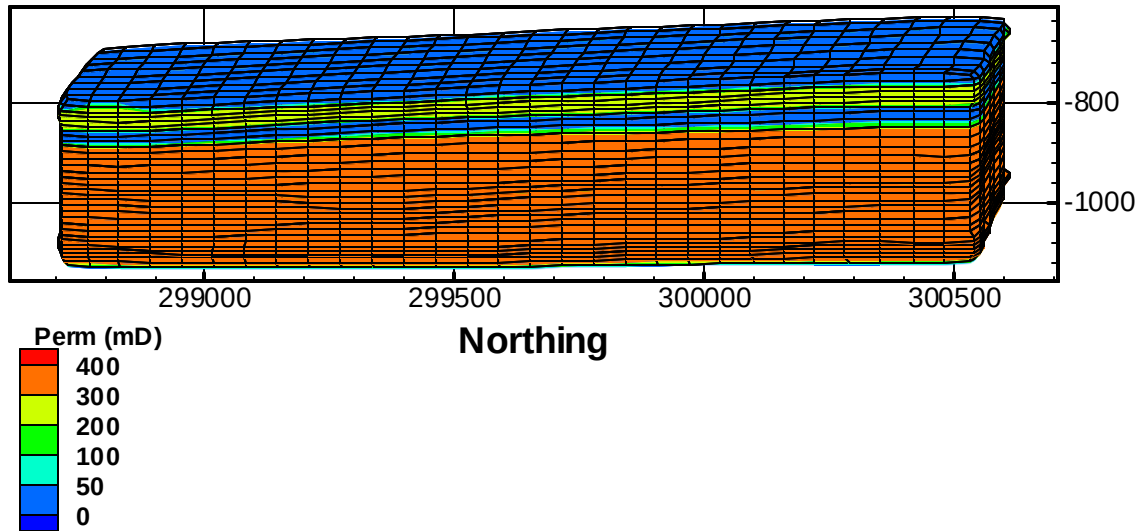


Figure 37. Facies tract permeability distribution in the Northing direction (East side).

Facies Group Model

Each facies group within the stratigraphic architecture was assigned a single value of mean permeability in the facies group model (Table 9). The resulting distribution is characterized by greater variability and a higher degree of vertical anisotropy than shown by the facies tract model (Figures 38 and 39).

Table 9. Permeability of each architectural unit of the facies group model.

Facies Group	Mean Permeability
Group 1	3180 md
Group 2	500 md
Group 3	255 md
Group 4	525 md

Group 5	225 md
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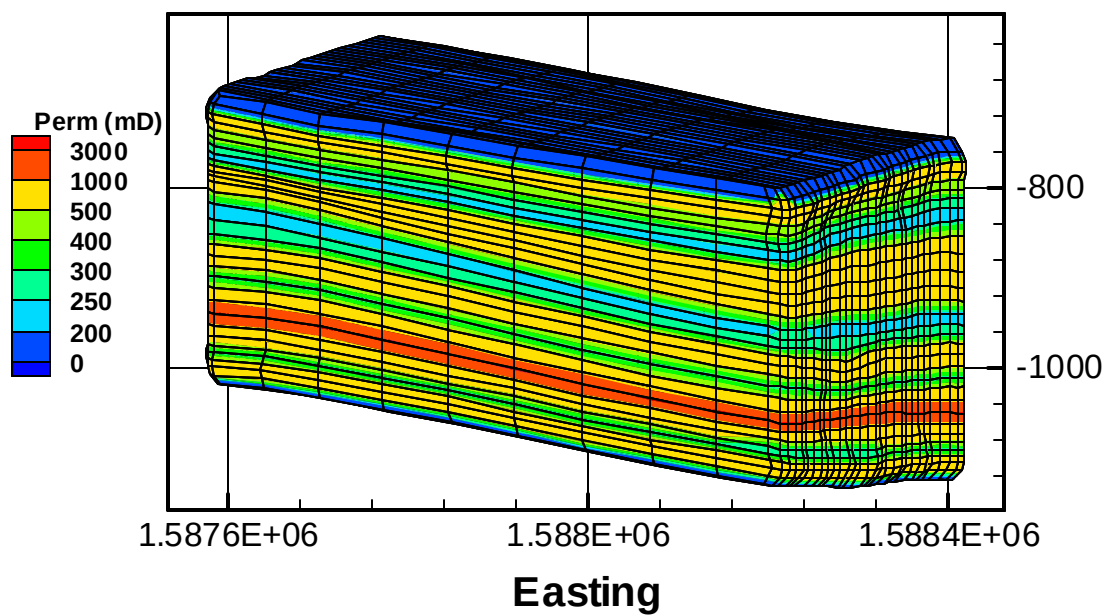


Figure 38. Facies group permeability distribution in the Easting direction (South end).

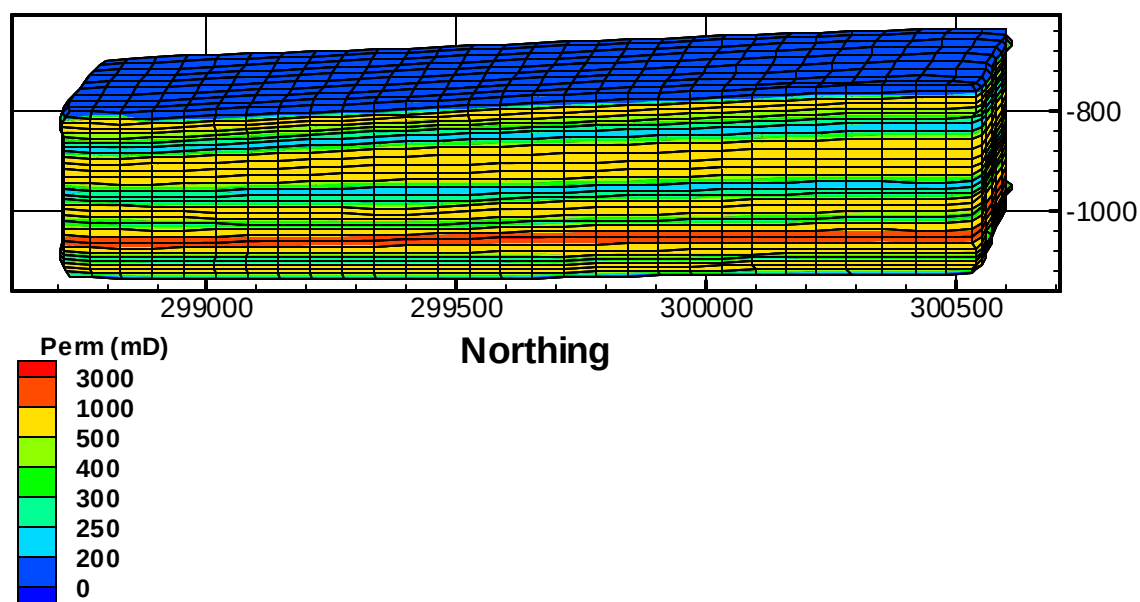


Figure 39. Facies group permeability distribution in the Northing direction (East side).
Fractal Model

A finer grid of fractal permeabilities was generated for each facies group, and then the corresponding values were assigned to each layer of the coarser simulation mesh depending upon the facies group designation of the layer. The finer grid was constructed on a 1.52 m by 1.52 m (5 feet by 5 feet) mesh, with a fractal permeability assigned to each node of the mesh.

Based on their location in the coarser simulation grid, the corresponding fractal permeability values were extracted, preserving the facies group structure in the model. The fine grid fractal permeability values were upscaled to the simulation grid using an arithmetic mean for the horizontal permeability, and a harmonic mean for the vertical permeability (Table 10). Compared to the facies tract and facies group models, a much higher degree of permeability heterogeneity is represented by the fractal model (Figures 40 and 41).

Table 10. Permeability of the units of the fractal group model

Fractal Group	Arithmetic Mean		Harmonic mean	
	Perm (mD)	Perm (m2)	Perm (mD)	Perm (m2)
1	1744	1.721E-12	1413	1.395E-12
2	662	6.537E-13	181	1.787E-13
3	397	3.918E-13	196	1.931E-13
4	918	9.060E-13	128	1.262E-13
5	606	5.978E-13	159	1.573E-13

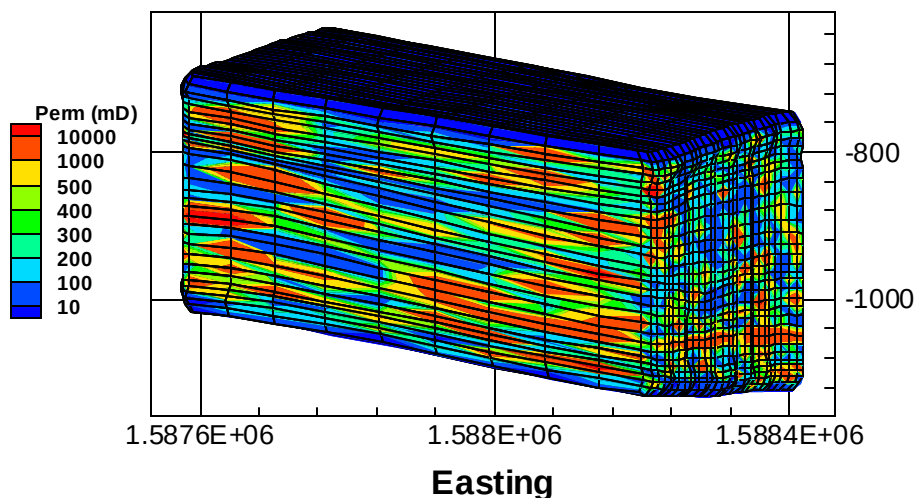


Fig 40. Fractal group permeability distribution in the Northing direction (West side)

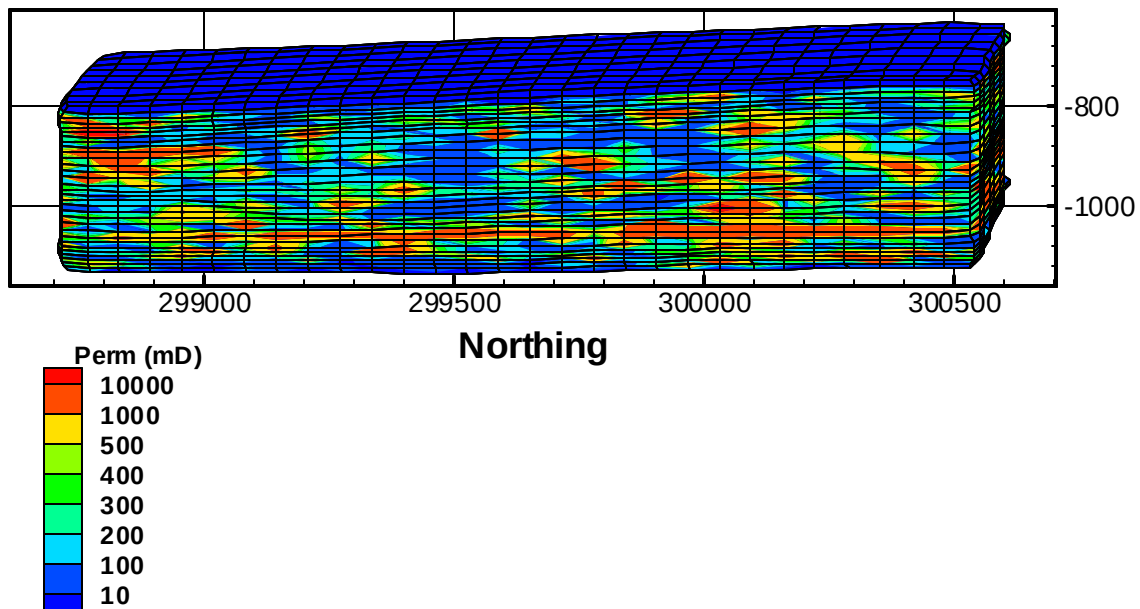


Figure 41. Fractal group permeability distribution in the Northing direction (East side)

Initial Oil Saturation and Relative Permeability

The oil and water phase relative permeability curves were obtained from core data and were provided by Chevron. However, flow simulations using these values generated results in which the water-to-oil ratio was off by a factor of 10 or more when compared to field values. This initiated a comprehensive sensitivity study to determine the factors contributing to this phenomenon. Two parameters were identified that primarily controlled the oil and water production rates. The parameter with the greatest influence on the water production was the endpoint for the relative permeability of the water phase in an oil-water mixture. The oil production was found to be controlled by both this parameter and by the initial oil saturation. Accordingly, to better match the field values, the overall oil saturations were increased by 20% above the values derived by Chevron from well logs (with an upper limit of 70% oil). As the initial oil saturations in the model were interpolations of the values provided, there was enough uncertainty to support the 20% increase. The resulting distribution of oil saturation is shown in Figure 42.

In a similar fashion, the endpoint for the water relative permeability curve at 100% water saturation was lowered from 0.56 (reported by Chevron) to 0.15. The adjustment of this parameter was justified by

the following:

- (1) The relative permeability data for the entire field was based on one small interval of core, which may not be representative of all the lithologies.
- (2) A similar modification was performed by Hazlett et al. (1997) in a modeling study of steam injection into the Midway-Sunset field in the San Joaquin Basin.

The resulting relative permeability curves are shown in Figure 43.

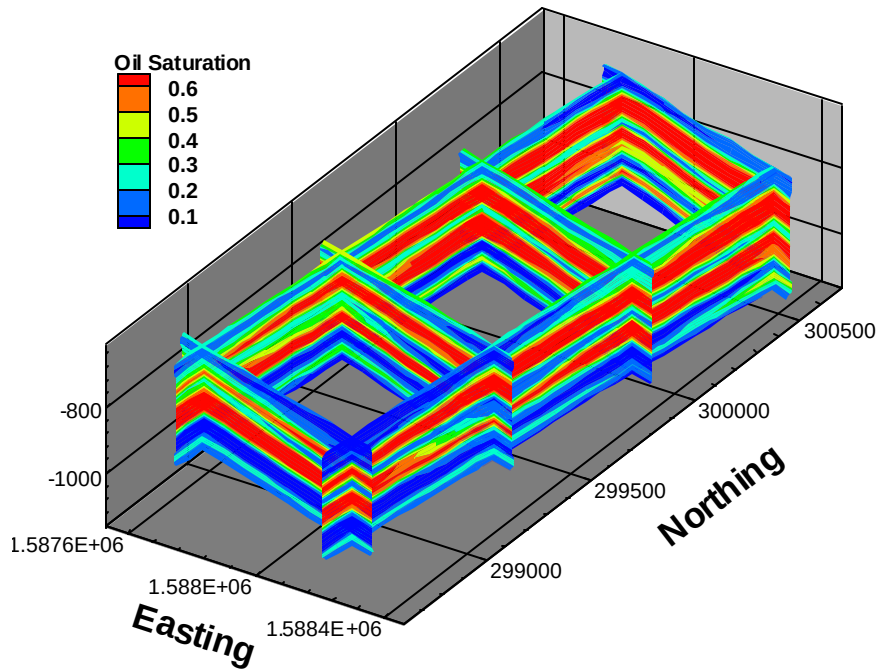


Figure 42. Initial oil saturations after 20% increase (up to 0.7 maximum).

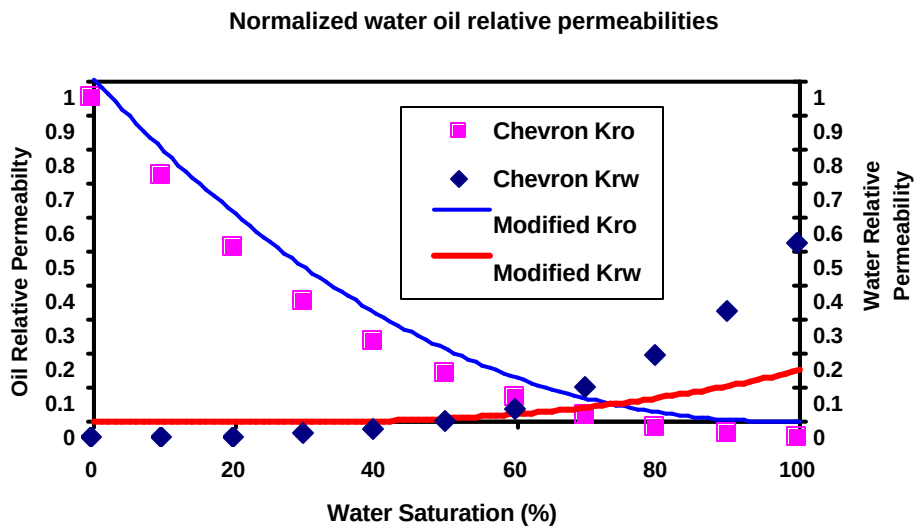


Figure 43. Modified relative permeability curve used in the model. The endpoint of the Modified Krw (red line) represents a deviation from the Chevron data, but is supported by data from a study of the Midway-

Sunset field (Hazlett et al., 1997).

Simulation Results

The oil saturations and temperatures in the reservoir at the end of the 5 year steam injection simulation for each of the three permeability distribution models are presented (Figures 44-49). Visually, the differences in the three models are minimal. It is likely that this implies reservoir response is controlled more by the imposed pressure regime and boundary conditions than by the permeability contrasts. The temperature distributions are a function of the injection history and pressure at the corner wells, and the resulting oil saturations are directly related. Where there is more heat (and pressure), the reservoir has been depleted to a greater extent. The oil saturation distribution for the fractal model (Figure 49) reflects the greater permeability contrast between the layers, and the temperature distribution reflects a slight decrease in the uniformity of the front as seen in the other cases.

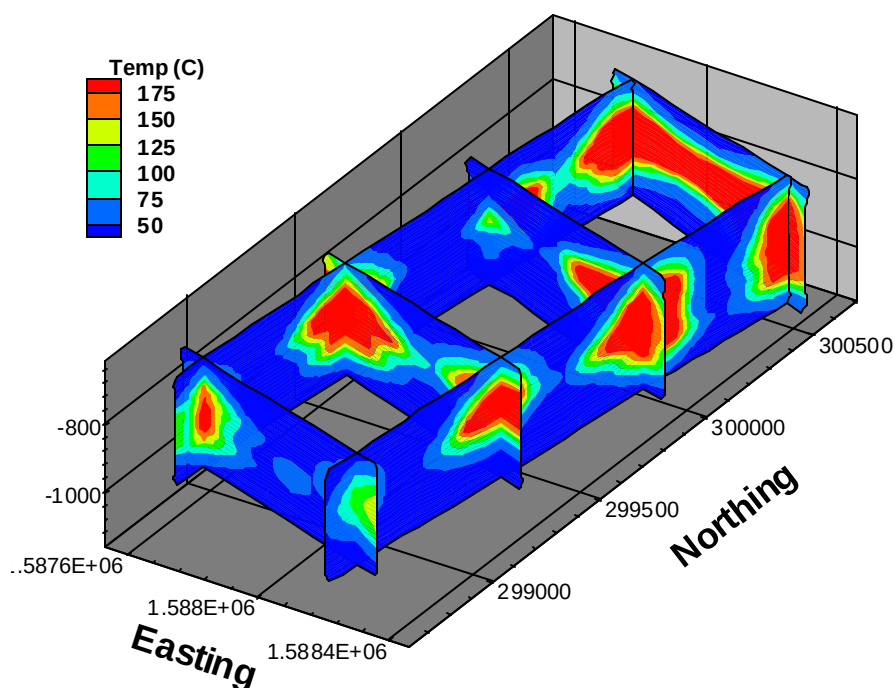


Figure 44. Facies tract temperatures at 5 years

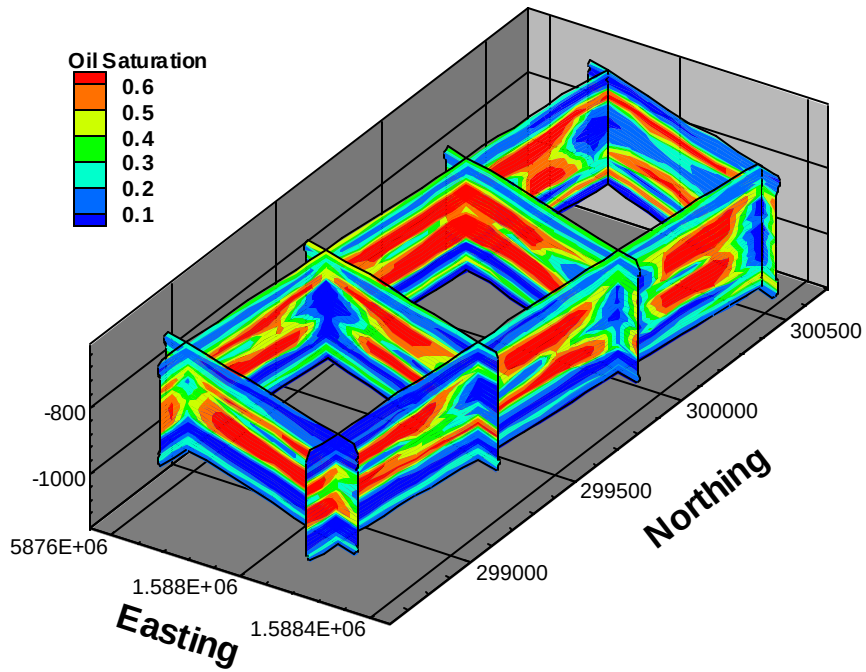


Figure 45. Facies tract oil saturations at 5 years.

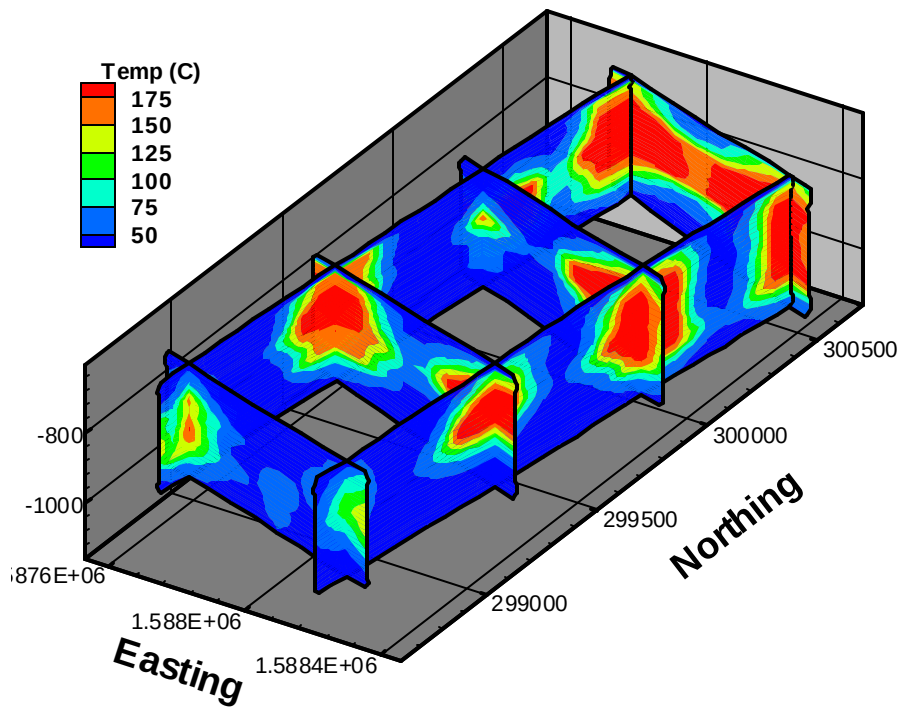


Figure 46. Facies group temperatures at 5 years

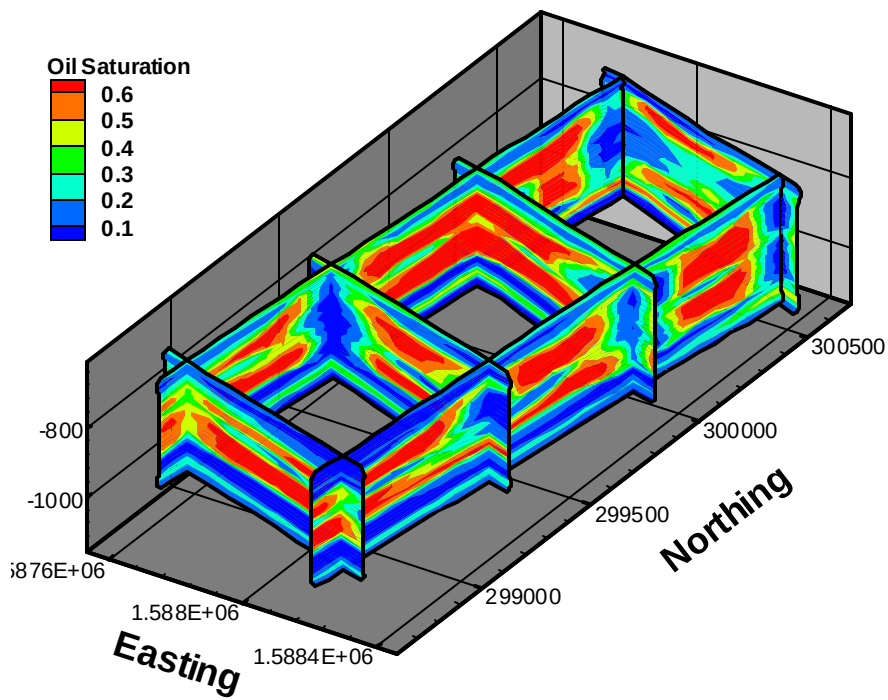


Figure 47. Facies group oil saturations at 5 years

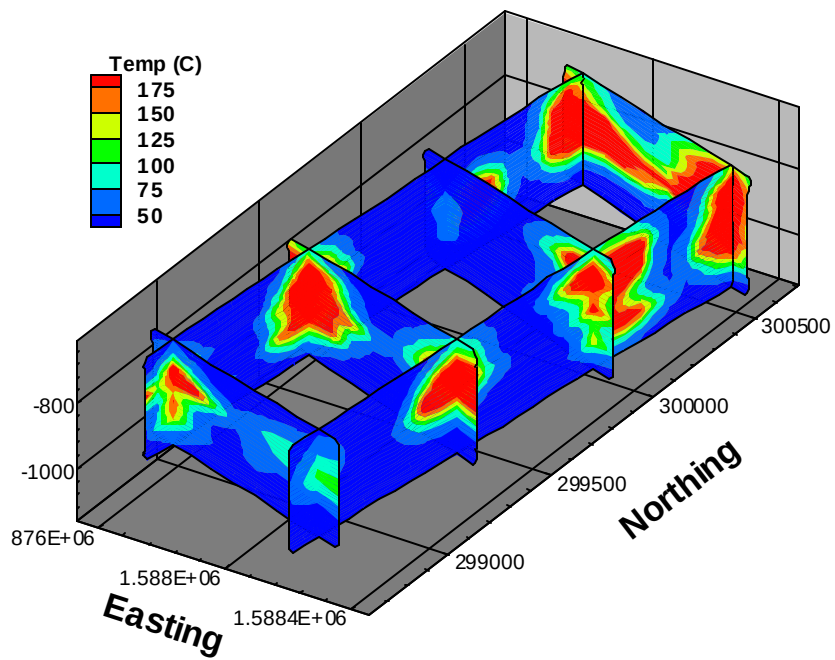


Figure 48. Fractal group temperatures at 5 years

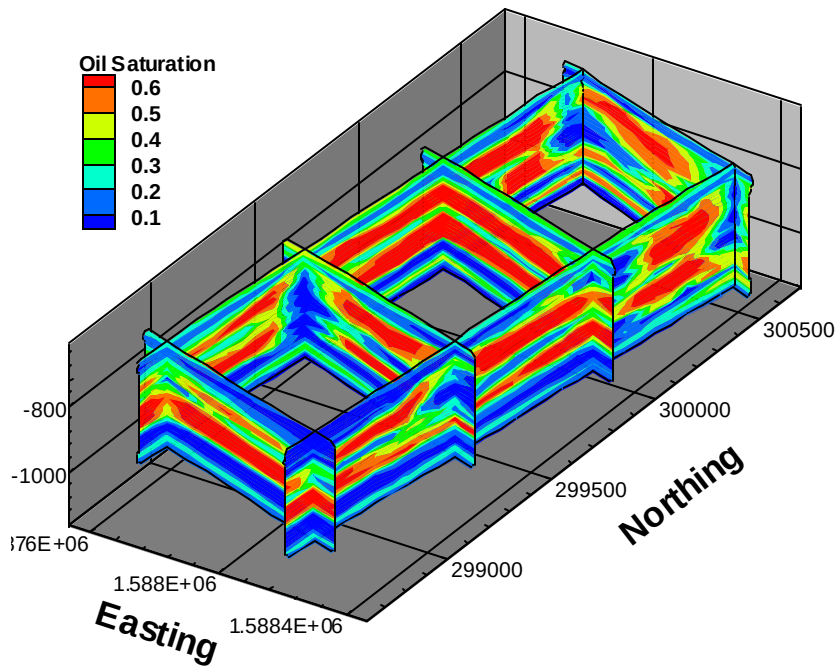


Figure 49. Fractal group oil saturations at 5 years.

The production history is best explained by considering the injection history over the simulation period. Figure 50 shows the combined injection volume in steam barrels of water. This figure shows that the steam injection reached a peak at about 1.5 years, and was then fairly steady from about 2.5 to 4 years, before beginning to decline.

The simulated versus actual (field) oil production is presented in Figure 51. This figure allows a direct comparison of the three models. For the first 2.5 years, there is general agreement between the models. All models show a similar response, particularly with respect to the spike in production at 1.5 years, which corresponds to the peak in the injection volume in Figure 50.

After three years, the facies tract and facies group models continue to follow the field trend, while oil is underproduced in the fractal group model. It must be remembered that this is just one fractal realization. Other realizations might, and probably would, produce a slightly (or greatly) different result. For the realization used, a possible explanation of its behavior might be that the high permeability reservoir connections have depleted the easily accessible cells, and that this process has been compounded by the overall decrease in injection fluid along with the resulting decline in the steam pressure drive.

Although the uniform geometry of the reservoir layers contained in the framework of the facies tract and facies group models provide reasonable matches of the oil production over the entire simulation period, the facies group model yields a slightly better match. Both models display a spike at about 3.75 years, with the facies tract showing a stronger response than the facies group (Figure 51). The greater response of the facies tract model is probably due to its greater homogeneity.

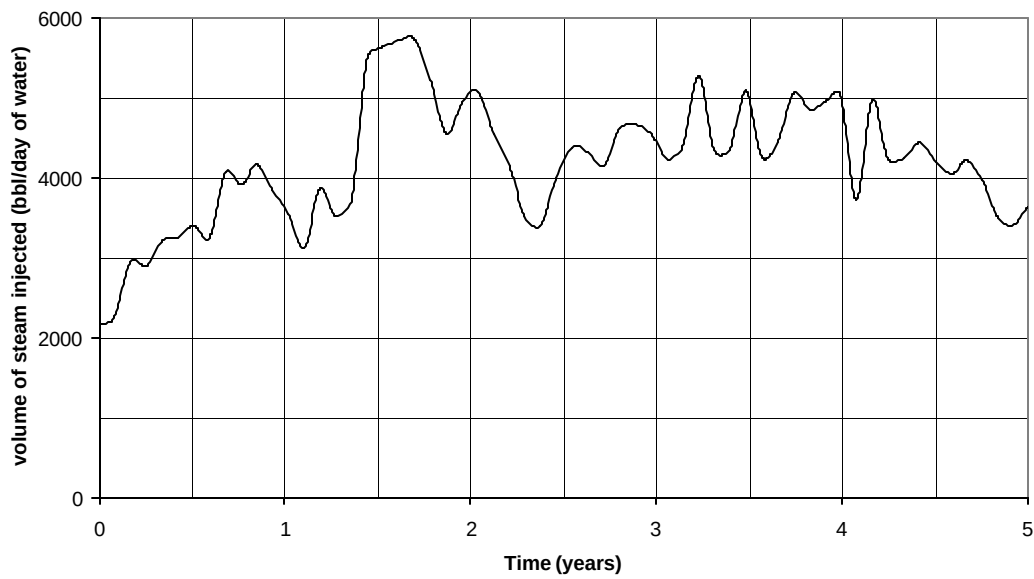


Figure 50. Combined steam injection volume in barrels of water for the three 5-spot areas over the 5-year simulation period.

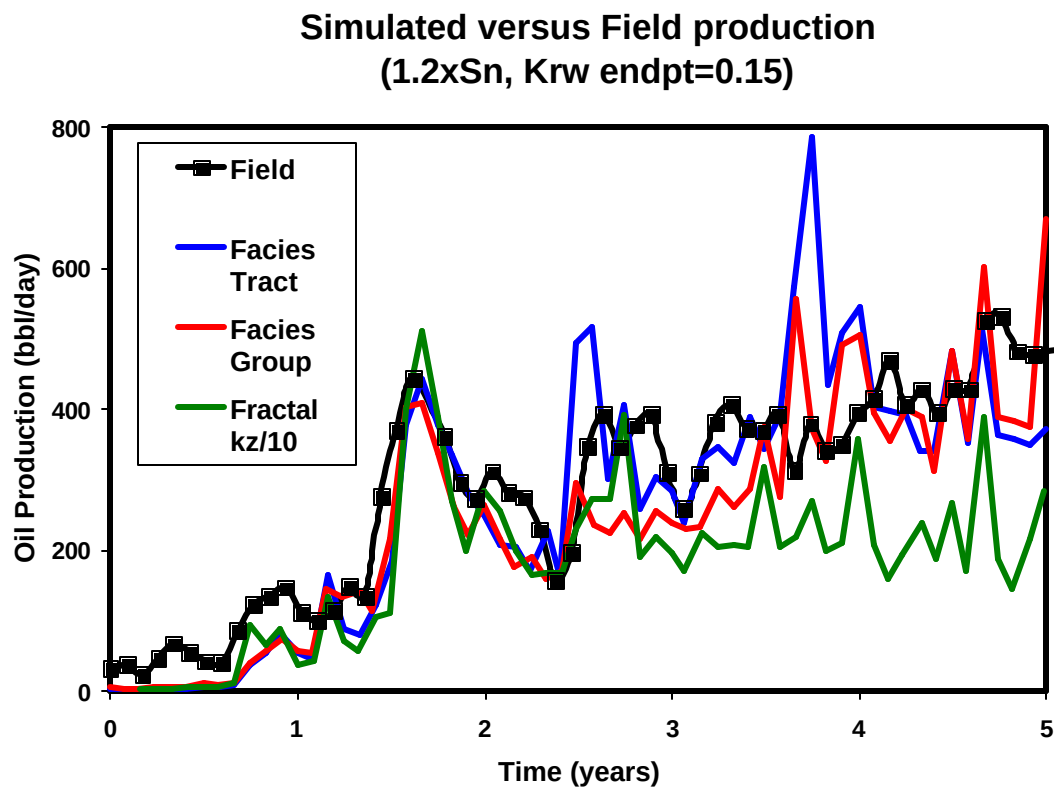


Figure 51. Simulated versus field production of oil (combined production).

The rate of water production in the model area is sensitive to the shape of the water relative permeability curve. The applicability of the measured core values in field scale simulation for West Coalinga appears to be questionable.

As can be seen in Figure 52, all three models over-predict the volume of water produced. This may indicate that the assumed boundary conditions are not valid. Usually no-flow boundaries are an appropriate assumption for a 5-spot production/injection setup, but this is not an ideal 5-spot configuration. An examination of the well-field presented in Figure 32 indicates that there are a number of additional production wells that potentially could be invalidating the boundary assumptions.

Another factor is that the simulated water production is comparable to the quantity of water actually being injected in the field, yet the field production of water is lower than the field-injected volume. This indicates that water is being lost to the formation or to other wells outside the simulated area.

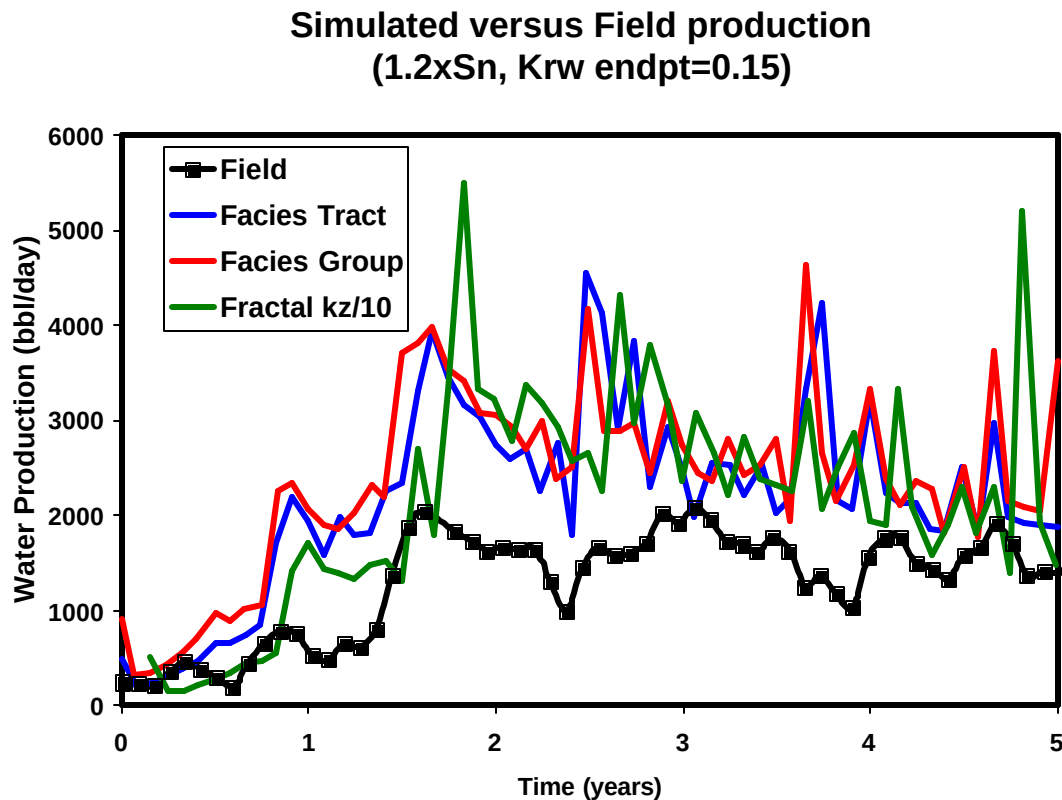


Figure 52. Simulated versus field production of water (combined production).

TECHNOLOGY TRANSFER

An important aspect of our project has involved the transfer of technology. More than 40 presentations, reports, papers, theses, and dissertations have resulted from our work. The presentations have been made at a range of technical meetings, including national meetings of the American Association of Petroleum Geologists and the American Geophysical Union.

Results of our completed project were presented at a Petroleum Technology Transfer Council (PTTC) Workshop in Bakersfield, California, on September 12, 2002. The complete presentations from this workshop, which describe the project methods and results, are available electronically from PTTC (web: <http://www.WestCoastPTTC.org/>; email: pttc@archie.usc.edu).

A listing of the publications and presentations that resulted either in whole or in part from the project is provided at the end of this report.

CONCLUSIONS

Observations of vertical sequences and lateral variability within Temblor Formation outcrops have contributed significantly to understanding the reservoir geology in West Coalinga Field. Erosional bounding surfaces in the outcrop exposures are laterally continuous and easily traced. These surfaces are recognized by their irregular topography and by the presence of bioturbated clay. Based on the characteristics of erosional surfaces in the outcrops, analogous surfaces were identified in cores. Field exposures of incised-valley fills display high relief at the lower contact, pebble lags, and a fining-upward trend. Variability in geometry of the lower boundary and stacked fining-upward sequences are well defined in the outcrops. Where sharp basal surfaces, pebble lags, and fining-upward trends are present in cores, incised-valley fills and their associated geometry are interpreted based on the outcrop analogs. Laterally continuous, well-cemented sand beds containing abundant shell debris are recognized in outcrop exposures as useful marker horizons. Analogous shell beds observed in cores represent laterally extensive zones of low permeability in the subsurface. This information was used in constructing 3D facies tract and facies group models for portions of West Coalinga Field.

A new small-drillhole minipermeameter probe was developed during this project and has important advantages over previous methods of measuring outcrop permeability. The device is useful for developing extensive, high-quality, data sets from outcrops (Dinwiddie, 2001; Molz et al., 2002a). The new probe measures permeability at the distal end of a 10-cm deep drillhole, which avoids surface weathering effects and provides a superior probe-to-outcrop seal when compared with previous methods used for measuring outcrop permeability. The new probe was successfully used for obtaining outcrop permeability data from southern Utah during this project, and has also proved useful in saprolitic soils (Clemson, South Carolina) and nonwelded tuffs (Bishop, California).

Results obtained from analyzing the fractal structure of permeability data collected from the southern Utah outcrop and from core permeability data provided by Chevron from West Coalinga Field were used to generate permeability distributions in 3D reservoir models. These models were used as input for reservoir simulation in a portion of West Coalinga Field. Spectral analyses and the Double Trace Moment method (Lavallee et al., 1991) were used to analyze the scaling and multifractality of permeability data from West Coalinga cores. This was accomplished by estimating the parameters of the Universal Multifractal (UM)

model (Schertzer and Lovejoy, 1987). The UM parameters α (the multifractality parameter and the Levy index), σ (the codimension of the mean field and the width parameter of the Levy distribution), and H_m (the stationarity parameters) were estimated at 1.78, 0.17, and 0.25, respectively. One- and two-dimensional isotropic k fields were generated following the procedure of Wilson et al. (1991) and Pecknold et al. (1993), and two-dimensional anisotropic fields were generated according to an empirical procedure that was developed. The results of this work indicate the presence of fractal scaling in the permeability data from West Coalinga Field.

T2VOC, which is a numerical flow simulator capable of modeling multiphase, multi-component, non-isothermal flow, was used to model steam injection and oil production for a portion of section 36D in West Coalinga Field. The layer structure and permeability distributions of the different models were incorporated into the numerical flow simulator. The injection and production histories were modeled, including well shutdowns, and the occasional conversion of production wells to steam injection wells. An exhaustive sensitivity analysis was performed to determine which reservoir and fluid properties have the greatest control on oil and water production. The sensitivity analysis revealed that lowering the endpoint for the water relative permeability curve had the greatest effect on decreasing water production, and that increasing the oil saturation had the greatest effect on increasing oil production. The framework provided by facies groups provides a more realistic representation of the reservoir conditions than facies tracts, which is revealed by a comparison of the history matching for the oil production. Fractal permeability distributions model the high degree of heterogeneity within the reservoir sands of West Coalinga Field. These results confirm that predictions of oil production are strongly influenced by the geologic framework and boundary conditions.

The results of this investigation indicate that to more fully apply a fractal/facies approach to reservoir simulation, additional work needs to be done on development of the fractal/facies concept (Lu et al., 2002). The permeability data collected from the southern Utah outcrop support this new concept for representing natural heterogeneity. This approach is one of the few simplifying concepts to emerge from recent studies of geological heterogeneity, and has the potential to be developed into a widely used method for reservoir modeling. Additional outcrop permeability data sets and further analysis is needed to fully develop this new concept.

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PUBLICATIONS, REPORTS, THESES, DISSERTATIONS, AND PRESENTATIONS

The following publications, annual technical reports, theses, dissertations, and presentations have resulted, in whole or in part, from this project (DE-AC26-98BC15119):

Bridges, R.A., 2001, *Sedimentology and reservoir characterization of the Miocene Temblor Formation, Coalinga, California* [unpublished Master's thesis]: Clemson University, 114 p.

Bridges, R.A., 2002, "Sedimentologic and Stratigraphic Interpretation of Geologic Data, Coalinga Area, California," Petroleum Technology Transfer Council (PTTC) Workshop, Bakersfield, California, September 12, 2002.

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

Units of Measure

cm	centimeter
m	meter
km	kilometer
md	millidarcy
C	celsius
F	Fahrenheit

Geologic Study

SS	sandstone
fs	fine sand
ms	medium sand
cs	coarse sand
vcs	very coarse sand
gran	granule
BS	bounding surface
HCS	hummocky cross stratification
k	permeability

Fractal Analysis

fBm	fractional Brownian motion
H	Hurst coefficient
CDF	cumulative distribution function
PDF	probability density function
DTM	Double Trace Moment
UM	Universal Multifractal
T	spectral slope
f	spectral frequency variable
α	the Levy index
σ	the codimension of the mean field and the width parameter of the Levy distribution
λ	scale ratio
η	double trace moment
q	order of the statistical moment
M(q, η)	moment scaling exponent
Hm	the multifractal Hurst coefficient
k	intrinsic permeability

Reservoir Simulation

T2VOC	numerical steam flooding simulator based on TOUGH2 formulation
TOUGH2	transport of u nsaturated groundwater and h eat, including other phases

PDE	partial differential equations
PI	productivity index
Δz	layer thickness
r_e	grid block radius
r_w	well radius
s	skin factor
P_{wb}	wellbore pressure
h_{mix}	enthalpy of the mixture
h_w	enthalpy of the water
h_s	enthalpy of the steam
χ_w	fraction of water
χ_s	fraction of steam
Kro	oil relative permeability
Krw	water relative permeability
Sn	non-aqueous phase liquid saturation
Kz/10	vertical permeability increased by a factor of 10
ϕ	porosity
S_g	gas phase saturation
C_g^w	mass concentration of water in the gas phase
S_w	aqueous phase saturation
C_g^w	mass concentration of water in the aqueous phase
k_{rg}	relative permeability of the gas phase
$\tilde{k}$	absolute permeability
μ_g	dynamic viscosity of the gas phase
P_g	fluid pressure in the gas phase
ρ_g	gas phase density
g	gravitational acceleration vector
z	vertical distance between cell nodes (layer thickness)
C_w^w	mass concentration of water in the aqueous phase
k_{rw}	relative permeability of the aqueous phase
μ_w	dynamic viscosity of the aqueous phase
P_{cgw}	capillary pressure between the gas and aqueous phases
ρ_w	gas phase density
q^w	rate of generation of the water component.
C_g^o	mass concentration of oil in the gas phase
S_o	oil phase saturation
C_o^o	mass concentration of oil in the oil phase
k_{ro}	relative permeability of the aqueous phase
μ_o	dynamic viscosity of the oil phase
P_{cow}	capillary pressure between the oil and aqueous phases

ρ_o	gas phase density
q^o	rate of generation of the oil component
ρ_R	rock grain density
C_R	soil grain heat capacity
T	temperature
h_g	specific enthalpy of the gas phase
h_w	specific enthalpy of the aqueous phase
h_o	specific enthalpy of the oil phase
λ_t	bulk thermal conductivity
q_j^h	rate of heat generation