HYDROCARBON POTENTIAL IN THE MONTEREY FORMATION AS A FUNCTION OF SEDIMENTATION, DIGENESIS, AND TECTONIC HISTORY IN THE SOUTHERN SAN JOAQUIN VALLEY, CALIFORNIA

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ABSTRACT

The Monterey Formation is the source rock of hydrocarbon for many oil fields in the San Joaquin Valley. It is also a reservoir for many of these fields. Many Monterey oil fields are fractured shale reservoirs. The presence of oil and gas "shows" in the Monterey can be expected practically everywhere it is penetrated and tested. The significance of these "shows" is a function of sedimentation, depth of burial, digenesis and tectonic history. Each of these variables must be considered in any exploration or development program for the Monterey.

DEFORMATIONAL STYLE AND FRACTURE GENERATION IN THE MONTEREY FORMATION

The southern San Joaquin valley is one of the worlds great oil provinces. It consists of a series of Upper Cretaceous to Quaternary sands and shales. The deepest portions of the basin have been explored to depths in excess of 25,000 feet, bottoming in Miocene sediments. The stratigraphy and basin development of the San Joaquin Valley, is discussed by Callaway (1971), MacPherson (1978), Walker (1978), Williams and Graham (1982), McGuire and Bowersox (1983), Bartow and McDougall (1984) and Graham and Williams (1985). The oil-trapping structures of the southern San Joaquin Valley have been recognized as a series often-echelon folds and faults trending parallel, or sub-parallel to the San Andreas fault. These structures have formed in a wrench fault environment as discussed by Wilson (1965), Harding, (1973, 1974, 1976), Dibblie (1977), Sylvester and Smith (1976), Harding and Lowell (1979), Crowell (1981), Sylvester (1984), and Harding and Tuminas (1988). In the wrench fault model, "flower structures" define the boundaries of major fault blocks. These faults dip 40° to 70° near the surface and become vertical at depth. Folds within these fault blocks form contemporaneously with faulting. The fault separations are all oblique and their combination with folded, dipping strata, and curved fault planes results in complicated structural arrangements.

In addition to the generalized structural model described above, it is important to recognize how this deformational style is related to the dynamics of fracture generation. This knowledge is important because many productive oil accumulations in the Monterey Formation are in fracture reservoirs (Snyder et al., 1983; Belfield et al., 1983). The geometric arrangement of fractures generated in response to simple shear is illustrated in Figure 2. The principal (synthetic) fracture set is at an angle of approximately 16 degrees to the principal direction of shear. Antithetic fractures form approximately normal to the principle direction of shear. In addition, there is a set of fractures that form perpendicular to the fold axis. These are called "a-c joints" (Dennis, 1972). All fractures undergo a rotation during deformation. The synthetic and antithetic fractures are penetrative, that is they extend

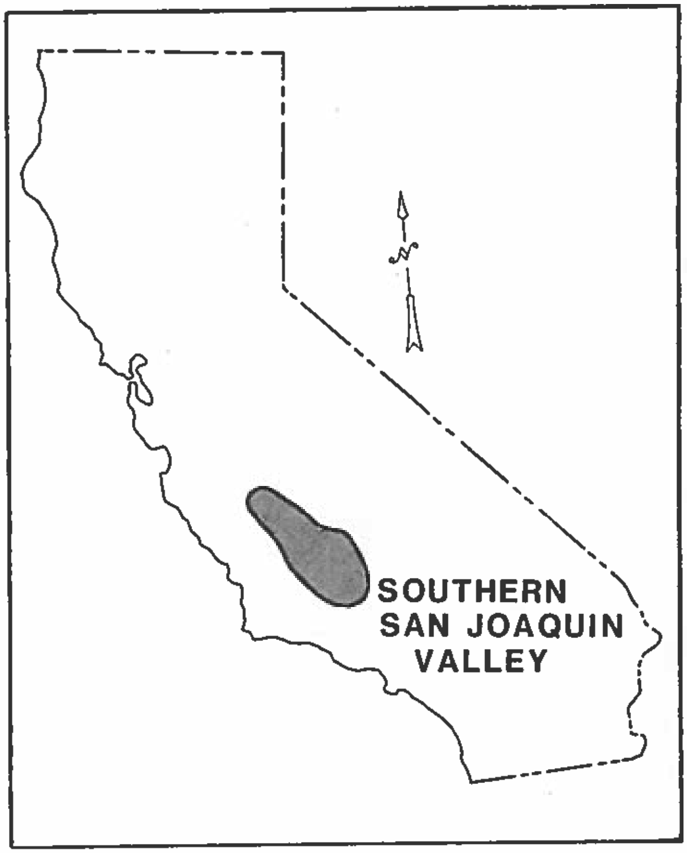

Figure 1. Location map of the Southern San Joaquin Valley.

throughout the fold. The normal faults which form perpendicular to the fold axis are also penetrative. Extension fractures having the same strike as the fold axis form near the apex of the folds. Extension fractures may become normal faults and are discrete (i.e. non-penetrative). An individual extension fracture does not extend throughout the fold. However, a set of extension fractures do form near the axial plane and, as a group, bisect the fold.

The non-penetrative fractures appear to be the ones which are responsible for the permeability of most fractured Monterey hydrocarbon reservoirs. The penetrative fractures (the a-c joints) are widespread throughout the southern San Joaquin basin and, in part, are the ones responsible for the ubiquitous hydrocarbon "shows" throughout the Monterey Formation. They are also responsible for providing pathways for oil migration from the synclines to the anticlines.

HYDROCARBON POTENTIAL IN THE FACIES OF THE MONTEREY FORMATION

An overview of the hydrocarbon potential in the Monterey Formation is given in Isaacs and Garrison (1983). The Monterey Formation has argillaceous, siliceous, distal turbidite and proximal turbidite facies in the Southern San Joaquin Valley. The dominant petroliferous shale member of the Monterey Formation in the southern San Joaquin Valley is named the Antelope Shale. This shale is considered to be the source rock for most oil fields of Miocene or later age in the San Joaquin Valley. Whenever penetrated, a "show" of gas or oil can be expected.

Within the Antelope Shale is a turbidite sand, the Stevens Sandstone. The facies changes within this interval are illustrated on Figure 3. The Antelope Shale undergoes a transition from argillaceous shale, through siliceous (diatomaceous) shale, through a distal turbidite to a well developed proximal turbidite sand facies. The hydrocarbon potential within these facies is a function of several variables. These include depositional lithology, digenetic history, tectonic history, and depth of burial.

The hydrocarbon potential of each facies of the Antelope Shale-Stevens Sandstone stratigraphic interval is discussed below. This discussion is a synthesis of the Stevens/Antelope facies data presented by Williams and Graham (1982) and McGuire, et al. (1983).

Four general sedimentary facies are in the Monterey Formation of the Southern San Joquin Valley. Within each of these sedimentary facies are digenetic facies which reflect differences in burial and chemical histories of the sediments. These facies are shown in Table 1. The hydrocarbon potential of the Monterey Formation is illustrated in Figure 3. In this figure and in the forthcoming discussion of hydrocarbon potential, "shallow" refers to depths above 5,000 feet subsea, and "deep" refers to depths below 5,000 feet subsea respectively.

ARGILLACEOUS SHALE FACIES

At shallow depths, fractured shale reservoirs in the Antelope Shale are found at the apex of anticlines. An example of this type of reservoir is the Antelope Shale Zone of the Buena Vista Hills oil field (Borkovich, 1958). The fractured reservoirs are generally encountered at the apex of anticlines because it is in these areas that extension fractures are numerous enough to create sufficient reservoir porosity and permeability for economic amounts of hydrocarbon to accumulate. Artificial fracturing can be successful in enhancing the productivity of wells within this facies.

Hydrocarbon "shows" are also found in shallow wells drilled along the flanks of structures in the Antelope argillaceous shale facies. These wells have low initial production rates or none at all. Attempts to increase the productivity of these wells by artificial fracturing are generally unsuccessful. Artificial fracturing is only successful in this facies where some natural non-penetrative fracturing already exists. Such natural fracturing is generally not present on the flanks of folds.

Reservoirs in the argillaceous facies do not form on the apex of folds at depths below 5,000 feet. The confining pressure at these depths seals any fractures which might form. Wells which penetrate this facies in deep wells have good "shows", but initial production during completion testing rapidly falls off. Attempts to enhance the permeability of deep argillaceous Antelope Shale are generally unsuccessful. The wells may be moderately productive after fracturing, but only for a limited time. The initial "flush" production from these wells may be a few hundred barrels per day. After approximately 60 days production falls to 2 to 8 barrels per day and, after testing, the wells are generally abandoned.

Wells which penetrate the argillaceous Antelope Shale facies at depths on the flanks of a fold also have "shows" with low initial production (5 to 10 bbls/day). Artificially fracturing and acidizing is not usually successful in these wells. The hydrocarbons which do come into the well bore during completion testing in this facies are due to the "bleeding" or slow migration of hydrocarbons from a oil-saturated shale. After testing, oil production declines rapidly. The wells are abandoned and a "show" of oil is recorded in the completion reports.

SILICEOUS SHALE FACIES

The diatomite/diatomaceous shale facies at shallow depths generally has experienced only moderate digenesis and

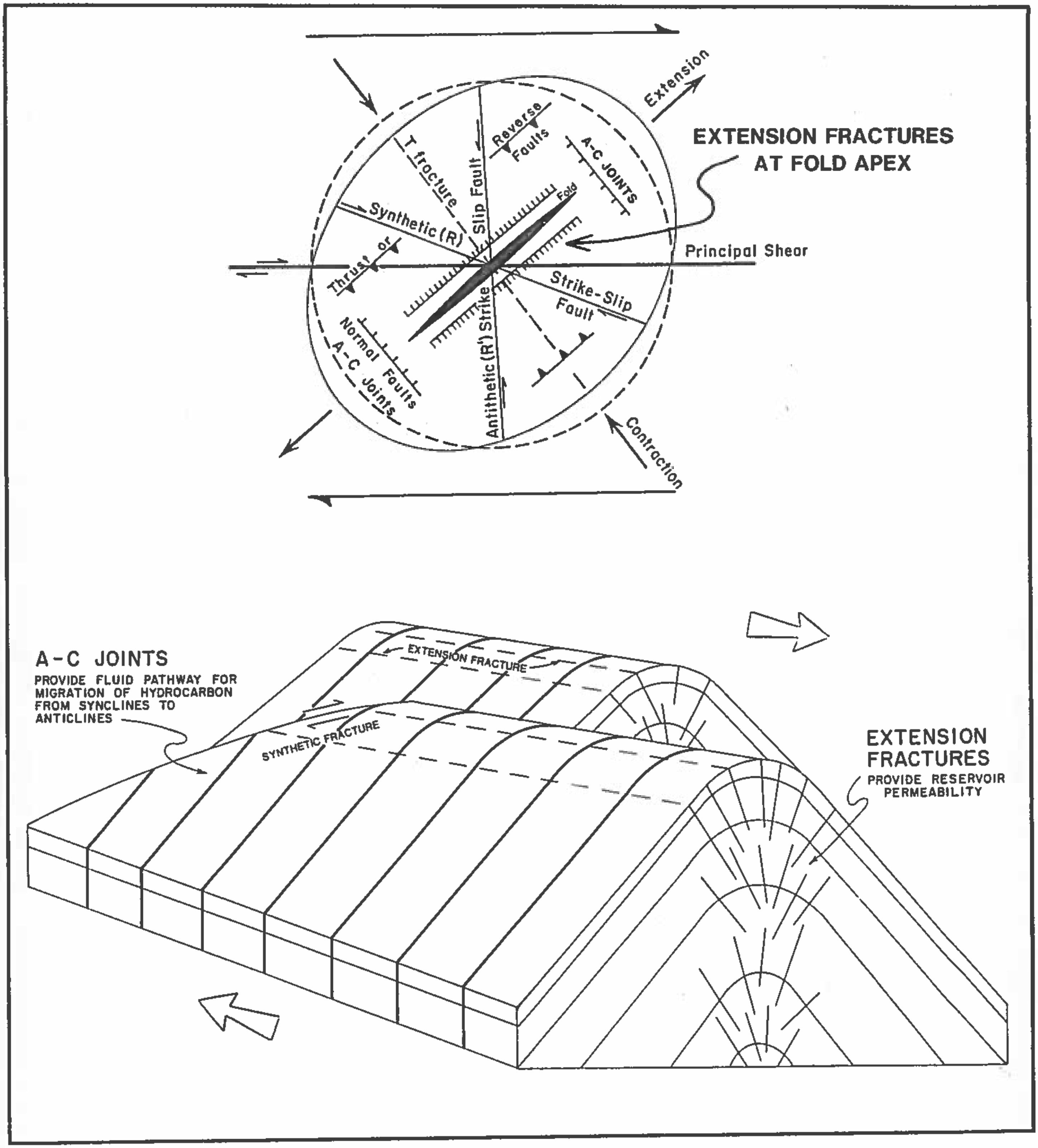

Figure 2. Fracture generation during simple sheer. (Upper portion of diagram modified from Harding, 1974, p.129 and Sylvester and Smith, 1976, p.2082)

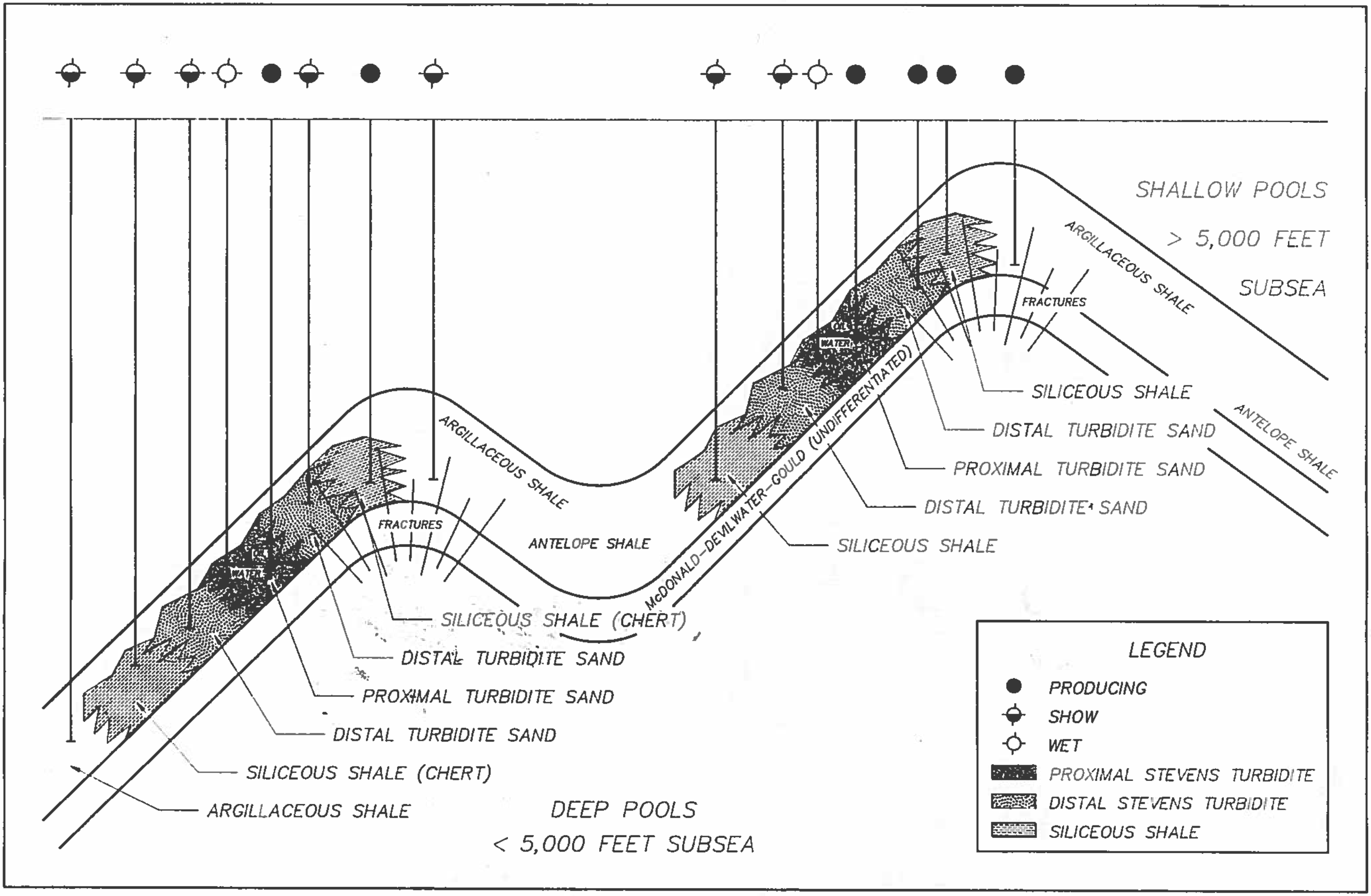

Figure 3. Hydrocarbon potential in the Monterey Formation. > means "above" and < means "below". All facies of the Monterey are productive at shallow depths. Only the chert and proximal turbidite sand facies are productive at depths below 5000 feet subsea. See text for elaboration.

has a high porosity. If capped by a sealing shale unit (e.g. San Joaquin Shale or Reef Ridge Shale), a trap is formed and oil can accumulate as in the South Belridge oil field (Ritzius, 1950). The diatomaceous facies at depths of 500-3,500 feet can be acidized to provide the permeability required to move hydrocarbons into a bore hole. The acidization removes the interstitial clay particles from the diatomite and thereby increases its porosity and permeability. Artificial fracturing and steaming also enhance production from the diatomaceous facies at shallow depths.

When the diatomaceous shale is off-structure on the flanks of a fold, "shows" are encountered. These wells can be acidized, but productivity is generally too low to warrant completion for production. Artificial fracturing does not appear to improve productivity for these wells over an extended time.

Where the diatomaceous shale facies is deeply buried it is converted by digenesis to chert. The burial imparts a brittleness to the rock which allows for the development of natural fractures within it. Hence, where the siliceous facies undergoes deformation at depth, a fractured chert reservoir is formed. These reservoirs, when encountered, sustain their production. Deeply buried cherts of the Monterey Formation in the Southern San Joaquin Valley are not expected to be productive along the flanks of folds unless a great density of a-c joints is present.

DISTAL TURBIDITE STEVENS SANDSTONE FACIES

At shallow depths, fractured Stevens distal turbidite sandstone reservoirs are found at the apex of anticlines because it is there that extension fractures are numerous enough to create sufficient porosity and permeability for economic amounts of hydrocarbon to accumulate. Artificial fracturing can successfully enhance the productivity of wells within this facies.

Hydrocarbon "shows" are also found in shallow wells drilled along the flanks of structures in the Stevens distal turbidite sandstone facies. These wells have low initial production rate or none at all. Attempts to increase the productivity of these wells by artificial fracturing are generally unsuccessful. Artificial fracturing is only successful in this facies where some natural fracturing already exists. Such natural fracturing is generally not present on the flanks of folds. Hence, these wells are generally abandoned.

Reservoirs in the Stevens distal turbidite sandstone facies are not known at depth, even at the apex of trapping structures. This is because the confining pressure at these depths seals any fractures which might form. Wells which penetrate the Stevens distal turbidite sandstone facies at depth have "shows" with low initial production (5 to 10 bbls/day). Neither artificial fracturing nor acidizing have successfully enhanced the permeability of these wells. The hydrocarbons which do come into the well bore after completion testing are due to the slow migration of hydrocarbons which ooze into the well bore from oil-saturated shales. After testing, these wells are almost always abandoned.

PROXIMAL TURBIDITE STEVENS SANDSTONE FACIES

The Stevens proximal turbidite sandstone is the primary target formation within the Antelope Shale-Stevens sandstone interval. Where it is present at the apex of a structure, good production can be anticipated. Stevens Sandstone reservoirs may be present along the flanks of a fold, and in fact may be better producers there than at the fold apex. This is probably due to fold formation occuring at the same time as turbidite deposition.

CONSEQUENCES FOR EXPLORATION

Hydrocarbon targets within the Monterey Formation are more likely to be encountered at depths of less than 5,000 feet subsea. These shallow reservoirs can occur in any Monterey facies. At depths below 5,000 feet, the best targets are reservoirs in the proximal Stevens turbidite sand or in the chert facies. The probability of encountering these facies at depth is much less than the probability of encountering the argillaceous or distal turbidite facies and greatly increases exploration risk.

A theory for the cyclic production of oil from certain low-grade Monterey reservoirs in the argillaceous facies at depths below 5,000 feet is given in my accompanying article in this publication.

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Table 1. Sedimentary and Digenetic Facies of the Monterey Formation, Southern San Joaquin Valley

Sedimentary Facies	Digenetic Facies
Argillaceous (Phosphatic) Shale	clay shale/claystone shale
Siliceous Shale	diatomite and diatomaceous shale porcelainite siliceous shale/siliceous mudstone chert mat-laminated siliceous shale
Calcareous/Siliceous Shale (Lower Monterey Formation only)	dolomite dolomitic shale
Clastic (Stevens Sandstone)	proximal turbidite sands distal turbidite sands