THE YOWLUMNE OIL FIELD: THE FIRST TEN YEARS

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From time to time it is both interesting and beneficial to recall the challenges that faced those who came before us in the development of now mature projects. It is interesting to follow how the model used in the development of an oil field changed as more drilling and production data became available, and how the interaction of various disciplines are essential to the full understanding of the reservoir. It is profitable to remember that our concepts of current projects should not be so rigid as to prohibit evolution and change as we gain more information.

The following account of the Yowlumne Field development is a story of successful change and adjustment. The authors would like to express our appreciation to those who were involved in the development of the field and those who provided historical material.

The Yowlumne Field is located in Central California at the southern end of the San Joaquin Valley (Figure 1). The topic area is located along a major anticlinal feature known as the San Emidio Nose which originates on the west side of the valley and plunges eastward (Figure 2).

Wildcat drilling on the nose began in 1935 and has continued into the present day. Prior to the Yowlumne discovery, the only field in the area was the San Emidio Nose Field, discovered in 1958, which will ultimately produce 10-12 million barrels of oil from Miocene aged sands (Figure 3). There were 27 dry holes in the area prior to the Yowlumne discovery well—23 of which penetrated the Miocene sediments.

The Yowlumne discovery well was a farm-out to Texaco from Tenneco in 1973. The well was intended to be an Eocene test, but was still in Miocene sediments when T.D.'d at 20,704 feet. After testing numerous oil shows in the lower portion of the well, it was completed in the shallowest prospective zone for 428 barrels of 33.1 gravity oil and 31 barrels of water. After 30 days, the well was producing over 800 barrels of clean oil per day. The productive Miocene age Stevens Sand is referred to as the Yowlumne sand.

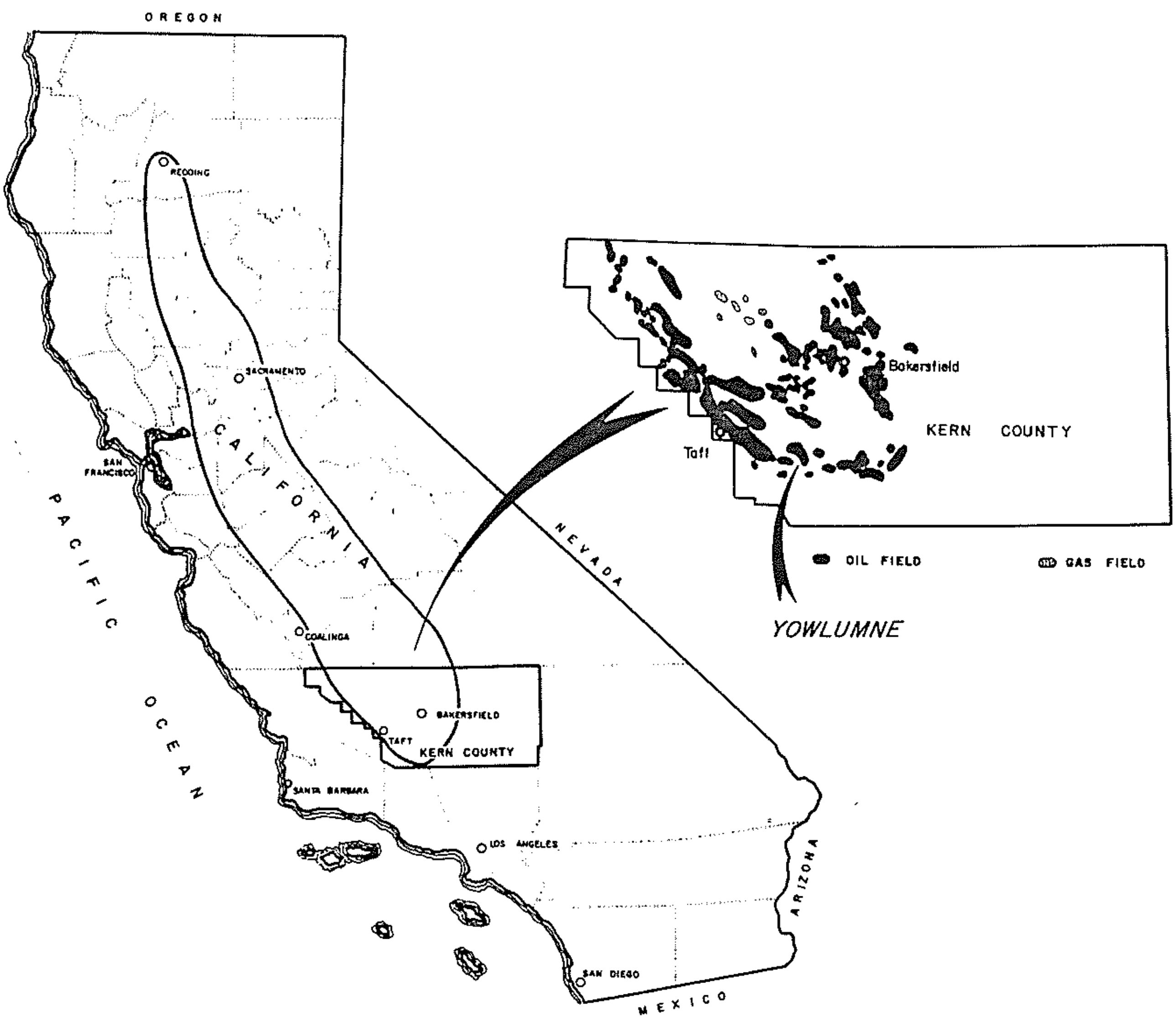

FIGURE 1 Location of the Yowlumne Oil Field in Kern County, California.

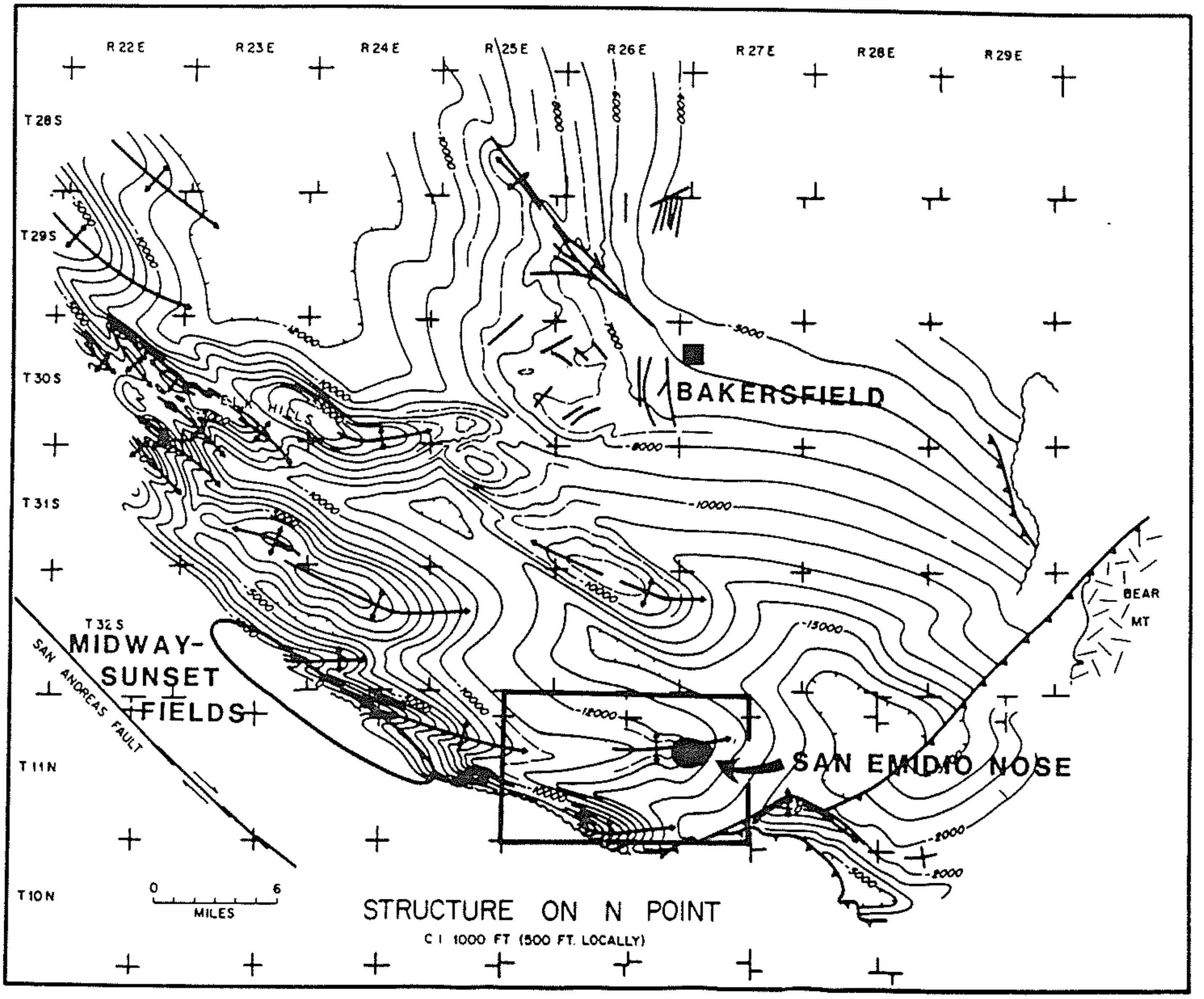

FIGURE 2 Structure map on "N" chert marker in the southern end of the San Joaquin Valley. The box outlines the topic area on the San Emidio Nose (from Webb, 1981).

The type log (Figure 4), shows the five producing zones in the Yowlumne field. This discussion concentrates on the main reservoir in the field, the Yowlumne sand, which occurs at an average depth of 11,300 feet. Basal Pliocene 800-900 feet shallower and the 10-4 about 600 feet deeper than the Yowlumne sand, were discovered during the development of the field. A small amount of production also comes from the fractured "P" chert. The structural mapping horizon is the "N" point marker, which is correlatable throughout a large part of the basin south of Bakersfield. The "P" marker is a similar horizon which occurs below the Yowlumne sand.

The basic depositional model for the field was developed using the traditional approach of incorporating published literature and previous experience. From the discovery well it was known that the Yowlumne sand is a thick feldspathic sandstone characterized by very sharp upper and lower contacts. The sand is encased in deep water siltstone and shales. Average porosity is 18% and permeability to air is 75 millidarcies. Initial reservoir pressure was 5660 psi and bubble point pressure is 2800 psi.

The model chosen to represent the mode of deposition was that of the deep marine turbidite typically found in other parts of the basin and common on the Bakersfield Arch to the north (Figure 5). Acording to the turbidite model, the sediments accumulated on the shelf and were periodically released down canyons or feeder channels. The sediments formed density or turbidity currents while flowing downslope. Upon reaching the bottom of the slope, they flowed out on the basin plain. When the turbidity current slowed and deposition occurred, a submarine fan was formed. Each portion of the fan has distinct depositional and reservoir quality characteristics. In 1974 it was interpreted that the discovery well had penetrated sands of the middle fan.

The challenge facing the geologists in 1974 was that of predicting the geometry of the Yowlumne sand. One possibility was that it represented a southeast-northwest trending channel (Figure 6). Another possibility was that the Yowlumne sand was correlative to the Upper Miocene sands productive in the Los Lobos Field. A third possibility was that the channel interpretation was incorrect and the Yowlumne sand was a much larger "blanket" sand with an east-west trending regional pinch-out south of the discovery well.

As a result of the farmout terms with Texaco, continuous development by Tenneco began in 1974. Due to the thickness of the Yowlumne sand, 40 acres per well spacing was economically justified. Two 40 acre offsets were drilled in early 1974 in order to establish the geometry of the reservoir and gain information concerning its size (Figure 7). Both of these wells were planned to be structurally equivalent or higher on the structure than the discovery well. Well 87X-11 twinned a shal-

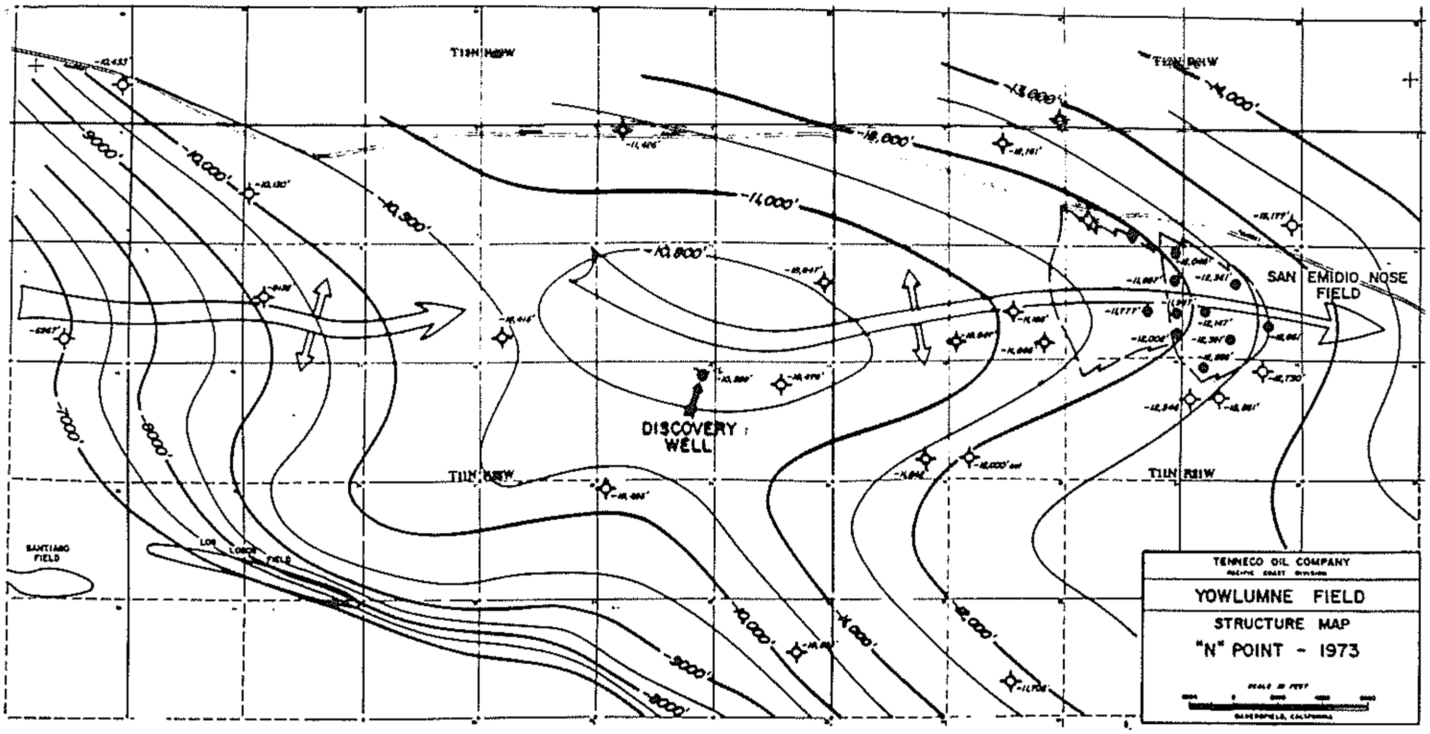

FIGURE 3 Location of the discovery well on San Emidio Nose as it was mapped in 1973. Structure contours are on the "N" chert marker.

lower wildcat, spud in 1935 by the Ohio Oil Company which, for mechanical reasons, T.D.'d six hundred feet short of the Yowlumne sand. The 87X-11 well was 75 feet structurally higher than the discovery well and flowed 863 BOPD from the Yowlumne sand. Well 61X-14 came in 77 feet lower than the discovery well and encountered an oil/water contact at −10,728 feet subsea. Three additional wells were drilled in 1974 (Figure 8). Well 25-12 missed the sand and helped determine the northwest-southeast orientation of the sand body. Wells 76-11 and 45-11 were completed as producers.

Twelve wells were drilled and completed in 1975, with three of the wells being dually completed in the basal Pliocene sand (Figure 9). Each Yowlumne well was drilled structurally high to the oil/water contact at − 10,728 feet in Well 61X-14.

The development strategy was along traditional lines, constructing detailed cross-sections, isopach maps and structure maps, and utilizing them to pick the well locations. Four main sands were correlated (Figure 10). These sands were always stacked on top of one another and the interpretation was that each sand was sourced and transported from the same feeder channel and deposited in the same area. Since the four sands were stacked as a single sand package, they were initially treated as a single sand reservoir. Isopach maps of gross sand, net pay, initial production rates, and bottom hole pressure from pressure buildups were constructed to determine additional drilling locations. Seismic interpretations were used not only to determine the structure, but seismic characteristics were helpful in locating the sand buildup. Several generations of seismic modeling were successfully used in this area.

As development continued, higher pressures were encountered in the northwest and they were interpreted as indicating additional fluid volume in that direction. Utilizing this concept 16 wells were drilled (with 12 completions) to the northwest during 1976 (Figure 11). Twenty-one wells were drilled to the northwest in 1977 (Figue 12). Development in that year was controlled by a competitive drainage situation in sections four and five, and since in the state of California the law of capture prevails, some of the wells were located to minimize the flow of oil across lease lines.

Prior to 1977, a simple depositional model was used. Yowlumne was treated as a single sand body which was deposited from the southeast to the northwest. The channel was given a constant width and a fairly linear direction of deposition (Figure 13). Wells 76-3 and 64-3 OH both encountered an oil/water contact which limited development to the north (Figure 14). In the middle of 1978 Well 44X-3 was completed downdip and did not encounter wet sand. As a result, the geologists began seeking an alternate hypothesis to the single channel model.

The geologists reviewed the basic stratigraphy of turbidites. Figure 15 illustrates a *complete* turbidite sequence. Coarse poorly sorted (*a*) fining upward into the horizontal laminated (*b*). The wavy and convolute (*c*) zone, is overlain by the silty and shaley laminated (*d*) and then pelitic (*e*) shales. The entire sequence is generally 1/2 to 3 feet in thickness. Complete bedsets are rare and each bedset represents a single periodic deposit of sediment. The individual bedsets are commonly stacked together forming *sands*. Sands are generally bounded by thin shales which can be identified on logs. However, they often cannot be correlated from well to well. Sands are also deposited together forming *sand sequences* which represent major periods of relatively continuous sedimentation. *Sand sequences* are separated by major shales (usually three to six feet thick). They can be correlated from well to well and act as reservoir barriers. Many *sand sequences* were deposited together forming the Yowlumne sand package. It became apparent that the "Yowlumne Sand" was such a series of *sand sequences*. As each sand sequence is a unique reservoir, the sequences could no longer be treated as having a single source with a single depositional direction.

As the schematic cross-section demonstrates, (Figure 16), the correlation of sand sequences between wells can be quite challenging. Although the outer two wells have three sand sequences each, they are not all correlative sands. Detailed cross-sections were used along with pressure data to help correlate the various sand sequences.

Pressure data were taken with a repeat formation tester in a few of the wells. Pressure reversals attested to the subtle, yet effective barriers between the different sands (Figure 17). Detailed stratigraphic and structural cross-sections were constructed throughout the field area and ultimately 17 different sand sequences were identified (Figure 18). Each sequence was mapped by: gross sand, gross sand/gross interval ratio, net sand,

YOWLUMNE TYPE LOG

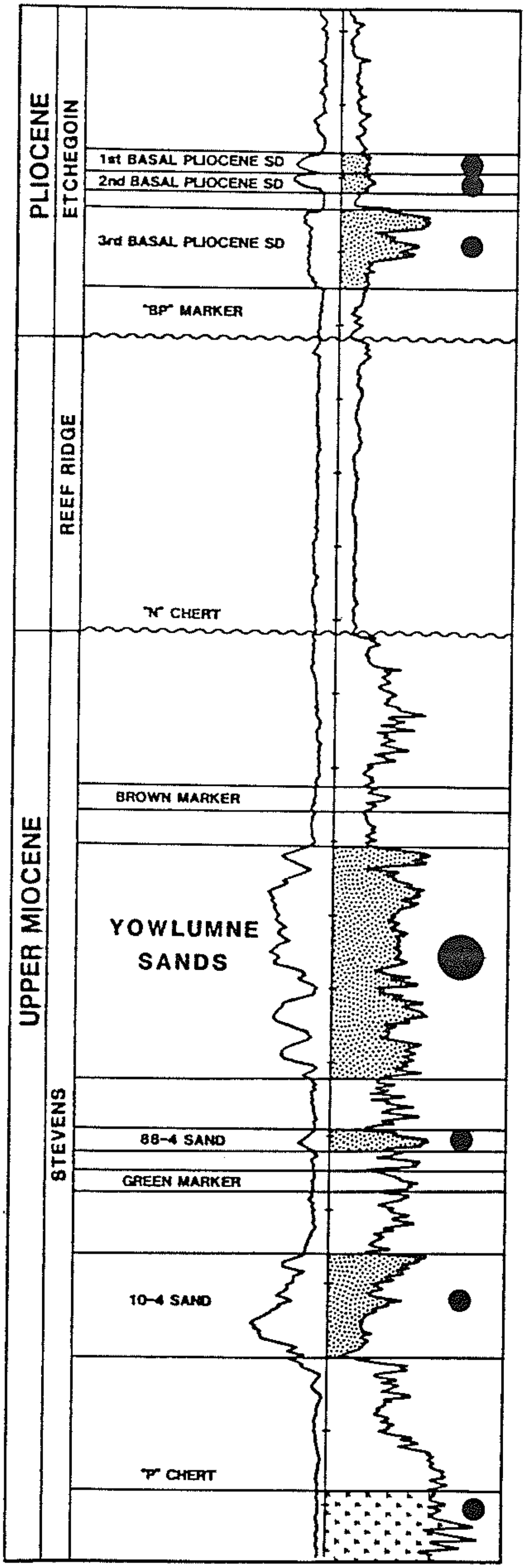

FIGURE 4 The type of log for the Yowlumne Field identifying productive zones with dots to the right of the dual-induction log. Also shown are the "N" and "P" chert markers.

net pay, net pay/gross sand ratio, and average porosity. These data were used to determine orientation and geometry of each sand sequence. The individual gross sand and net pay maps for the sand sequences were combined into a total composite gross sand and net pay map (Figure 19).

Development continued from 1978-1980 using gross sand and net pay isopach maps. In addition, several maps were constructed using pressure and production data. Even before the field was completely developed, contrasting production patterns began to appear. The gas/oil ratio remained low in the northeast and pressures remained higher in the northeast and in portions of the southeast. The pressure anomalies in the southeast were the result of an attempt to repressure the reservoir by water injection along the axis in the newly formed Unit "A". Since it was clear in this portion of the field the sediments were confined to a narrow channel it was predicted that there would be a tendency for the sands to have greater permeability parallel to the channel axis, and water injectors were positioned in lines parallel to the axis. It was confirmed after injection began in 1976 that fluid traveled up to 10 times easier parallel to the channel axis than it did perpedicular to the axis, however injection anomalies did exist. The directional permeability along with the pressure and GOR anomalies induced the re-examination of the hypothesis of the layered sand turbidite reservoir. In 1980 the geologists returned to the turbidite model and looked at the individual sands separately.

Further analyses of cores and log shapes allowed the identification of three distinct types of stratigraphic units, each of which represents a particular environment of deposition. About 80% of the sands are in thick sequences of superimposed channelized layers. These are identified by fining- and thinning-up-

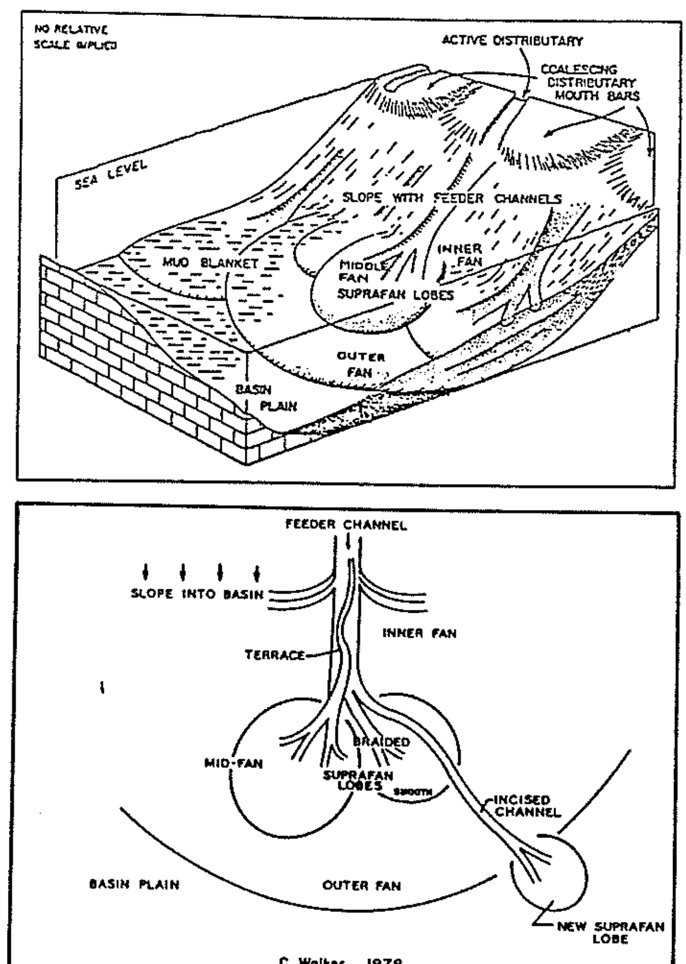

FIGURE 5 The turbidite model used to describe the Yowlumne sand environment of depostition includes narrow, linear channels much like the one penetrated by the Yowlumne discovery well (from Walker, 1966, 1978).

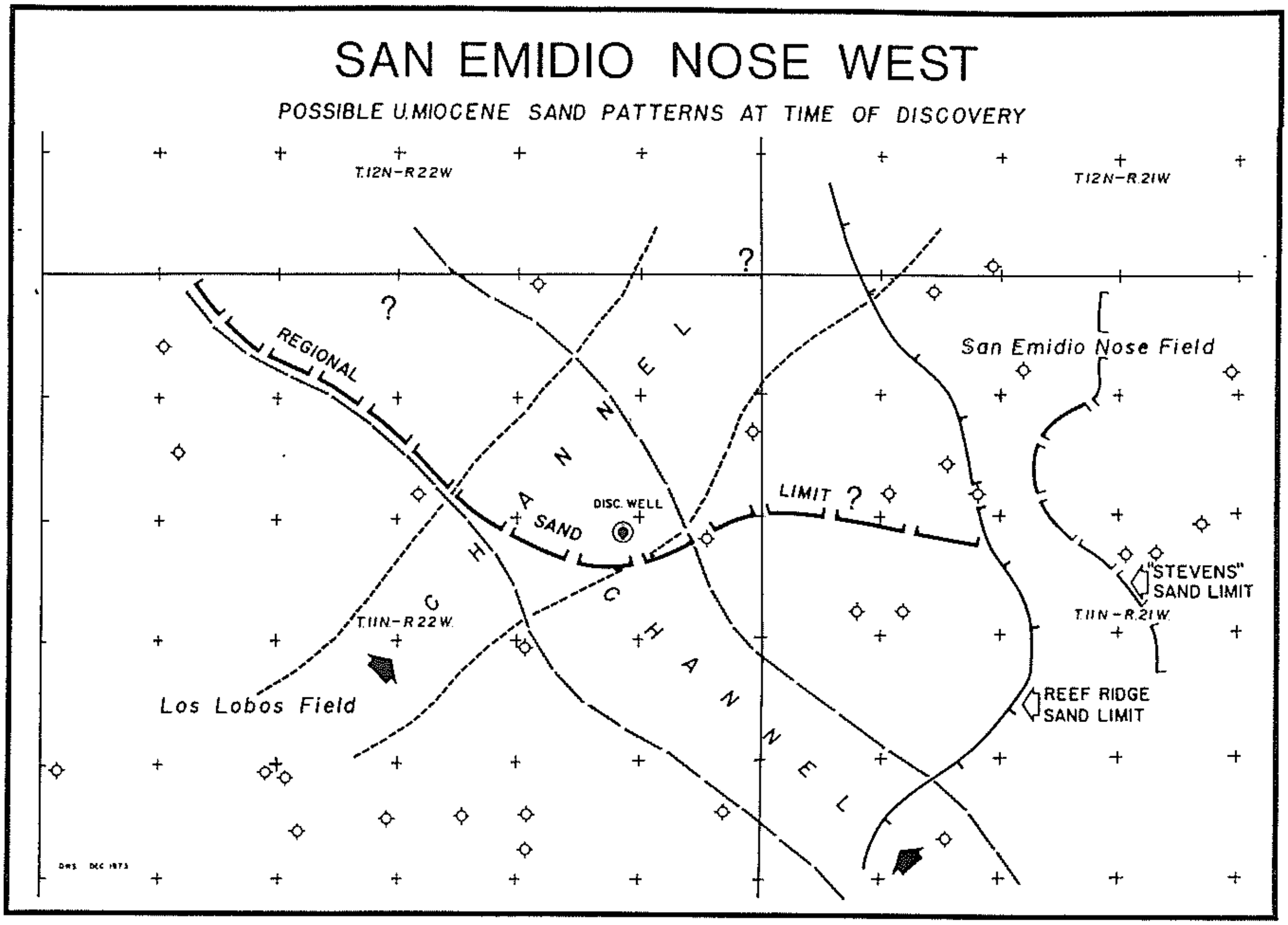

FIGURE 6 Following the completion of the discovery well, the geologists considered three possible reservoir geometries including a regionally extensive sand body. (D. Sprouse).

ward megasequences, the predominance of Bouma "a" and "b" beds, the abundance of tractive features, and the lack of bioturbation. Less commonly are found megasequences which have predominantly thickening and coarsening upward cycles, more complete Bouma sequences, and a lower sand/shale ratio. These sequences were interpreted to be mid-fan channels, crevasse-splay deposits, and interchannel deposits. The blanket sands found at the top of the Yowlumne sands are made up of thinner beds with greater amounts of interbedded shale. By identifying the various stratigraphic units in each well, a complete depositional model for the entire field was constructed.

Following a period of chert and shale deposition in the relatively quiet basin, sand was transported in a northwesterly direction. The initial turbidity current must have been influenced by subtle topography on the gently dipping basin floor. Levees were constructed on either side by overbank deposits, but the western levee was breached three or more times, and crevasse-splays and lesser channelized sequences were deposited to the northwest. The lobate sands in this portion of the field thin continuously to the north and west and are generally siltier and finer grained than the sediments to the east. The youngest sediments were infilling channel deposits representing the final stages of deposition before the cutoff of sediment supply.

In Unit "B" which was formed in 1982, the northeast area is composed mostly of channelized stratigraphic units, and the southwest has a greater percentage of crevasse-splay, or lobe-type deposits. Contrasting reservoir characteristics include gas/oil ratio, formation volume factor, and decline rate (Figure 21). Distinguishing between the southwest and northeast areas has been important in formulating waterflood plans and predicting future oil response and recoveries. A staggered line drive design was chosen for the southwest area of Unit "B", and a combination of peripheral and 5-spot pattern was chosen for the northeast. Injection in the southwest was started in 1982, and we are currently injecting over 40,000 BWPD in 16 injectors. Predicted secondary oil recovery is 25.0 million barrels (12.5% OOIP). Added to 29.9 million barrels of primary oil the total Unit B recovery should be around 55 million barrels (27.5% OOIP). The field's production grew from 1974 until 1978, peaking at over 34,000 BOPD. Since 1978 the field has seen waterflood response. Current production is about 9000 BOPD. To date, the field has developed over 275 million barrels of oil in place of which 77 million (28%) is estimated as recoverable from combined primary and secondary methods.

The geological model of the Yowlumne field has changed several times in the last ten years. The first interpretation treated the Yowlumne sand as one sand body. It was later divided into four sands based on log correlations. Later still, it was divided into 17 individual reservoirs based on several different parameters. Today a coordinated effort of geologists and engineers is adding to our ability to correlate from well to well and to define individual reservoirs. The ability to define individual reservoirs has greatly influenced enhanced recovery project designs and will ultimately lead to a greater percentage of the original oil in place produced. The teamwork of geologists, geophysicists and engineers is responsible for the overall 92% success rate which has been achieved in the development of the field.

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FIGURES 7-22 ON FOLLOWING PAGES

STRUCTURE
1974

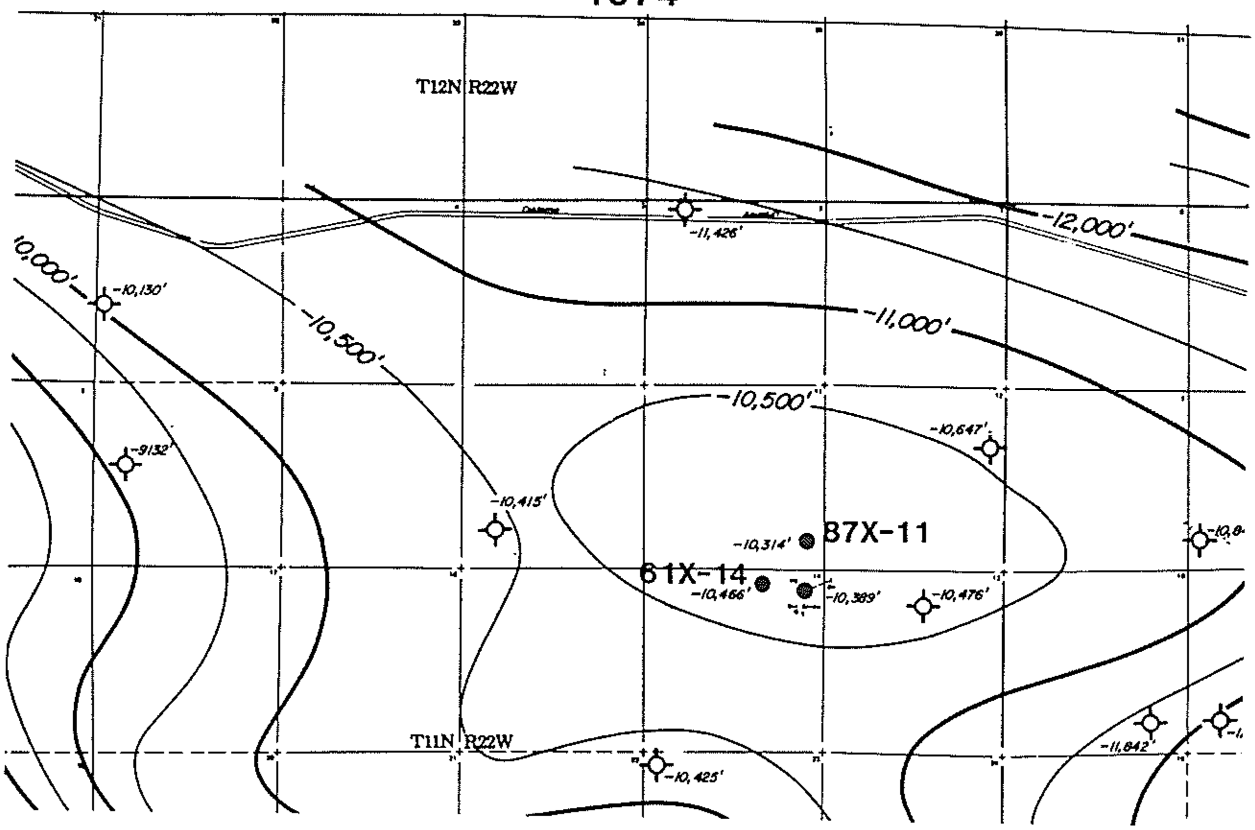


FIGURE 7 Confirmation wells were located to be structurally equivalent or higher than the discovery well. Well 61X-14 located an oil/water contact at −10,728 feet.

STRUCTURE
1974

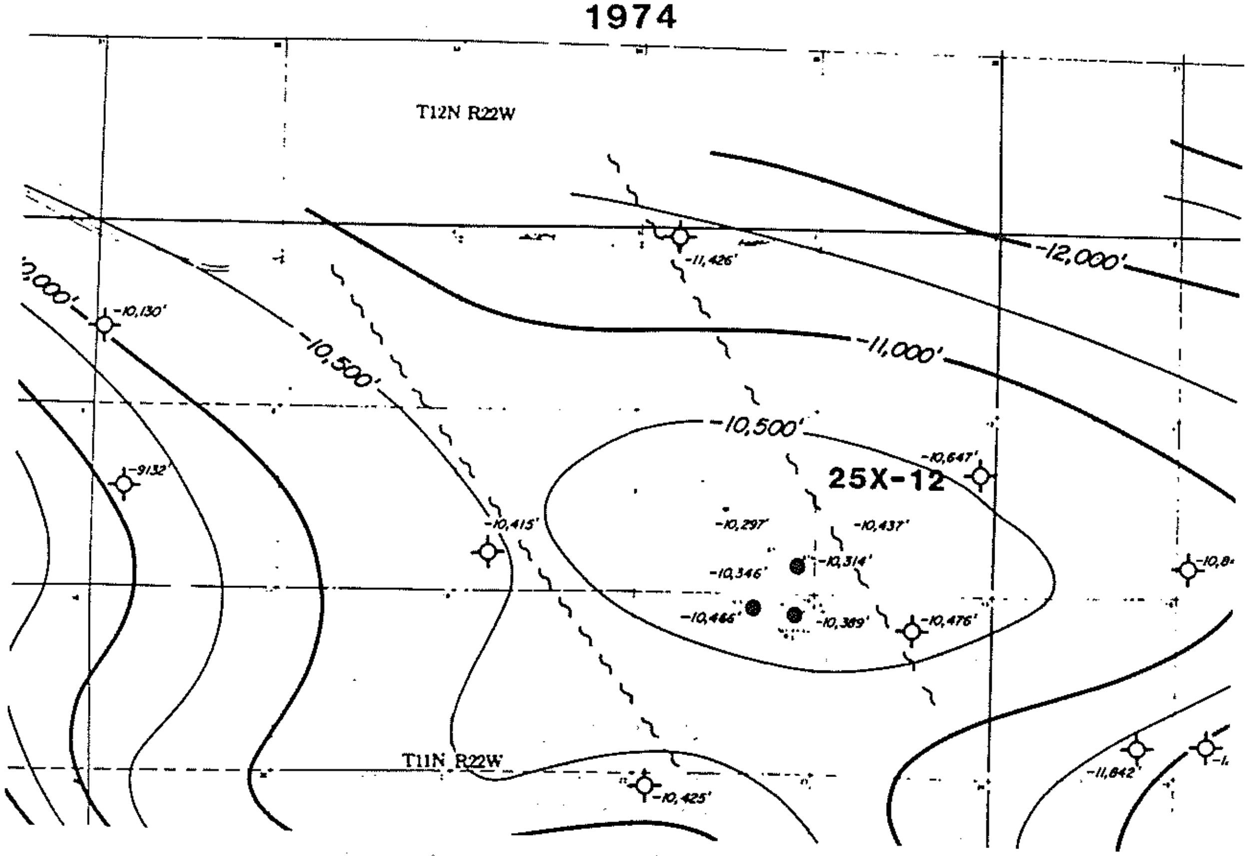


FIGURE 8 Well 25X-12 did not penetrate the channel and helped determine the sand orientation.

STRUCTURE 1975

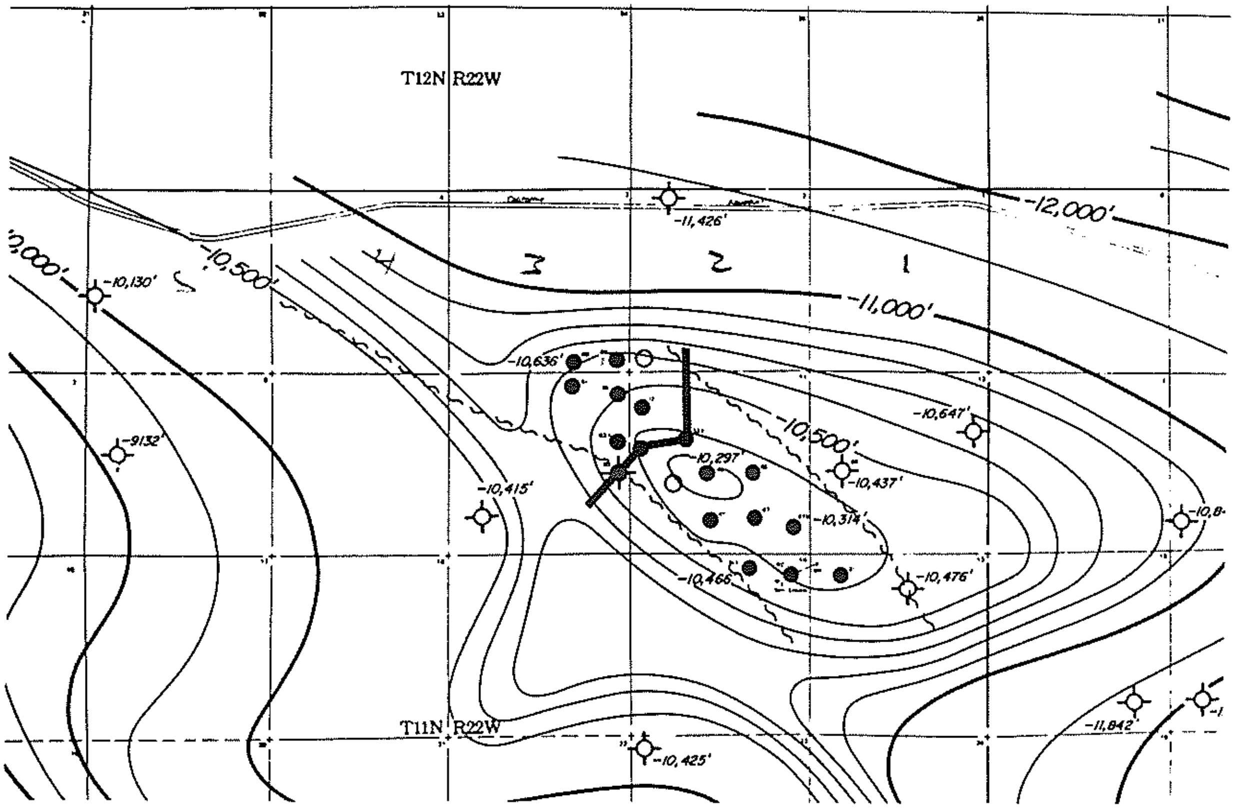
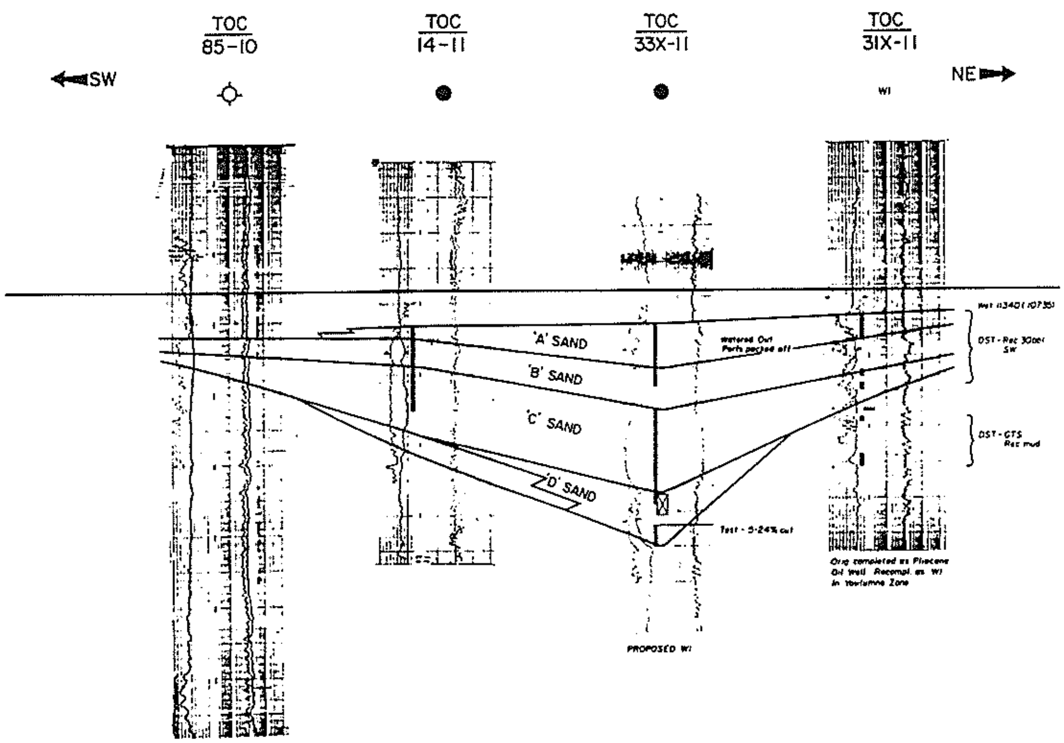


FIGURE 9 The wells drilled in 1975 were located in the northwest. The trace of cross-section B-B′ (Figure 10) is shown as a solid line.



YOWLUMNE FIELD STRATIGRAPHIC CROSS-SECTION B-B′(Transverse)

FIGURE 10 Four main sands were correlated in the Yowlumne channel. Cross-section B-B′ runs southwest to northeast.

STRUCTURE 1976

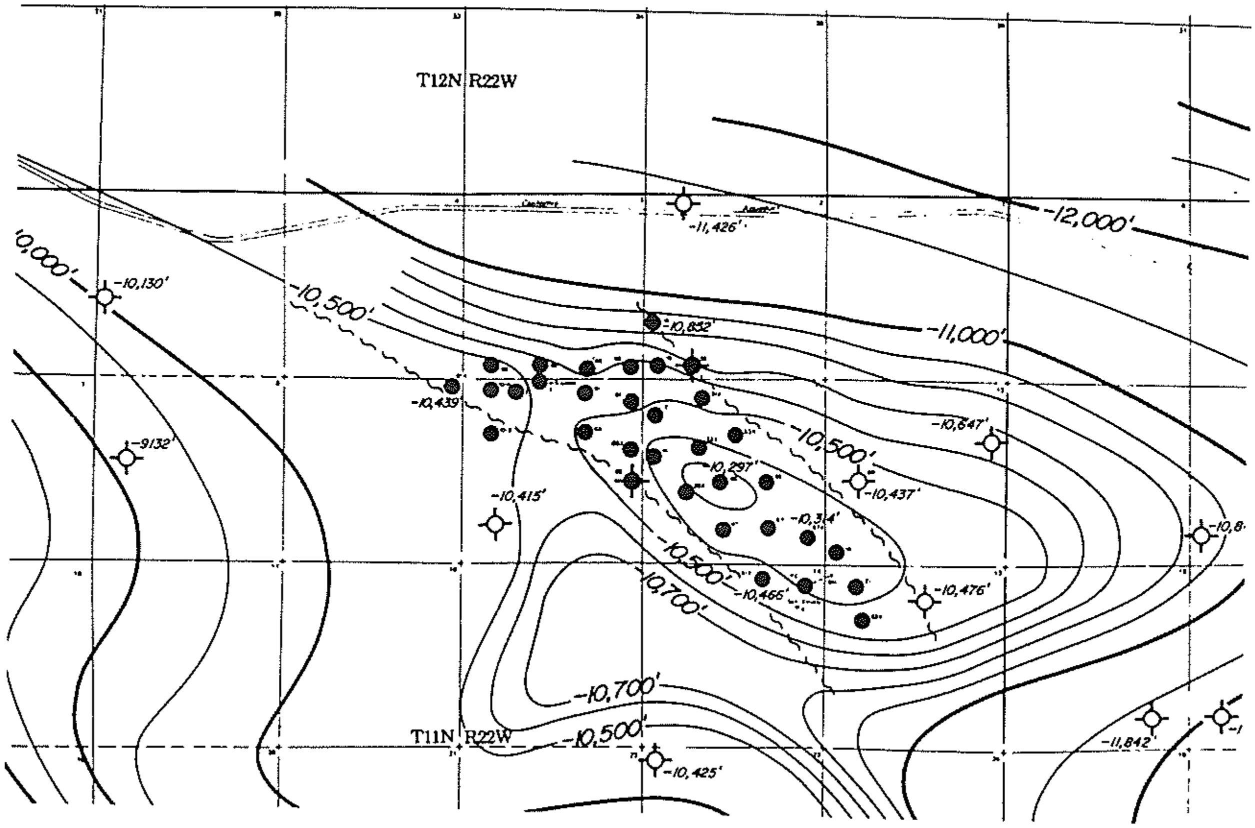


FIGURE 11 Drilling in 1976 was in the northeast and included one well in the southeast.

STRUCTURE 1977

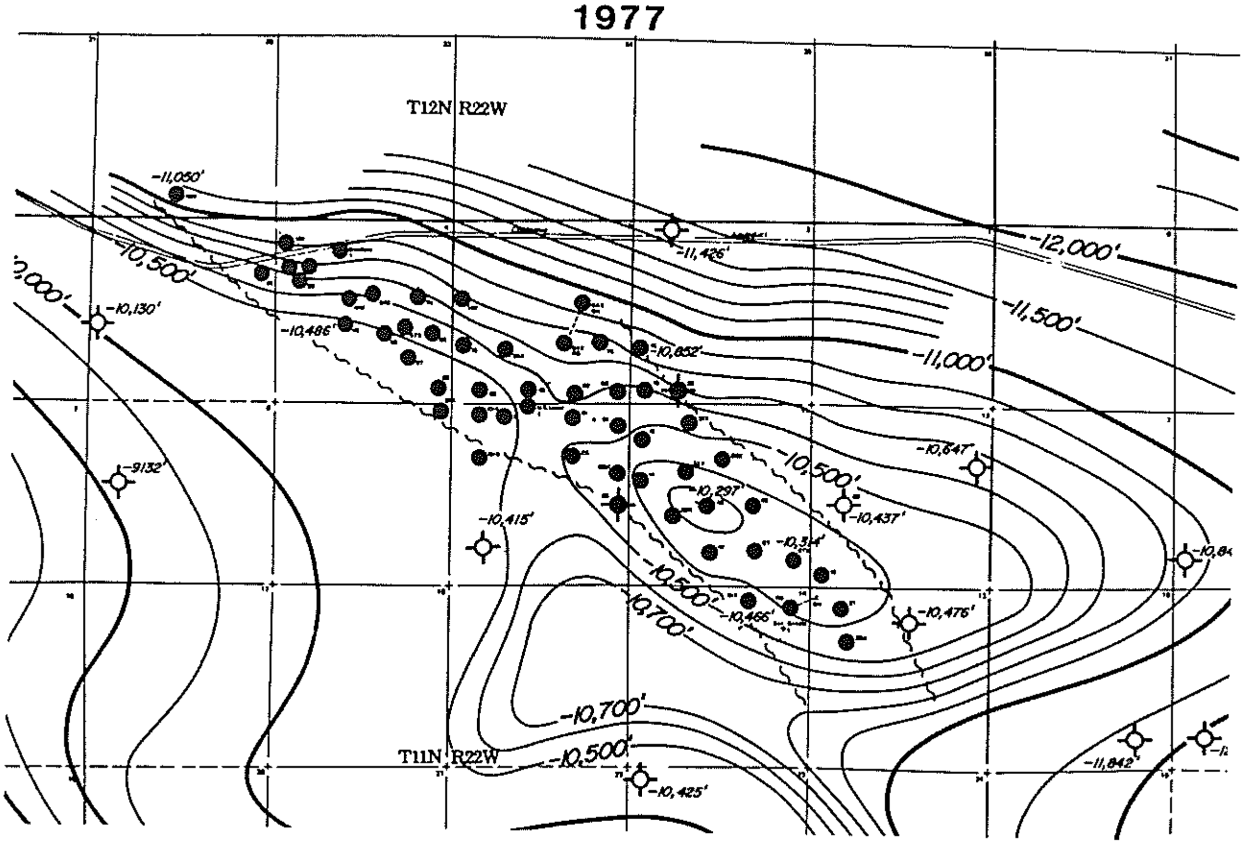


FIGURE 12 Development continued to the northwest in 1977.

GROSS SAND
1976 - 1977

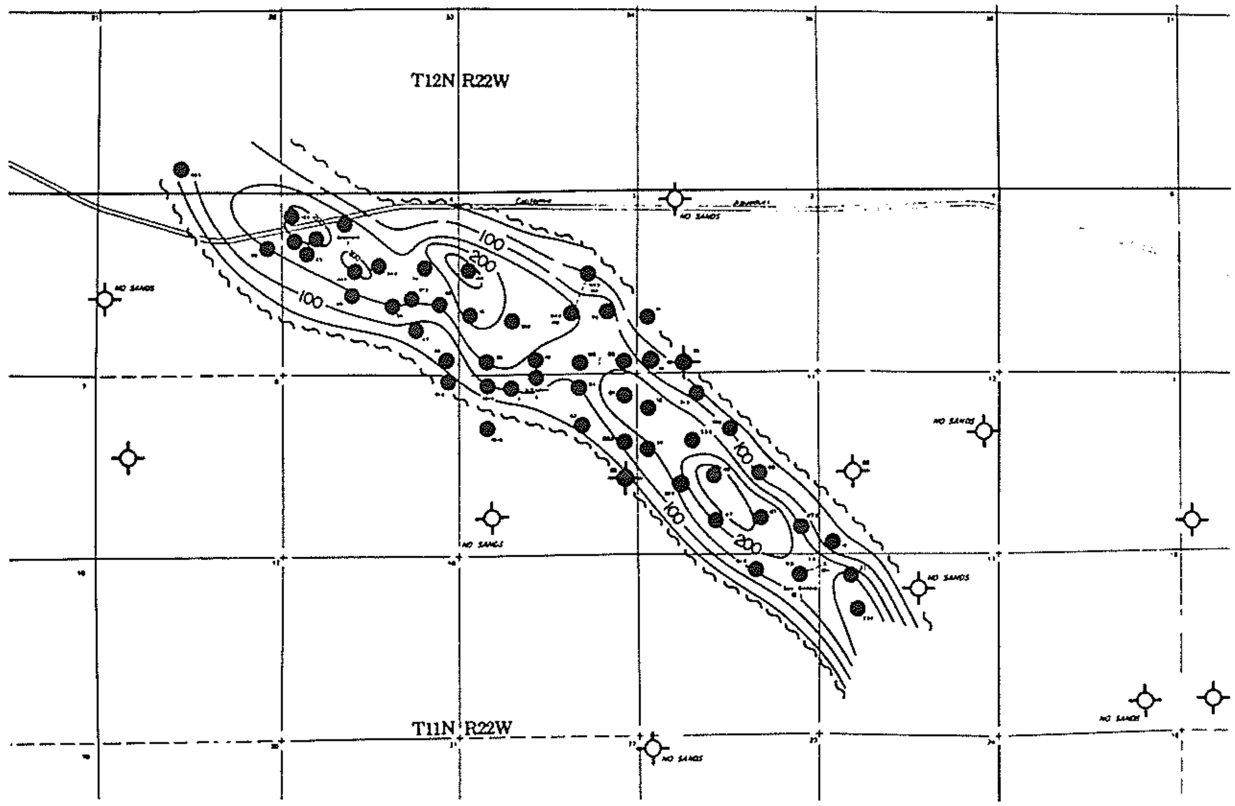


FIGURE 13 During 1976 and 1977 the reservoir was assumed to be a fairly linear channel with sub-parallel lateral limits.

STRUCTURE
1977

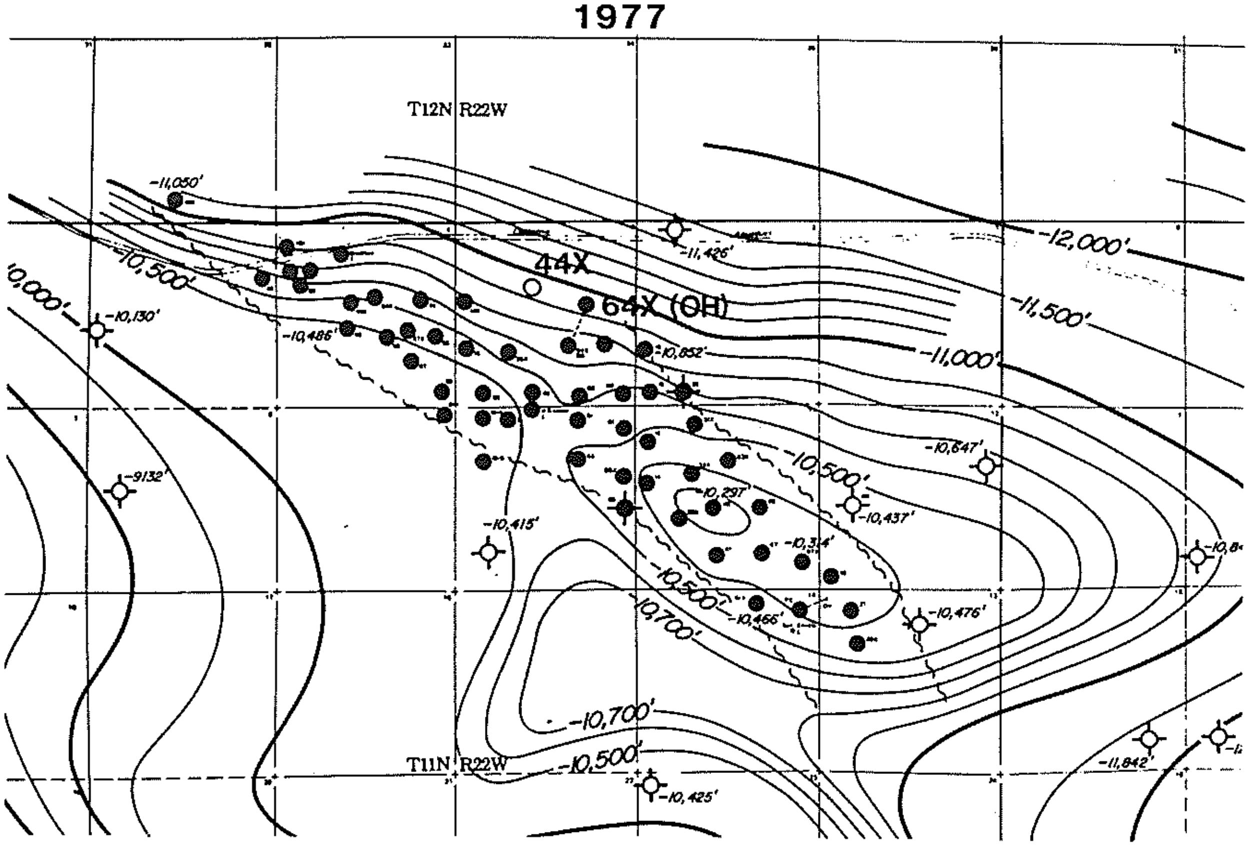


FIGURE 14 In 1978 Well 44X-3 was completed downdip without encountering an oil/water contact. The geologists began to modify the single channel model.

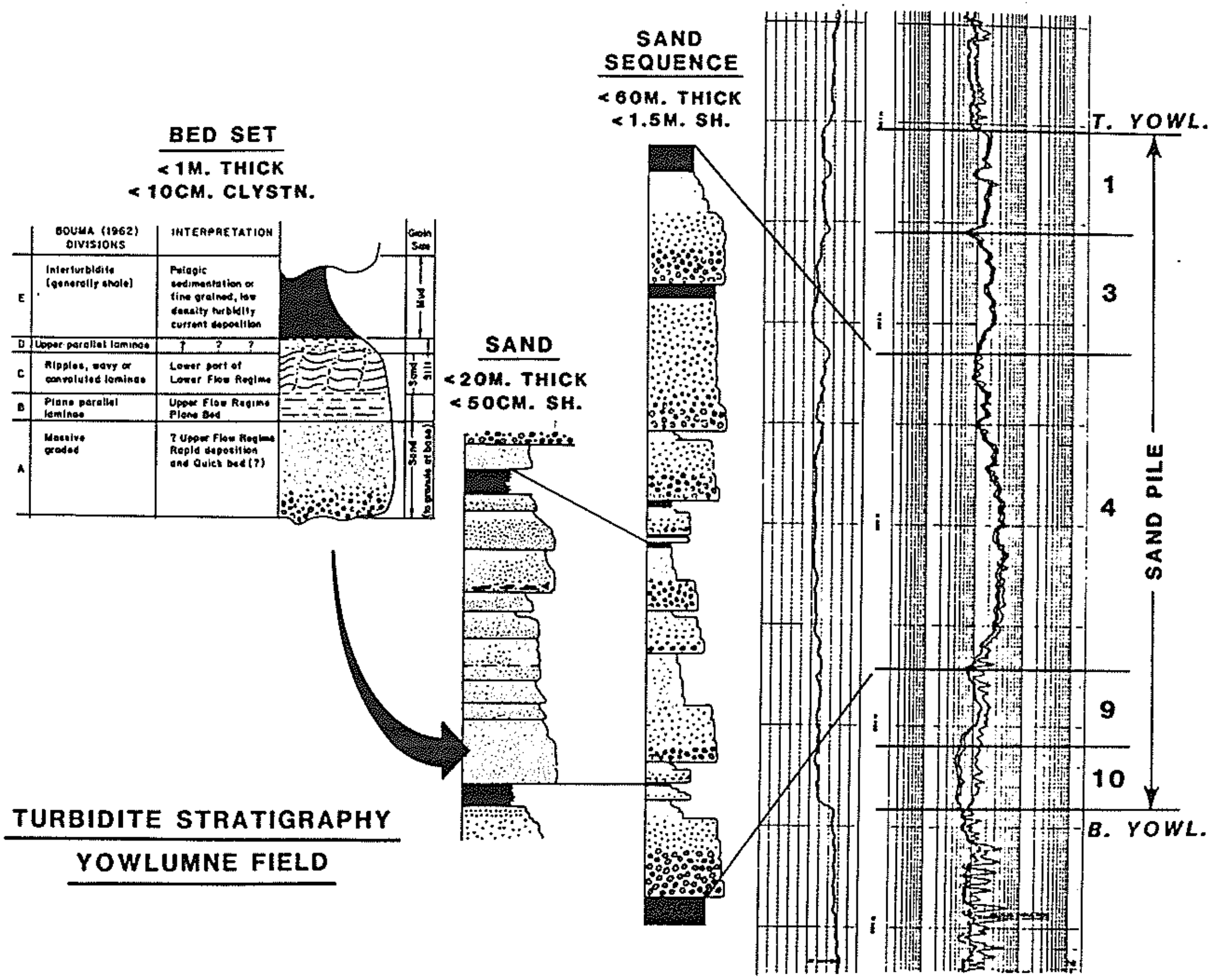


FIGURE 15 The stratigraphy of the Yowlumne sand is composed of individual bed sets stacked together forming sands. A series of sands make up a sand sequence. The Yowlumne sand numbered reservoirs are a combination of sand sequences.

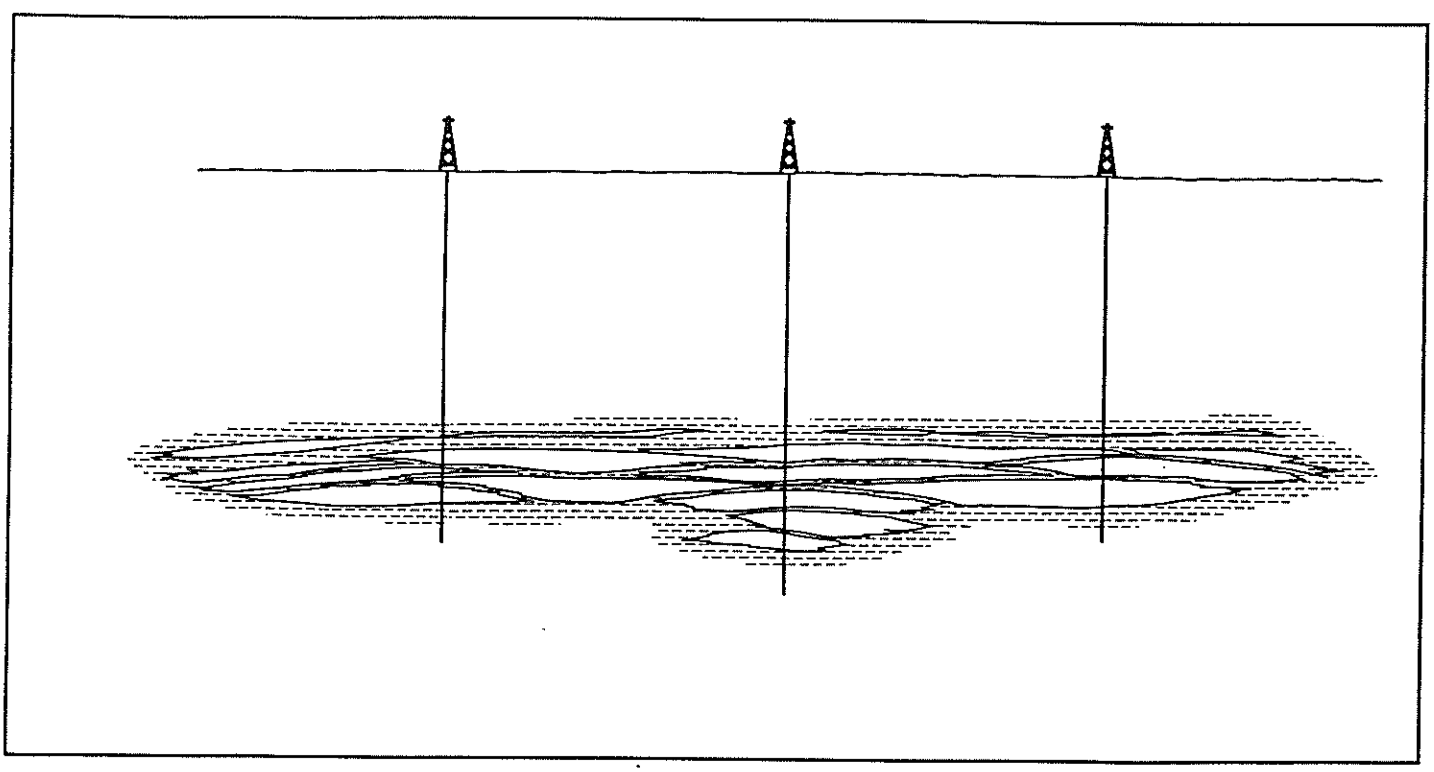


FIGURE 16 The schematic cross-section illustrates the lenticular nature of the individual sand reservoirs.

YOWLUMNE FIELD

REPEAT FORMATION TESTER RESULTS
STATIC RESERVOIR PRESSURE, PSIG

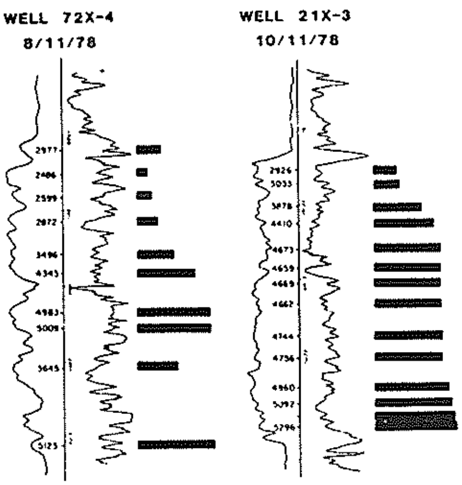


FIGURE 17
Pressures recorded by repeat formation pressure tests in adjacent wells reveal pressure reversal in Well 72X-4. Bars indicate pressure magnitude increasing to the right. These data were used to delineate isolated reservoirs within the Yowlumne sand.

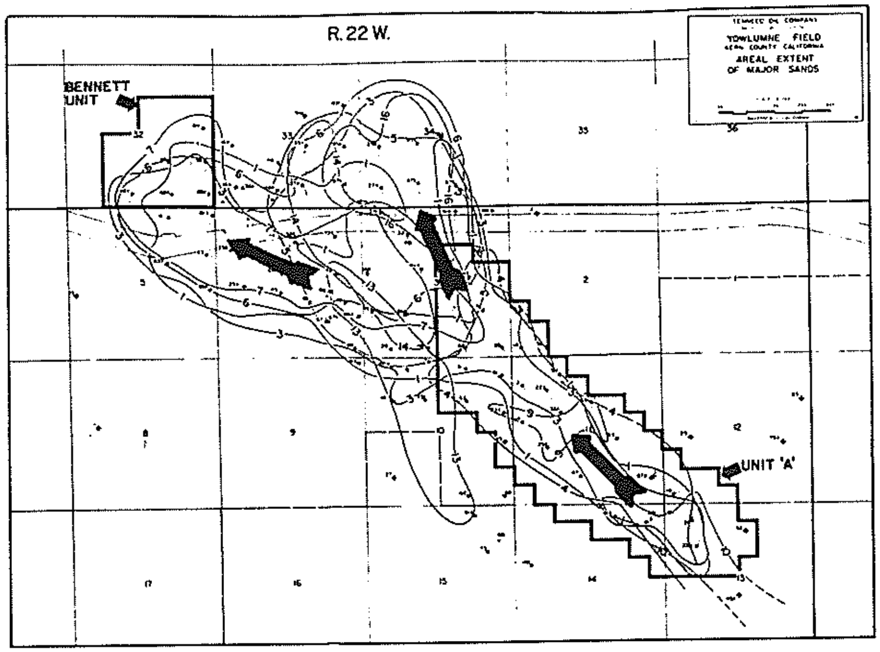


FIGURE 18
The areal extent of major sand map outlined the seventeen individual sands identified in 1980. Arrows inticate major sediment transport directions. Also shown is the Bennett Unit in the northwest which is now part of Unit B.

COMPOSITE NET PAY 1980

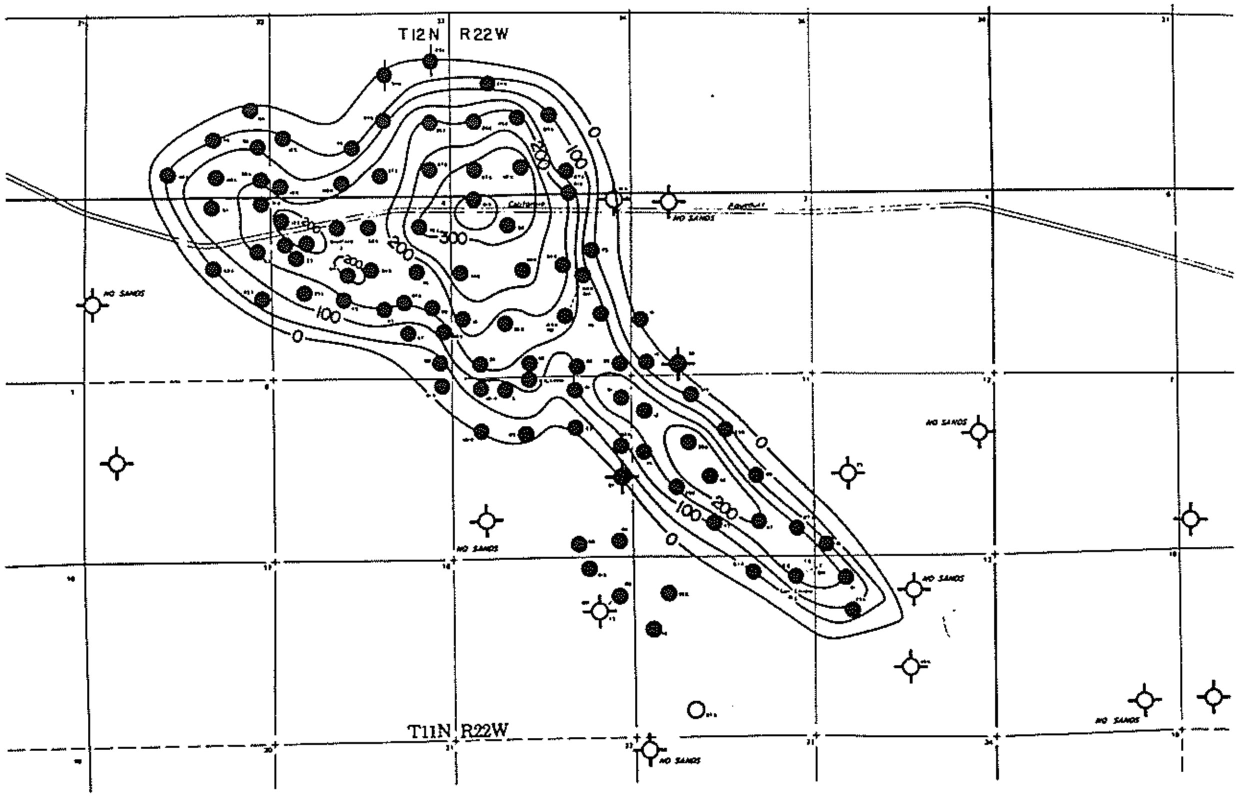


FIGURE 19 Composite net pay map constructed in 1980.

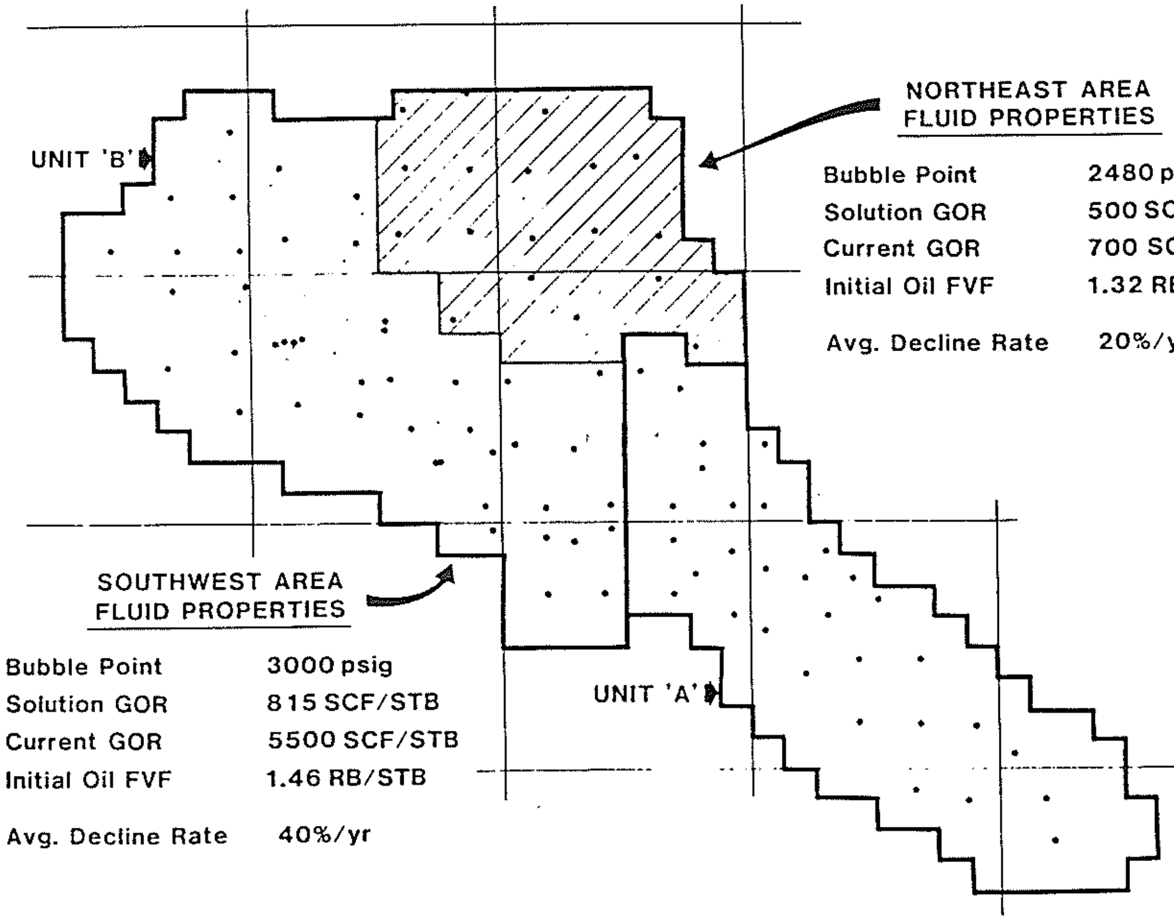


FIGURE 21 The contrasting reservoir properties of the northeast-southwest portions of Unit B contributed to the development of the current field model (from Burzlaff, 1983).

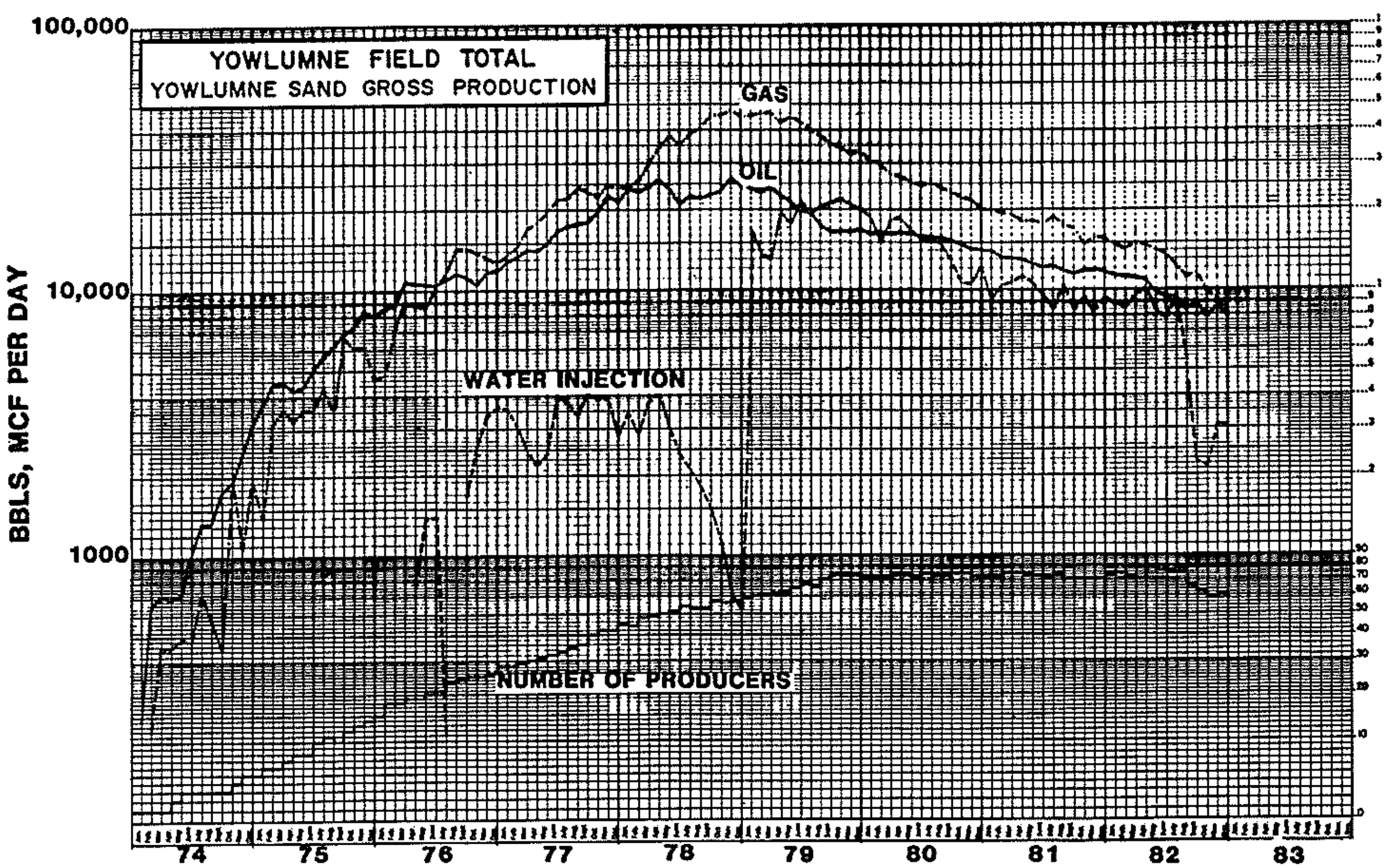


FIGURE 22 Yowlumne field production curve (all reservoirs).