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INTRODUCTION

The San Joaquin Geological Society is pleased to present Volume II in what is intended to be a continuing series of annual publications. The papers herein, as in Volume I, were delivered at regular monthly dinner meetings of the Society.

Not all papers presented to the Society lend themselves to this type of publication: those which are suitable deserve to be preserved and further disseminated. An historical committee recently formed within the Society is, among other things, attempting to trace back papers presented in earlier years with an eye to the eventual publication of one or more occasional papers.

The authors represented here have given unstintingly of their time and talents not only in the original preparations and presentations before the Society but also in the further shaping of the material for appearance in print.

In closing, we would like to thank those companies whose advertisements have provided financial help toward making this publication possible.

The Officers of the San Joaquin Geological Society

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EDITOR'S FORWARD

Three of the papers presented in this publication pertain to the subsurface geology of the Northern San Joaquin Valley. The original presentation of these papers revealed that there was no commonly accepted agreement on the use of formation names for many of the subsurface units in this area. In order to alleviate this problem and provide continuity to the papers presented in this volume a columnar chart has been prepared showing formation names and their positions relative to Tertiary epochs and the Upper Cretaceous foraminiferal zones of Paul P. Goudkoff. Stratigraphic interrelationships are also indicated. This chart was prepared with the assistance of the various authors who have used its formational terminology in their papers. This chart is on page 4 and is intended to supplement each of the papers on the geology and gas fields of the Northern San Joaquin Valley.

When possible, formation names of commonly accepted usage have been chosen. Certain portions of the section which are distinct entities with more than local distribution have not been formally named in any previous published work; new formation names are introduced for those units. It is hoped that the chart will help to organize and clarify subsurface terminology for this area and that it will serve as the basis for formational terminology used in any future papers and publications dealing with the subsurface of the Northern San Joaquin Valley.

STRATIGRAPHIC UNITS OF NORTHERN SAN JOAQUIN VALLEY AND SOUTHERN SACRAMENTO VALLEY

By W. F. Edmondson, D. C. Callaway, R. D. Hoffman and R. A. Teitsworth

AGE		Northern San Joaquin Valley – West Side	Northern San Joaquin Valley – East Side	Southern Sacramento Valle East of Midland Fault
Pleistocene		Undifferentiated Non-marine	Undifferentiated Non-marine	Undifferentiated Non-mari
Pliocene				
Miocene		Mehrten Formation Valley Springs Formation	Mehrten Formation Valley Springs Formation	Mehrten Formation Valley Springs Formatic
Eocene				Markley Formation
		Kreyenhagen Shale	Kreyenhagen Shale	Nortonville Shale
		Domengine Sand	Domengine Sand	Domengine–Ione Sand
				Capay Shale
Paleocene		Paleocene – Cretaceous Undifferentiated	Paleocene – Cretaceous Undifferentiated	Paleocene – Cretaceous Undifferentiated
UPPER CRETACEOUS	C Zone	Hall Shale	Hall Shale	Hall Shale
		Garzas Sand	Garzas Sand	Garzas Sand
		Moreno Shale	Moreno Shale	H & T Shale
		Azevedo Sand		Starkey Sand
	D-I Zone	Blewett Sand	Blewett Sand	
	D-2 Zone	Ragged Valley Silt	Ragged Valley Silt	
		Tracy Sands	Starkey Sands	
		Sawtooth Shale		Upper Delta Shale
	E Zone	Winters Sand (=Benetti Sand)	E Zone Shale	Winters Sand
		E Zone Shale		
		Lathrop Sand	Lathrop Sand; Unnamed Sand	Lower Delta Shale
		Sacramento Shale	Sacramento Shale	Sacramento Shale
	F Zone	Forbes Formation	Forbes Formation	Forbes Formation
	G Zone	Dobbins Shale	Dobbins Shale	Dobbins Shale
		Unnamed G and H Zone Formations	Unnamed G Zone Formation	Guinda Sand
	H Zone			

DISTRIBUTION OF UPPERMOST CRETACEOUS SANDS IN THE SACRAMENTO-NORTHERN SAN JOAQUIN BASIN OF CALIFORNIA[1]

DAVID C. CALLAWAY[2]
Bakersfield, California

ABSTRACT

The earlier phase of late Cretaceous sedimentation ended with a widespread transgression of the sea and deposition of the "E" Zone Sacramento Shale. The final phase began when compressional forces reduced the size of the basin by more than one half. The Sacramento-Northern San Joaquin Valleys of California are the topographic expression of the Cretaceous basin in its final phase. The basin was asymmetrical, shallow and gently sloping on the east, deeper and steep on the west, and was periodically filled with sands which originated from three different and independent sources.

One period of major uplift and erosion plus the cut and fill of one submarine river channel were the only modifications of pre-existing sediments that took place during the late Cretaceous. Later modifications of the Cretaceous occurred during pre-Paleocene, pre-Eocene, and pre-Miocene time, the result of uplift and erosion, and during Eocene and Oligo-Miocene time, the result of submarine river channel erosion.

INTRODUCTION

The Stockton Arch, a pre-Miocene structural arch, was readily apparent to early geologists from surface geological studies and shallow drilling data. The concept that the arch separated two entirely different geological worlds took firm hold and soon there were Sacramento Basin geologists working north of the arch, and San Joaquin Basin geologists working south of the arch. The arch itself became the property of the latter group. Geological understanding and associated nomenclature developed from each side of the arch, neither side paying much attention to the other. Today this segregation of basins, though valid to a degree for the Eocene, has severely hampered the understanding of the stratigraphy and distribution of Cretaceous sediments. This paper is an attempt to alleviate some of this lack of understanding.

LIMITS AND SCOPE

The area covered by this paper is bounded on the east and west by basement outcrops, extends north to the Marysville Buttes (T. 16 N.) and south to the Coalinga Oil Field (T. 20 S.).

Createceous sediments older than Goudkoff's "E" Zone are not discussed[3]. The correlation chart on page 4, indicates the upper portion of the Winters Sand to be "D-2" Zone age. The "D-2" and "E" Zones were originally considered by Goudkoff to be one zone, the *Nodosaria spinifera* Zone. Goudkoff later divided this into the *Bolivina incrassata* Zone ("D-2") and the *Planulina constricta* Zone ("E"). About 95 per cent of the species found in these zones are common to both and the rarity of the index forams together with the many variables of environment and sampling may be distorting the true picture. In many cases the lack of "E" Zone index forams coupled with the absence of "D-2" Zone index forams often results in paleontologists reporting long intervals in wells as "D-2 and/or E Zone, undifferentiated." It may be that the Winters Sand in the Sacramento Basin was deposited during "E" Zone time, as it was in the Northern San Joaquin Basin, but ecologic conditions being different further north, the rare index forams failed to thrive or even exist. It is just as possible that the index forams for the "D-2" and "E" Zones are facies faunas (Edmondson, 1962, p. 26). In either case the writer includes the Winters Sands in the "E" Zone and places the only major unconformity within the later Cretaceous at the contact of the "D-2" and "E" Zones.

STRATIGRAPHY

This paper is primarily concerned with sands so it must be understood from the onset that sand differentiation is dependent upon a number of easily recognizable (electrically and paleontologically) and relatively widespread shales.

Cretaceous Shales

The *Sacramento Shale*, which occurs at the base of the "E" Zone and rests on "F" Zone Forbes Shale, frequently has a recurrent fauna with some "G-1" Zone faunal affinities. Paleontological data suggests the depositional basin was open to the ocean. The shale shows an extremely low electrical resistivity compared to the shales above and below. The contact with the overlying shale is known as the "Neck" marker. The Sacramento Shale occurs throughout the entire area covered by this paper.

The *Sawtooth Shale* is basal "D-2" Zone in age, unconformably overlying the "E" Zone. Its name is indicative of its ragged appearance on the amplified normal curve of electric logs. The shale can readily be identified in the western two thirds of the basin.

The *Ragged Valley Silt* is uppermost "D-2" in age. This shale has some excellent electrical markers which can be correlated over a large area. The shale is easily identified on the west side of the basin south of Rio Vista.

The *Moreno Shale* is "C/D-1" Zone in age and is found throughout the basin south of Rio Vista. Because of its homogeneous and electrically characterless nature, the Moreno can be correlated only locally and with difficulty.

The *H & T Shale* is equivalent to the uppermost part of the Moreno Shale. It is also "C/D-1" in age and is found north of Township 3 North.

The *Hall Shale* is found on the north side of the Stockton Arch in the Seaboard "Hall-1", Section 6, T. 2 S., R. 5 E., between 5380 and 5555 and on the south side

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1. Presented to the San Joaquin Geological Society, January 15, 1963.

2. Consulting Geologist.

3. The faunal subdivisions of Goudkoff are used throughout this paper as time subdivisions of the Uppermost Cretaceous. In his paper (Goudkoff, 1945, pp. 956-1007) Goudkoff desiginated stages on the basis of his faunal zones.

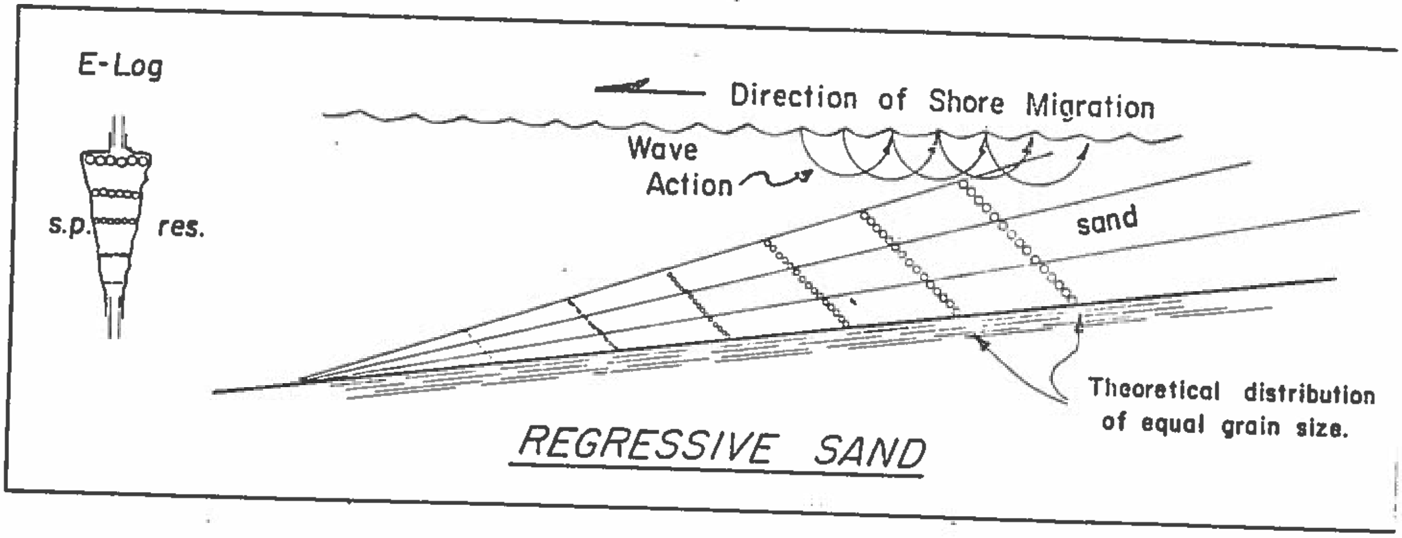


Fig. 1a. Theoretical development of regressive sands.

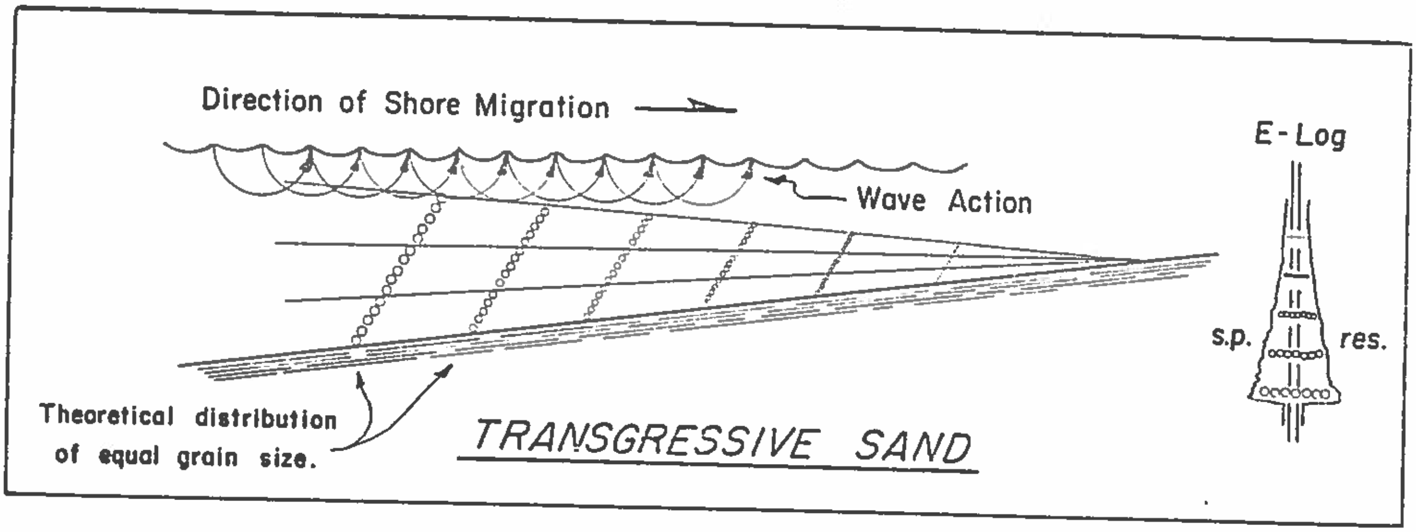


Fig. 1b. Theoretical development of transgressive sands.

of the arch it is found in the Superior "Sinclear-1", in Section 5, T. 5 S., R. 9 E., between 3970 and 4120. Upper Cretaceous forams of indefinite age are found in the shale, but its position above the "C/D-1" Zone Garzas Sand indicates that it should also be "C/D-1" Zone in age or younger.

Sand Classification

To facilitate sand identification, the writer has utilized a sand classification of Murray Nadler based on electrical differences which result from energy influences during deposition. This classification divides sands into four major groups which, considerably simplified and slightly modified, are:

1. *Regressive Sands*: Sands deposited on a shallow, gently sloping shelf in a diminishing depositional basin. Basin shrinkage could be the result of onshore uplift, offshore sinking, or any cause that would effect a seaward migration of the shore. Electrically this sand has a characteristic "carrot" shape (fig. 1a) due to progressively better cleaning and sorting of near surface sands by wave action.

2. *Transgressive Sands*: This sand type is the exact opposite of regressive sands. They have a "Christmas Tree" shape (fig. 1b) electrically, which is the result of deposition in an increasing basin, a basin with a landward migrating shore.

3. *Bar Sands*: Electrically these sands have a blocky appearance. They have flat tops and bottoms due to current and near surface wave action.

4. *Channel or Deltaic Sands*: Because of the erratic and rapidly fluctuating condition of deposition of these sands, they are dirty and silty with variable grain size. Electrically the sand appears very ragged.

"E" Zone Cretecous Sands

The *Lathrop Sand* is a deltaic deposit whose source was in the Diablo Range between the Livermore Valley and Oristimba Creek. This local uplift was not far from the present basin edge (Safonov, 1962, p. 85). Southwest of the Vernalis Gas Field, in T. 4 S., R. 5 E., these sands are massive, coarse grained, angular, unsorted, and appear unweathered, similar to granite wash, implying proximity to source. From west to east the grain size and overall sandiness decreases until the sand shales out completely (fig. 3). The areal distribution of the sand depicts a fan shape centering on the Diablo Range (fig. 4). More than 3000 feet of Lathrop Sand is present in the center of the fan. The Lathrop Sand interfingers with the Joaquin

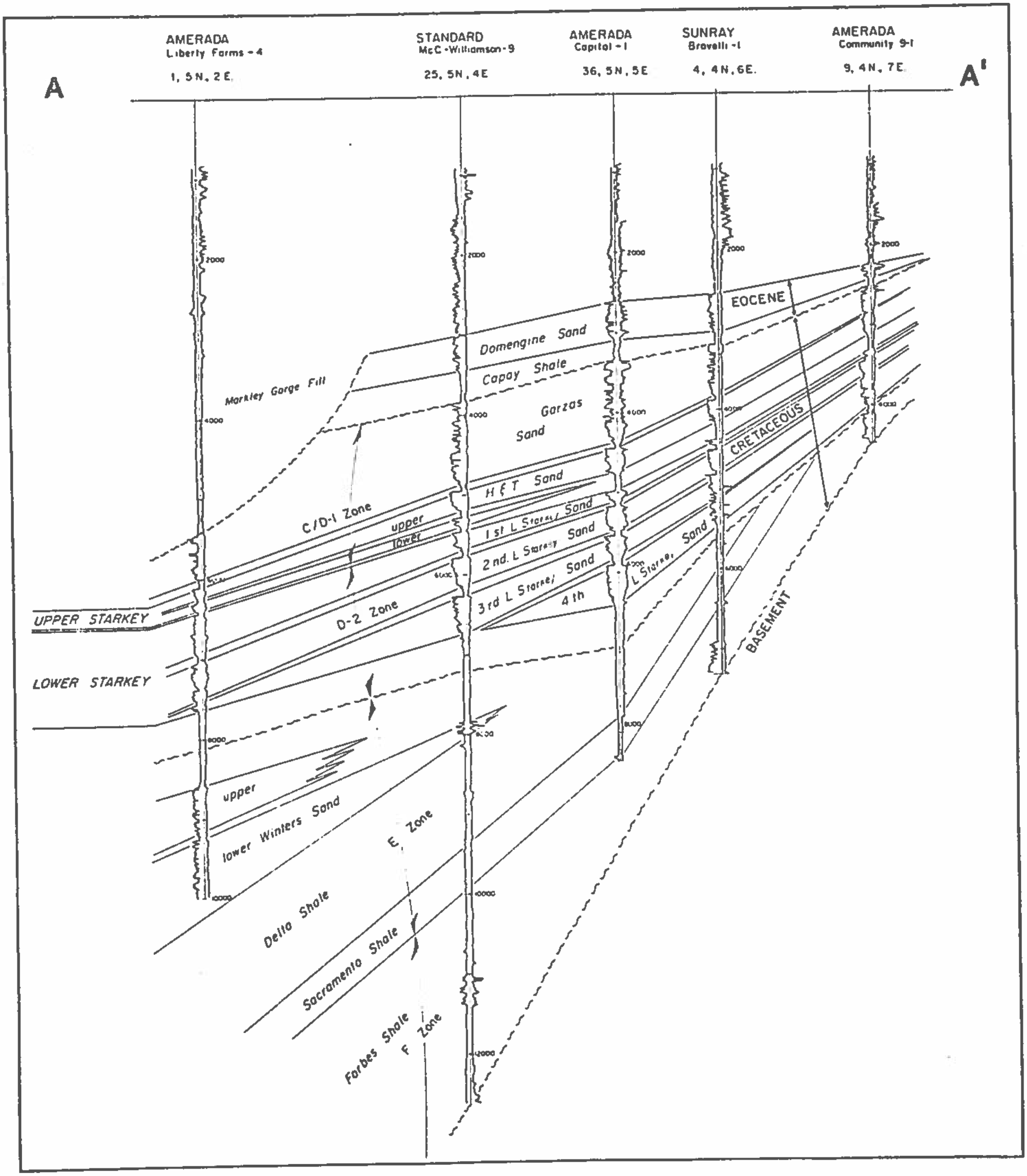
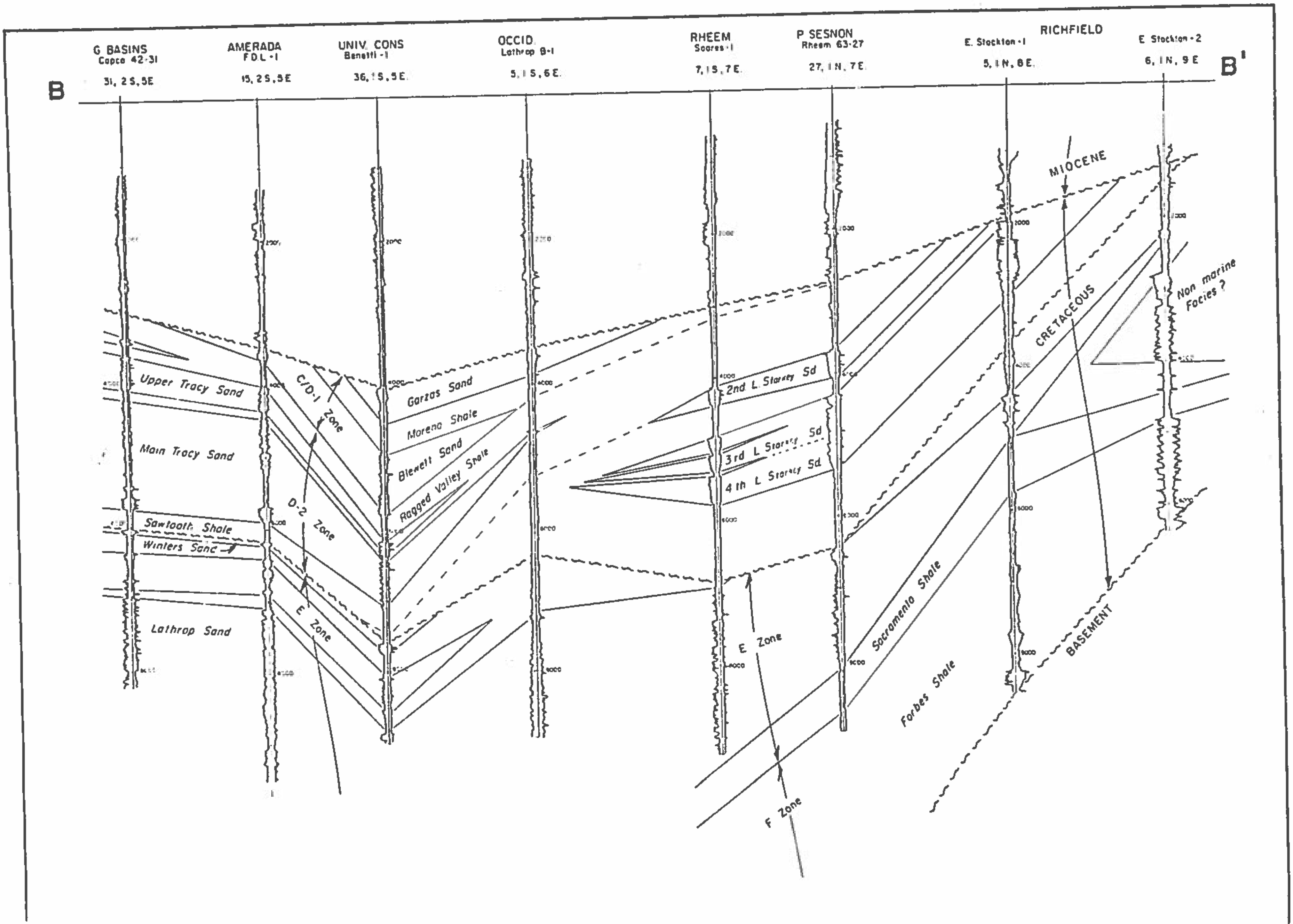


Fig. 2. Correlation section A-A'.


B
B'
G BASINS
Capco 42-31
31, 2S, 5E
AMERADA
FDL-1
15, 2S, 5E
UNIV. CONS
Benetti-1
36, 1S, 5E.
OCCID.
Lathrop B-1
5, 1S, 6E.
RHEEM
Soares-1
7, 1S, 7E.
P SESNON
Rheem 63-27
27, 1N, 7E.
E. Stockton-1
5, 1N, 8E.
RICHFIELD
E Stockton-2
6, 1N, 9E
MIOCENE
CRETACEOUS
BASEMENT
Non marine Facies ?
Upper Tracy Sand
Main Tracy Sand
Sawtooth Shale
Winters Sand
Lathrop Sand
C/D-1 Zone
D-2 Zone
E Zone
Garzas Sand
Moreno Shale
Blewett Sand
Ragged Valley Shale
2nd L. Starkey Sd
3rd L Starkey Sd
4th L Starkey Sd
E Zone
F Zone
Sacramento Shale
Forbes Shale

Ridge Sand to the south. The rarity of wells penetrating to the Joaquin Ridge Sand precludes any positive geological interpretation, although it is likely that these sands are also deltaic, but from a more southerly source.

The *Stockton Sand* was penetrated in the Richfield "East Stockton-2", Section 6, T. 1 N., R. 9 E., between 2800 and 4000 (fig. 3). The sand appears very massive and has a slight tendancy towards regressive characteristics. Few wells have been drilled this far east, so little that is definite can be concluded about the sand except that it has an easterly source. It may be equivalent to the massive sand immediately above the Sacramento Shale in the Great Basins "Ambassador-Modesto A-1", Section 14, T. 3 S., R. 8 E., and the Standard "Young Community-1", Section 34, T. 3 S., R. 8 E. Between these two wells the sand thins to the west. Another equivalent could be the non-marine or brackish sand in the "E" Zone found east of Chowchilla in T. 8 and 9 S., R. 14 and 15 E. (fig. 8). The "E" Zone map (fig. 4) refers to the Stockton Sand as the "Non-Marine Facies" and only intimates the correlations described above.

The *Winters Sand* is a channel sand from a local uplifted source north of Mount Diablo, possibly west of the Dunnigan Hills. It shales out to the east and west from a maximum thickness in excess of 1700 feet in the center of the channel. On the east a distinction can be made between the upper and lower Winters Sand (fig. 2) because the lower sand shales out further east than the upper sand. Both sand zeros have an approximate north-south trend. As noted on Figure 4, a long tongue of Winters Sand extends as far south as Township 6 South. On the Stockton Arch the sand ranges up to 250 feet in thickness and has been locally named the Benetti Sand.

Scattered offshore bar sands are found east of the Winters Sand zero. One of these, the Simms Sand, is productive at the Freeport Gas Field.

"D-2" Zone Cretaceous Sands

The *Lower Starkey Sand* is a typical regressive sand. It is massive and thick on the east side of the basin and pinches out in the center. Near the pinchout the Lower Starkey can be divided into four distinct sands, each of which represents a cycle of slow regression followed by a rapid transgression. The lower three sands (4th, 3rd, and 2nd) have zero lines which trend northwest-southeast, paralleling the edge of the basin. This suggests that the Sierra Nevadas were oriented about as they are today, and uniformly contributed sediments the entire length of the basin. The zero line of the uppermost (1st) Lower Starkey Sand trends east-west indicating a shift of the Sierra Nevada source to the north.

Lithologically the sands are silty at the base grading upward into coarser and cleaner sand. The top of the sand usually has a slightly resistive grit representing the transgressive part of its depositional cycle.

The *McCune Sand* is an offshore bar which appears to have been deposited at the same time as the earliest (4th) Lower Starkey Sand. It is found in T. 8 and 9 N., R. 1 E., and it is productive at the Winters Gas Field.

The *Main Tracy Sands* are deltaic sands originating from the Diablo Range. They attain a maximum thickness of 900 feet and are confined to the western one third of the basin. The zero line of the sand, which is a pinch out line, has a very broad fan shape (fig. 5) except for a small spur on the southeast in T. 10 S., R. 12 and 13 E., which represents a local reentrant.

The *Upper Tracy Sand* occupies the center of the western half of the basin. The sand pinches out to the east, west and south from a maximum of 600 feet in the center, a pattern suggesting channel deposition with the source near Mount Diablo.

The *Skiles Sand* is seen in only one well, the Christiana "Skiles-1", Section 28, T. 2 S., R. 8 E. It is an offshore bar reaching a thickness of 100 feet and is associated with the Tracy Sands to the west.

"C/D-1" Zone Cretaceous Sands

The *Upper Starkey Sands* are regressive sands which occupy the northern portion of the basin and continue the pattern of deposition established in "D-2" time. They can be separated into Upper and Lower H & T Sand members. The zero lines of these sands are pinchout lines that trend east-west. The source was the Sierra Nevadas to the north and northeast.

The *Blewett Sands* were deposited contemporaneously with the Upper Starkey Sands. Their typical fan shaped areal distribution (fig. 6) on the west side of the basin indicates deltaic deposition from a source in the Diablo Range. On the Stockton Arch the upper part of the Blewett Sand is locally called Azevedo. To the south the name Brown Mountain is synonomous with Blewett.

The *Gorge Fore Sands* are represented by three small, isolated sand bodies located in T. 9 and 10 S., R. 13 E. Figure 9, a north-south cross section, indicates a missing portion of the Lower Starkey regressive sands in the Shell "Strat Test-16". Because of the uniform nature of the deposition of regressive sands, any section missing from the top as shown must be the result of erosion. The pattern of wells with incomplete or missing upper portions of the Lower Starkey, as indicated in Figure 9, suggests channel-like erosion very similar to the gorge erosion common in the Sacramento Basin. The west-east cross section (fig. 8) shows an interpretation of "C/D-1" age submarine river erosion acting on the "D-2" age Lower Starkey Sands. Upon reaching a base level of erosion, the sand was redeposited as "Gorge Fore Sand". It was overlain by Moreno Shale which also filled the gorge cut. There was apparently a small barrier in the southeast corner of T. 9 S., R. 13 E., which caused a separation of these Gorge Fore Sands. The lowest sand occupies both lobes, while the upper sand is found only in the south lobe.

The *Garzas Sand* is a regressive sand which overlies the Moreno Shale throughout the entire Sacramento Basin and most of the Northern San Joaquin Basin. To the southeast the sand is called the Wheatville Sand and is definitely marine Cretaceous. On the Stockton Arch the sand is termed Garzas and is also marine Cretaceous. To the north the sand is known as the "Martinez". It has brackish water characteristics and has been placed in the Paleocene for lack of a definite fauna. The Cretaceous Hall Shale has a stratigraphic position 1300 to 1500 feet above the base of the Garzas on the Stockton Arch and 1000 to 1200 feet above the base of the "Martinez" in the Rio Vista area. The writer suggests that the Garzas Sand, the Wheatville Sand and the "Martinez" Sand of Rio Vista are contemporaneous, with Garzas and Wheatville the marine facies and "Martinez" the brackish water facies. In the Rio Vista area there is a few hundred feet of massive sand below the Eocene Capay Shale that may be Paleocene in age.

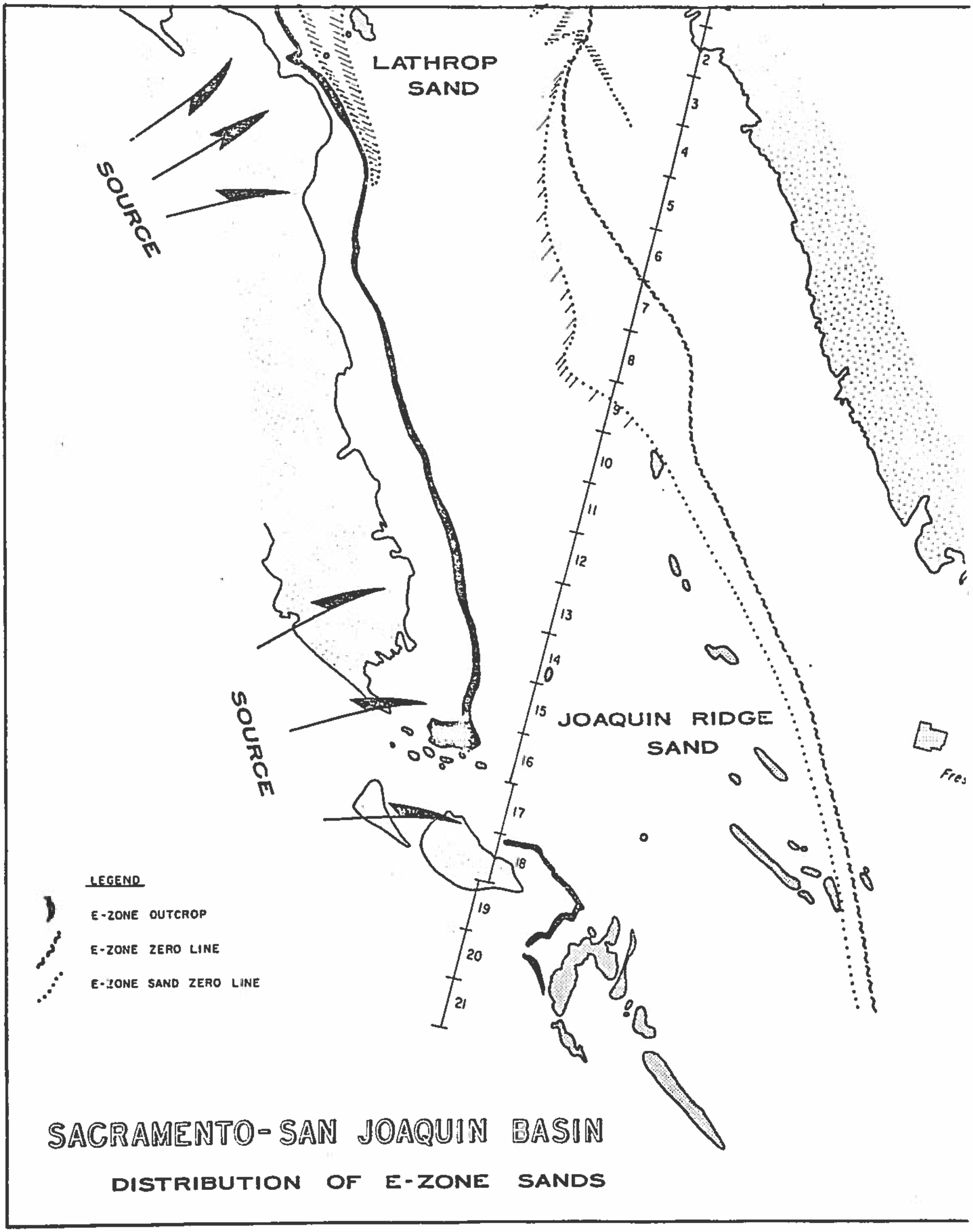


Fig. 4a. Distribution of sands in Cretaceous E Zone—southern portion.

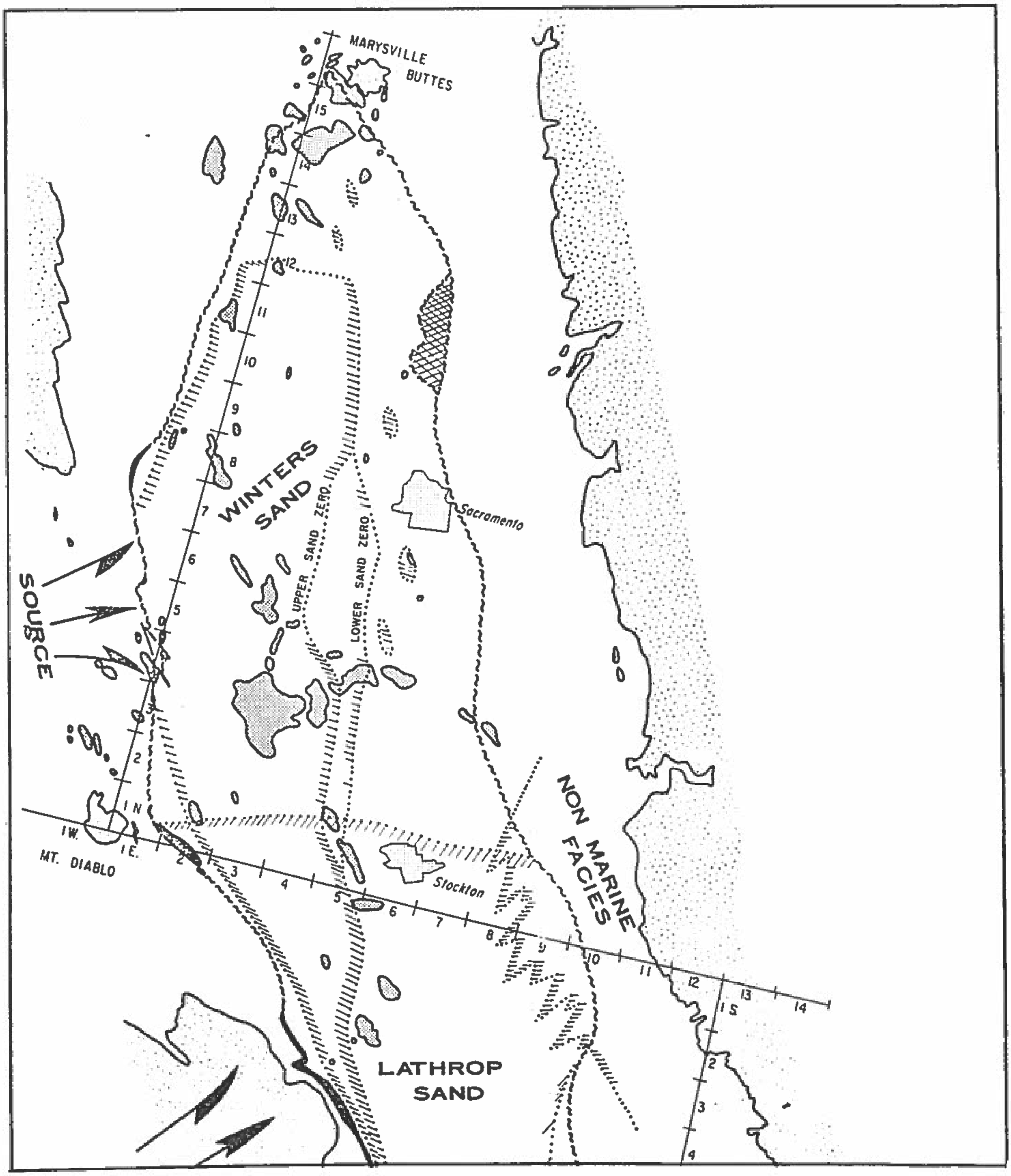
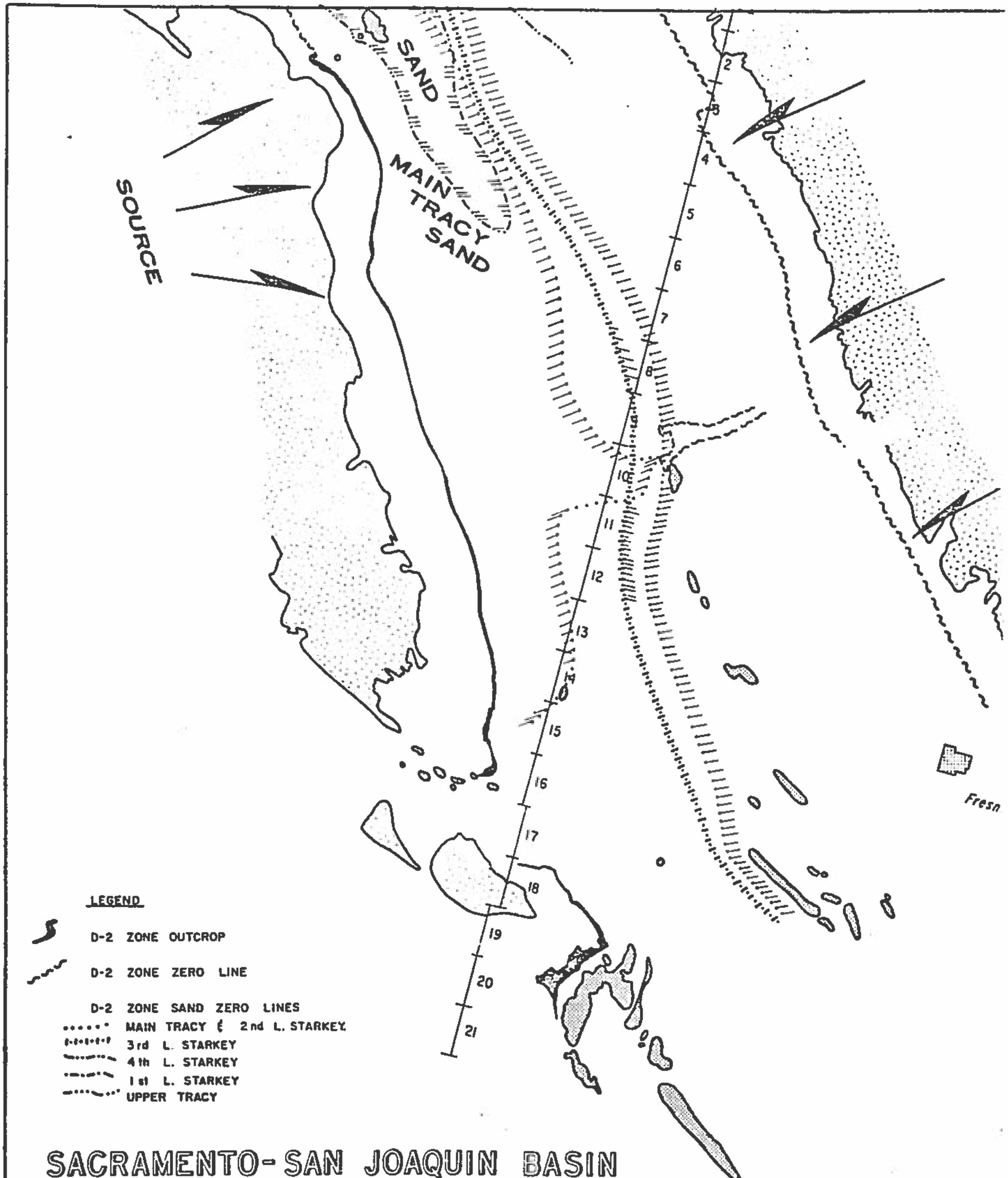


Fig. 4b. Distribution of sands in Cretaceous E Zone—northern portion.



SACRAMENTO-SAN JOAQUIN BASIN

DISTRIBUTION OF D-2 ZONE SANDS

Fig. 5b. Distribution of sands in Cretaceous D-2 Zone—northern portion.

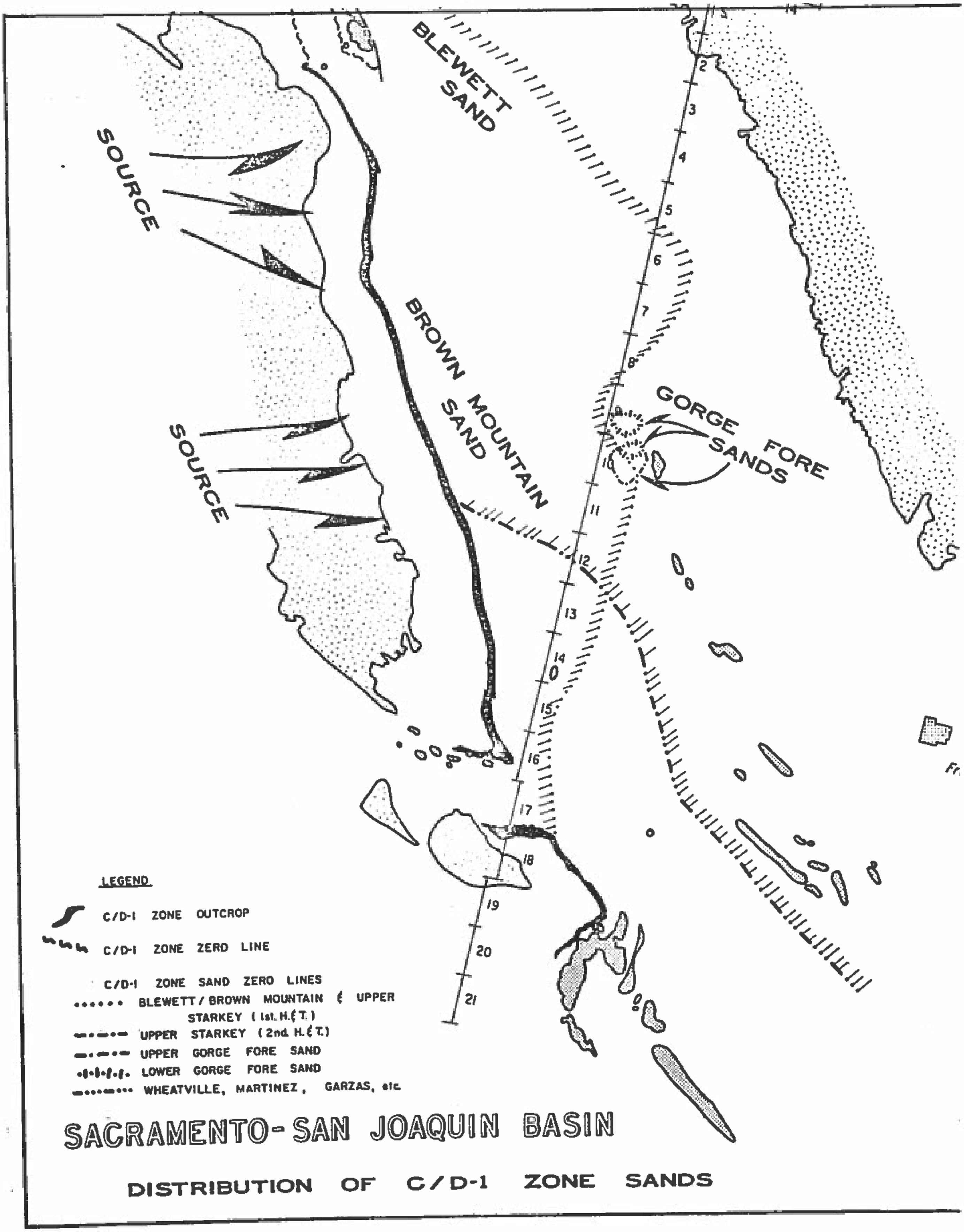


Fig. 6a. Distribution of sands in Cretaceous C/D-1 Zones—southern portion.

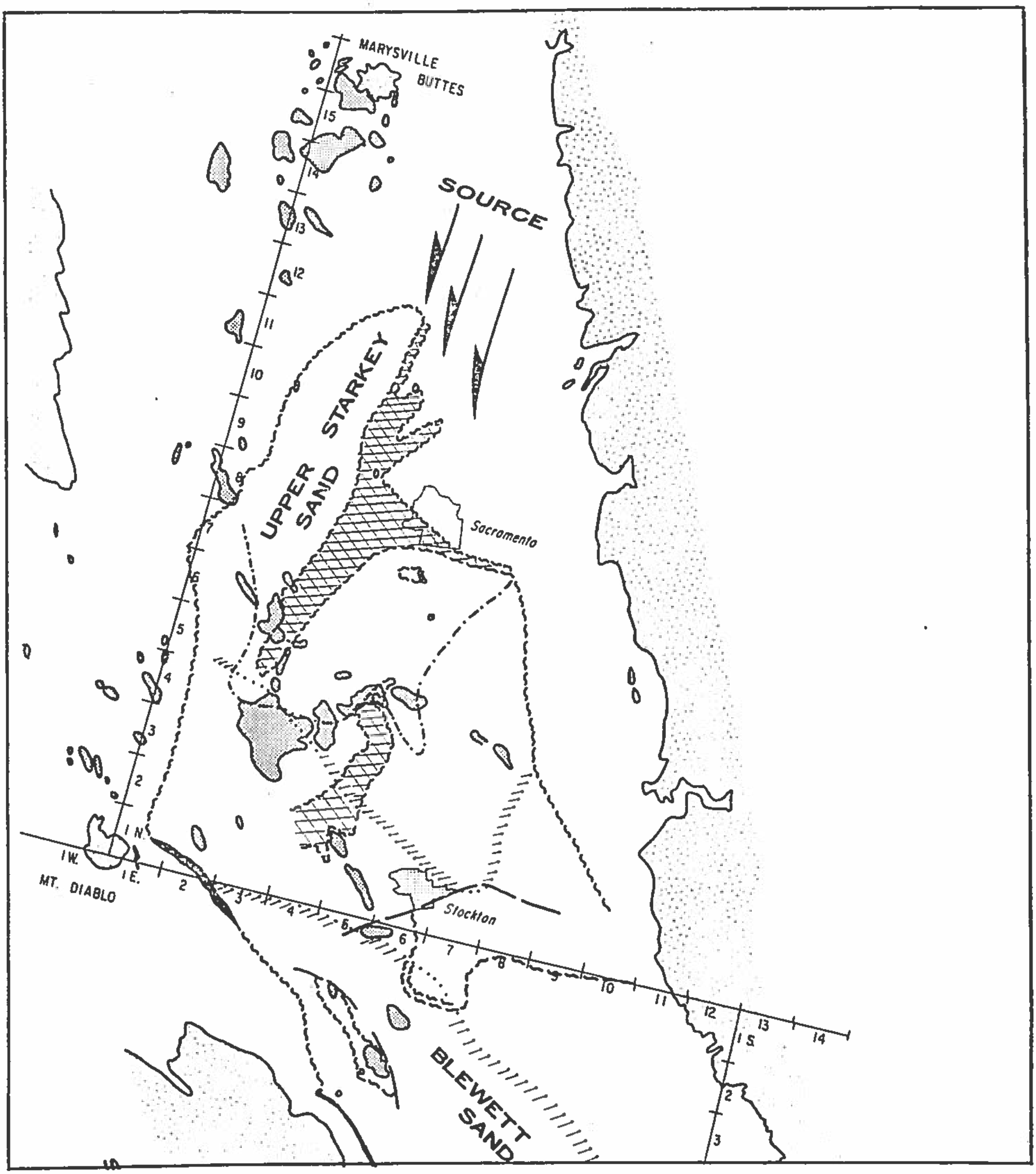


Fig. 6b. Distribution of sands in Cretaceous C/D-1 Zones—northern portion.

DEPOSITIONAL HISTORY

"E" Zone Time

The deep, widespread Cretaceous basin at the beginning of "E" Zone time was probably an inland sea as much as two or three times larger than the modern topographic basin, with a large open channel to the ocean, either to the south or in the vicinity of the Carquinez Straits north of Mount Diablo. After deposition of the Sacramento Shale, compression from the western Coast Ranges squeezed and restricted the basin against the stable Sierra Nevada Range giving the basin an asymmetrical shape; deep and steep sided on the west, shallow and gently sloping on the east. A strong local uplift developed in the Diablo Range southeast of Mount Diablo. Deltaic Lathrop and Joaquin Ridge Sands from the Diablo Range filled the basin while the regressive Stockton Sands from the Sierra Nevada source were deposited on the eastern shelf. The Diablo Range subsided, giving way to local uplifting north of Mount Diablo which became the source for the Winters channel and bar sands. A renewal of westerly compression elevated the basin flanks exposing the "E" Zone sediments to erosion.

"D-2" Zone Time

A general subsidence of the basin was initiated at this time and the Sawtooth Shale was deposited. Compression of the basin was then renewed, elevating the Sierra Nevadas on the east where regressive sand deposition began again with the first two Lower Starkey Sands and the McCune bar sand. Resumption of deposition from the Diablo Range filled the basin with the Main Tracy deltaic sands. Almost simultaneously the Sierra Nevada source shifted to the north, filling the northern portion of the basin with the rest of the Lower Starkey Sands while the Diablo Range source shifted slightly north to Mount Diablo to furnish the Upper Tracy channel sand. The portion of the basin south of Rio Vista subsided to allow the deposition of the Ragged Valley Silt at the end of "D-2" time.

"C/D-1" Zone Time

Coincident unlifting of the Diablo Range and the northern Sierra Nevada Range started "C/D-1" time by filling the basin with delatic Blewett/Brown Mountain Sands on the west and regressive Upper Starkey Sands on the north. Widespread subsidence of the basin allowed the deposition of the Moreno shale. Also at this time the development of the ancestral Chowchilla River caused the local "gorge" removal of "D-2" age sands and their redeposition as Gorge Fore Sands. The gorge cut was filled with Moreno Shale.

The Sierra Nevada Range began slow but powerful growth and the final, major phase of deposition filled the basin from northeast to southwest with the regressive Garzas Sand. A brief transgression interrupted the blanketing by the Garzas long enough for the deposition of the Hall Shale.

Post-Cretaceous Modifications

Three periods of uplift and erosion have affected the Cretaceous basin.

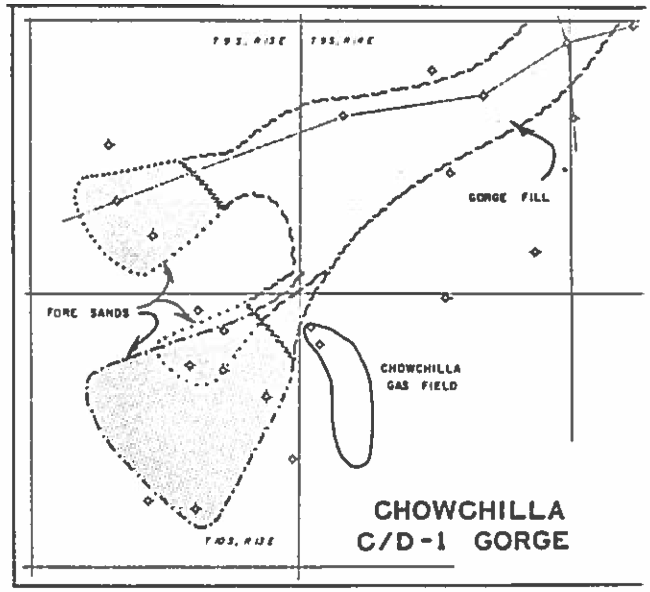


Fig. 7. Map of Chowchilla Gorge.

1. Post-Cretaceous/Pre-Paleocene period of defo tion: The entire west side of the basin was uplifted a end of the Cretaceous. This was followed by erosion. eral subsidence and the deposition of Paleocene sedim South of the Stockton Arch the Paleocene overlies only "C/D-1" Zone of the Cretaceous, as the older zones exposed in outcrop. North of the Stockton Arch, exten north from the outcrops on the north flank of M Diablo to Township 6 North, the Paleocene Martinez S overlies with angular discordance Cretaceous sedin which become progressively older from east to west.

2. Post-Paleocene/Pre-Eocene period of deforma At the end of Paleocene deposition the northwest sid the basin was uplifted and the resulting erosion rem large amounts of Paleocene and Cretaceous sediments the entire northern third of the basin. After subsid the Eocene Capay Shale was deposited unconformabl the "C/D-1" Zone sediments throughout the entire l north of Township 4 North. On the southwestern ma of the basin, from Marysville Buttes south to Townsh North, the Capay Shale unconformably overlies "D-2" "E" Zone sediments (figs. 4 and 5). East of the River Is Gas Field and west of the Thornton Gas Field a subma river, the "Meganos Channel" (Silcox, 1962, p. 143), a gorge into the underlying "C/D-1" Zone sediments. channel trends south, passing along the west side of McDonald Island Gas Field (fig. 6) dying out a reached the base level of erosion further into the b The channel was filled with Lower Eocene Meganos S for the most part, except for local areas between Thor and McDonald Island where erratic sand developn occur.

3. Post-Eocene/Pre-Miocene period of deforma The uplift of the Stockton Arch resulted in develop of two (possibly more) large, bowed, high angle rev faults or fault systems known as the Stockton Arcl French Camp and Vernalis Faults. Erosion of the s tural highs and elevated sides of the basin on the was followed by basin subsidence and non-marine

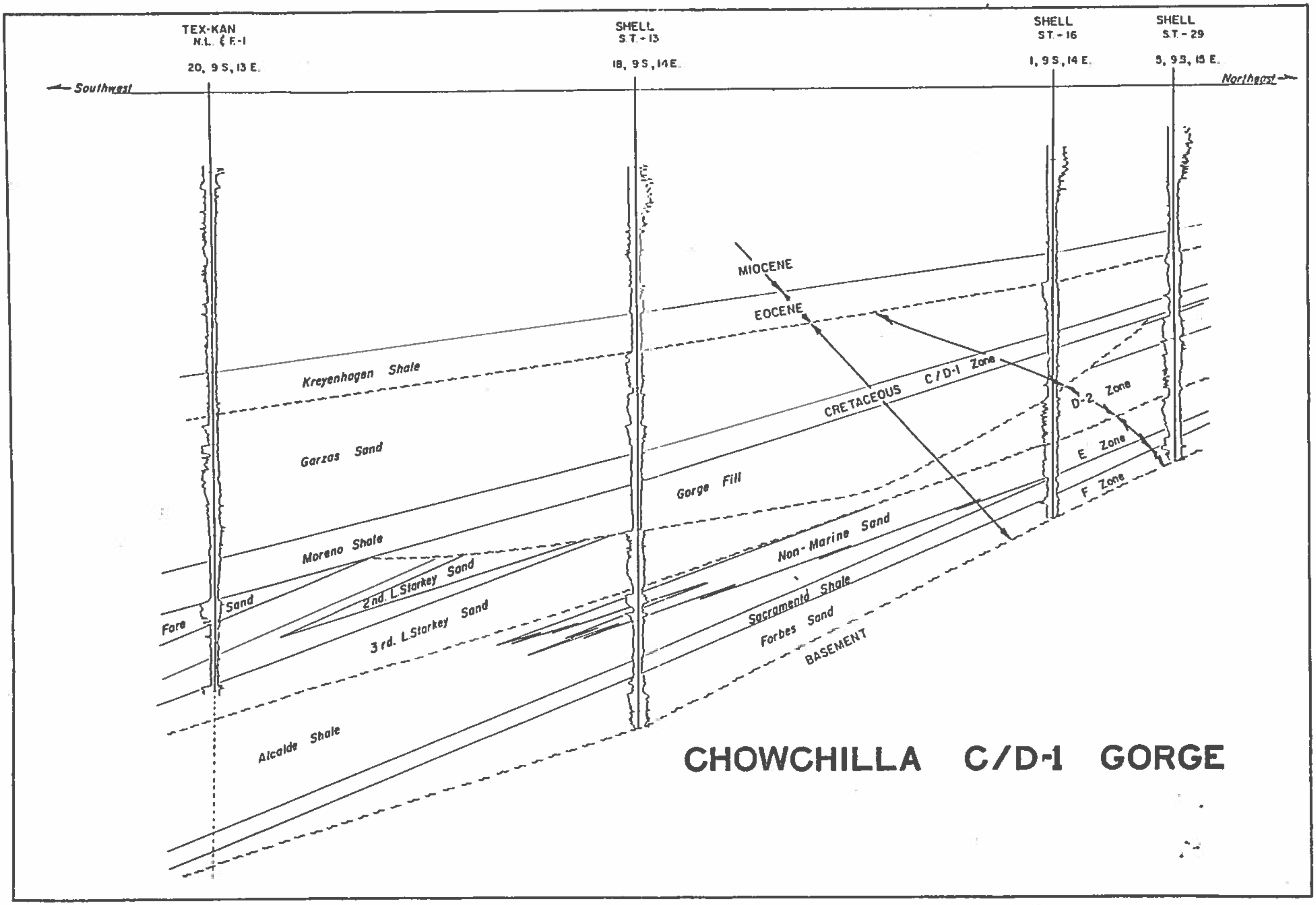


Fig. 8. West to east section through Chowchilla Gorge.

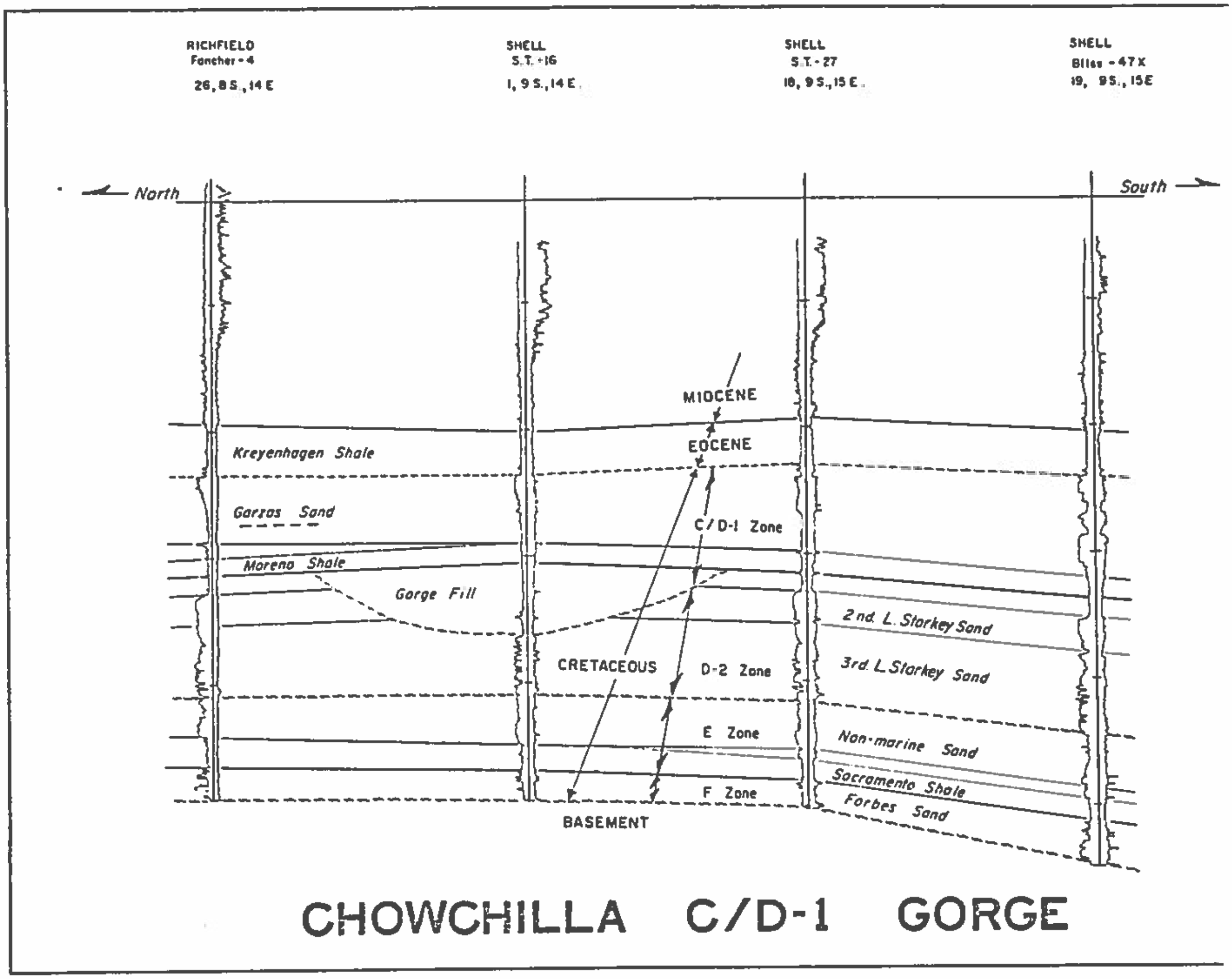


Fig. 9. North to south section across Chowchilla Gorge.

cene deposition. Zero lines on Figures 4, 5, and 6, between T. 1 S. and T. 5 S. on the west, and between T. 1 N. and T. 4 S. on the east are the result of Miocene unconformably overlying the Cretaceous. The "C/D-1" Zone Blewett and Garzas Sands are truncated by the Miocene west of the Vernalis Fault and south of the Stockton Arch or French Camp Fault as are the Garzas Sands south of Sacramento in T. 7 N., R. 5 E. (fig. 6). Erosion by a post-Miocene/pre-Eocene river channel, known as the "Markley Gorge", removed portions of the "C/D-1, D-2 and E" Zones west of Sacramento, as indicated by hatchures on Figures 4, 5, and 6.

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GEOLOGY AND DEVELOPMENT OF THE LATHROP GAS FIELD SAN JOAQUIN COUNTY, CALIFORNIA[1]

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ABSTRACT

The Lathrop Gas Field lies near the city of Stockton at the northern extremity of the San Joaquin Basin in that area known as the Manteca Arch. Continental Plio-Miocene sediments overlie unconformably a thick series of Upper Cretaceous clastics of mid-valley facies at Lathrop. The Stockton Fault, a large cross-valley reverse fault with a complex structural history, nearly intersects the field's north limit.

Natural gas is trapped primarily in sands of Upper Cretaceous "E" zone age due to anticlinal folding. Shallow drilling on the Lathrop fold dates back to 1937. Discovery of gas occurred 26 years later in October, 1961 with the completion of Occidental Ptroleum's "Lathrop Unit A" 1 for an initial rate of 13,550 Mcf/D. Nine distinct "E" zone reservoirs occur at Lathrop, separated by thin bounding shales. The "3700 Pound" zone is the most extensive reservoir and shows a productive closure of 2400 acres with up to 600 feet of relief and gas-phase pressure continuity over 550 feet of section.

Thirteen dual zone and seven single zone wells have been completed for initial flow rates of up to 42,000 Mcf/D per well. Individual wells penetrate up to 600 feet of net pay. Deliveries of gas commenced in January, 1963 and averaged approximately 50,000 Mcf/D for 1963. Independent volumetric reserve estimates have ranged from 578 million to over 700 million Mcf.

INTRODUCTION

The purpose of this article is to provide the regional geologic setting of the Lathrop Area, a discussion of the Stockton Fault, and a presentation of the more interesting geologic and engineering details of the Lathrop Gas Field. Figure 1 shows Lathrop's location in relation to other gas fields of the area and to the Stockton Fault (French Camp Fault of others). The Manteca Arch (Stockton Arch of others) comprises that general high structural area south of the Stockton Fault.

GENERAL STRATIGRAPHY

The stratigraphic sequence at Lathrop is shown in Table 1 with appropriate average interval thicknesses. The regional structural pattern and the Upper Cretaceous facies relationships are best visualized by examining cross sections A-A′ and B-B′ shown in Figures 2 and 3 respectively. The Plio-Miocene Continental beds are a series of poorly sorted gravels, sands and clays resting unconformably upon the Upper Cretaceous. The Paleocene and Eocene beds are missing by erosion on the south side of the Stockton Fault. Subsurface data indicate this missing section to have been deposited, uplifted and eroded on the south side of the fault prior to the Plio-Miocene non-marine deposition. The Upper Cretaceous section can generally be classified as the mid-valley facies. Figure 2 shows this relationship to both east and west side facies. The Azevedo section is predominantly shale as compared with its sandy west side facies in the Vernalis-Tracy area. The Azevedo has unconformably overlapped a majority of the Blewett section due to uplift in the Lathrop Area. Only minor gas production occurs from the Blewett remnants at Lathrop. The Tracy-Sawtooth interval is composed predominantly of shale with occasional sand erratics in the central and east portion of the area. Regional sands develop on the west side of Lathrop and increase towards Tracy. Minor gas production is obtained from the Tracy section. The latter interval is underlain by a section of Upper "E" zone shale with erratic sands. This interval characteristically exhibits rapid facies change with common current bedding. The above section overlies the Lathrop sand series with slight unconformity. These "E" zone sands contain over 99 per cent of the gas reserves established at Lathrop. The Lathrop series grades from very fine grained, silty and lensing sands at the top to massive, medium grained sands in the middle and basal portions. The sands are interpreted to have been deposited under moderately shallow conditions. The section carries abundant fossil wood, carbonaceous material, megafossil fragments and worm borings. The Sacramento shale, Forbes shale, and Dobbins shale underlie the Lathrop sand series. Only one well, the "Lathrop B" 5, has penetrated this older section in the immediate area and therefore current interpretations are based on a very limited amount of widely scattered subsurface data.

GENERAL STRUCTURE

The Lathrop Gas Field lies immediately south of the Stockton Fault and at the northern extremity of the Manteca Arch. The Manteca Arch is generally referred to as the area between Modesto and Stockton and extending across the valley. This is a regional high area dropping off into the San Joaquin Basin to the south.

The Stockton Fault is possibly the most intriguing geologic feature of this entire area and is deserving of special note. Figure 4 shows the subsurface trace of the fault, which can be seen very nearly to intersect the productive area at Lathrop. Studies indicate that a complex history exists along this fault. First, note the contours on basement in the East Stockton area on Figure 4 showing a south dipping scarp in the fault area with basement contours displaced down to the south. In the same area, isopachs from a Starkey marker to the Sacramento shale clearly indicate a left lateral offset with thicker section present south of the fault. On the same figure, note in the West Lathrop Area that the Tracy and Benetti sands shale out along linear trends and are offset approximately two

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2. Vice President, Occidental Petroleum Corporation. The author is indebted to Richard H. Vaughan and Bruce P. Hill of the Occidental Petroleum Corp. for their critical review of this paper.

STRATIGRAPHIC SEQUENCE AT LATHROP

AGE	FORMATION-LITHOLOGY	THICKNESS
Plio-Miocene	Continental Sands & Shales	3600
	Unconformity	
Goudkoff's Upper Cretaceous "A" to "C"	Garzas-Azevedo Sand, Silt and Shale	500
	Unconformity	
"C" to "D-2"	Basal Blewett Sand and Ragged Valley Shale	450
"D-2"	Tracy Shale and Sand and Sawtooth Shale	1800
"E"	Upper "E" Zone Shale and Sand Lenses	550
	Unconformity	
"E"	Lathrop Sands	3000
"E" or "F-1"	Sacramento Shale	900
"F-1" & "F-2"	Forbes Shale	1600
	Unconformity	
"G-1"	Undifferentiated Dobbins Shale and Older	> 700

Table 1.

miles left laterally clearly indicating strike-slip movement along the Stockton Fault. In addition, strike-slip offsets can be mapped using interval isopachs in the Azevedo-Tracy section. Two prominent kinks are shown in the fault opposite the Lathrop and East Stockton folds. With the foregoing data in mind, the geologic history of the Stockton Fault can now be reconstructed. First, a basement scarp existed during Upper Cretaceous "G" and "F" zone times dropping off to the south with possible normal faulting down to the south. Second, left lateral fault movement of at least two miles occurred after Blewett deposition but prior to Continental erosion. Third, uplift occurred on the south side of the fault zone as a reverse fault with attendant folding of the fault zone contemporaneous with Lathrop and East Stockton folding. The major movement of this third period occurred after Garzas deposition and probably after Middle Eocene time but prior to the Miocene-Continental erosion.

HISTORY OF EXPLORATION AT LATHROP

Figure 5 shows contours in the Lathrop Field on the top of the "3700 Pound" zone near the top of the Lathrop sand section. This figure is used for location purposes at this point. The history of exploration on this fold dates back some 27 years. Texaco drilled their "Lawrence-Stephan" 1 in the southeast portion of the field in 1937 to a depth of 5839 feet. This well bottomed above the Lathrop sands, which are topped in the 6900-7500 foot range and recorded only minor gas shows in the shaley Blewett and Tracy zones. In 1947 the Ohio Oil Con drilled its "Avila" 1 in the west central portion field to a total depth of 4400 feet and abandoned Ragged Valley shale. It is believed that both of attempts were based on seismic surveys primarily Eocene objectives in mind, following up the Mcl Island-Roberts Island trend to the northwest. Occi Petroleum drilled its "Lathrop Unit A" 1 in Sept 1961 to explore for Lower Tracy and Upper Cret "E" zone sands across the Lathrop fold postulating a stratigraphic and/or structural trap. A thick se silty gas sands were encountered in the Upper Cret "E" zone between 7230 and 7650 feet. Three pro drill stem tests were run and pressures indicated that though separated by shales, were in pressure comn tion in the gas phase throughout a 420 foot interval t indicating an extensive gas column. The "Lathrop U 1 was completed on October 3, 1961 from a thick of Upper Cretaceous "E" zone gas sand selective forated between 7230 and 7642 feet for an initial 13,550 Mcf D. This zone was subsequently nam "3700 Pound" reservoir. Subsequent development at a rapid pace. In a period of approximately one y productive wells were drilled including a deep test. rop Unit B" 5, which was carried to a depth of feet. Seven dry holes were drilled surrounding the fi clearly delineating the productive limits which t proximately 2400 acres. Gas commenced flowing i Pacific Gas and Electric pipeline system from the Gas Field just 14 months after the initial discover

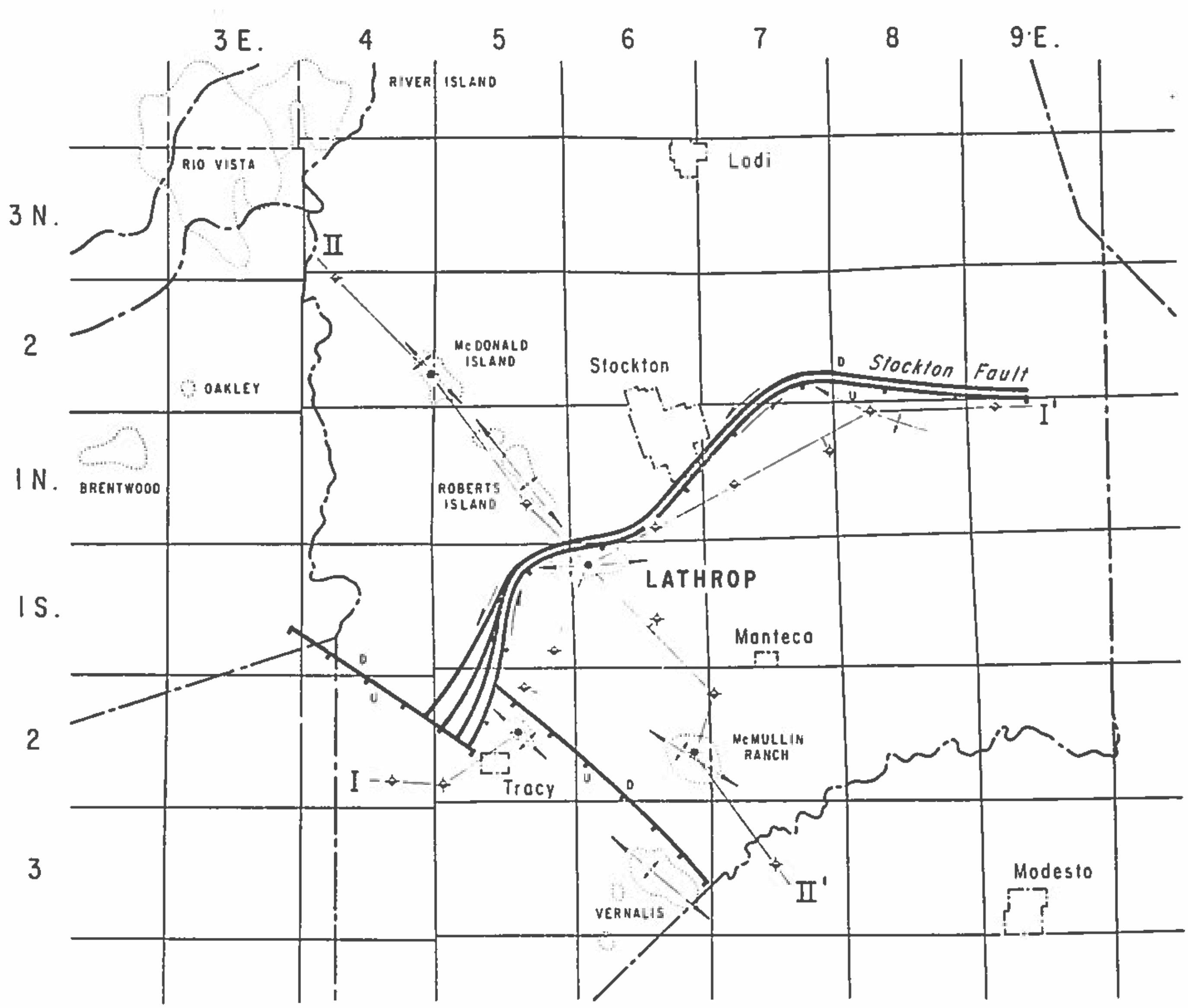


Fig. 1. Location map of Lathrop Gas Field.

LATHROP STRUCTURE

The Lathrop fold as seen in Figure 5 is an asymmetric faulted anticline with up to 600 feet of fold closure. Flank dips range from 12° on the south to 20° on the north with shallow easterly dip limiting the magnitude of closure. The structural axis migrates northwesterly with depth. Faults within the productive limits are small with displacements of up to 150 feet providing only partial fluid-pressure barriers. The Stockton Fault Zone dips southerly at an angle of approximately 50°, very nearly intersecting the productive zones with approximately 3000 feet of apparent vertical and two miles of left lateral movement. Figure 6 is a cross-section from the northwest to southeast across the field showing the relation of the productive zones and structure across the Lathrop fold. Figure 7 shows the structure at Ragged Valley depth (approximately 200 feet above the equivalent of the Tracy sand). The Ragged Valley structure closely simulates the "3700 Pound" structure. Figure 8 shows the structure of a Basal Continental marker Stockton Fault ceased its movement prior to the Continental Although no fold closure exists on the horizon, it is evident that folding did continue into Miocene time as indicate by the strong nosing across the Lathrop Field. The Stockton Fault ceased its movement prior to the Continental erosion as Continental beds pass uninterrupted across the top of the fault zone. Detailed studies indicate that the first anticlinal folding at Lathrop occurred after Blewett deposition and prior to the Azevedo erosion. The majority of the folding occurred in post-Garzas time and prior to the Continental erosion.

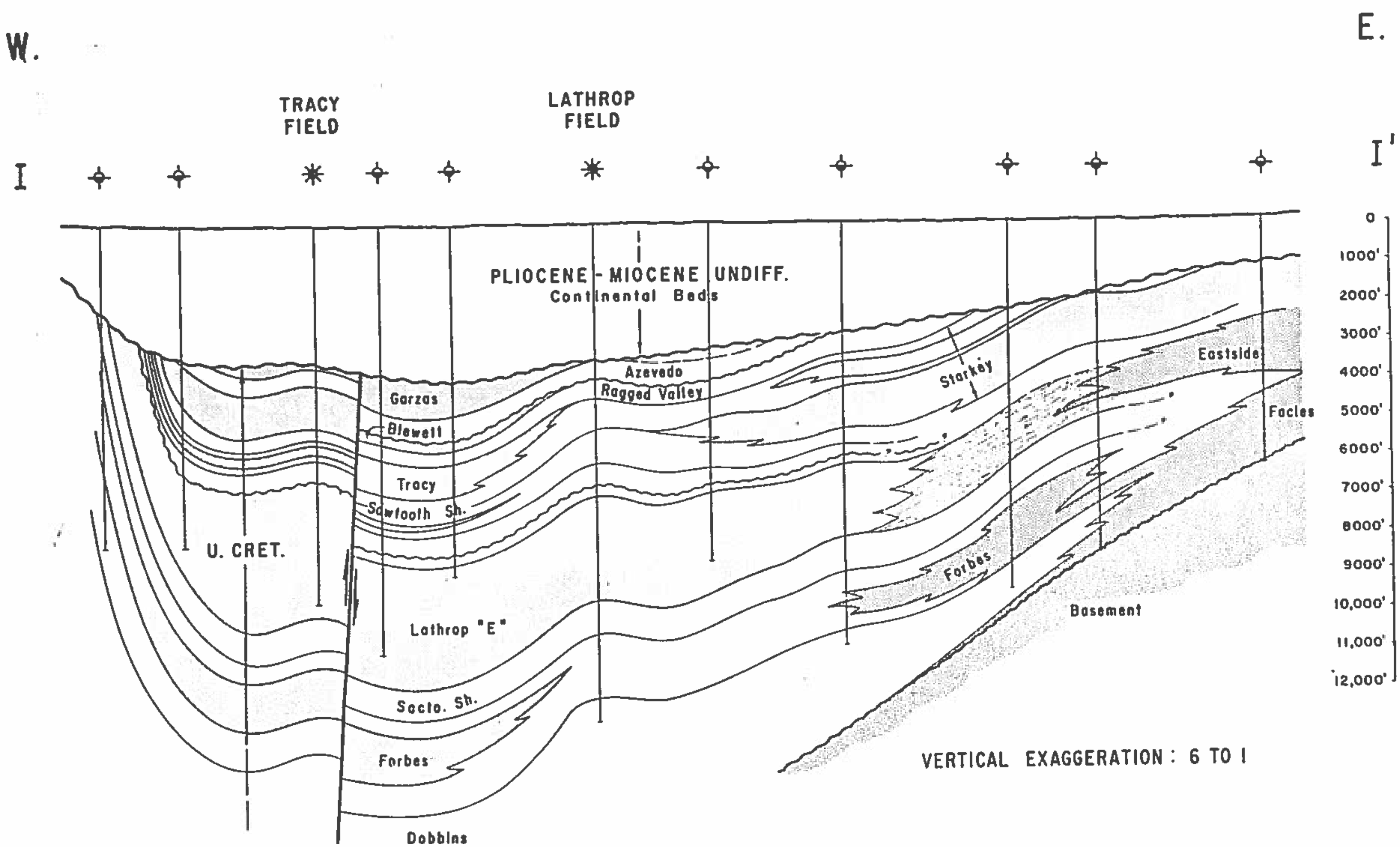


Fig. 2. Regional cross-section I-I'.

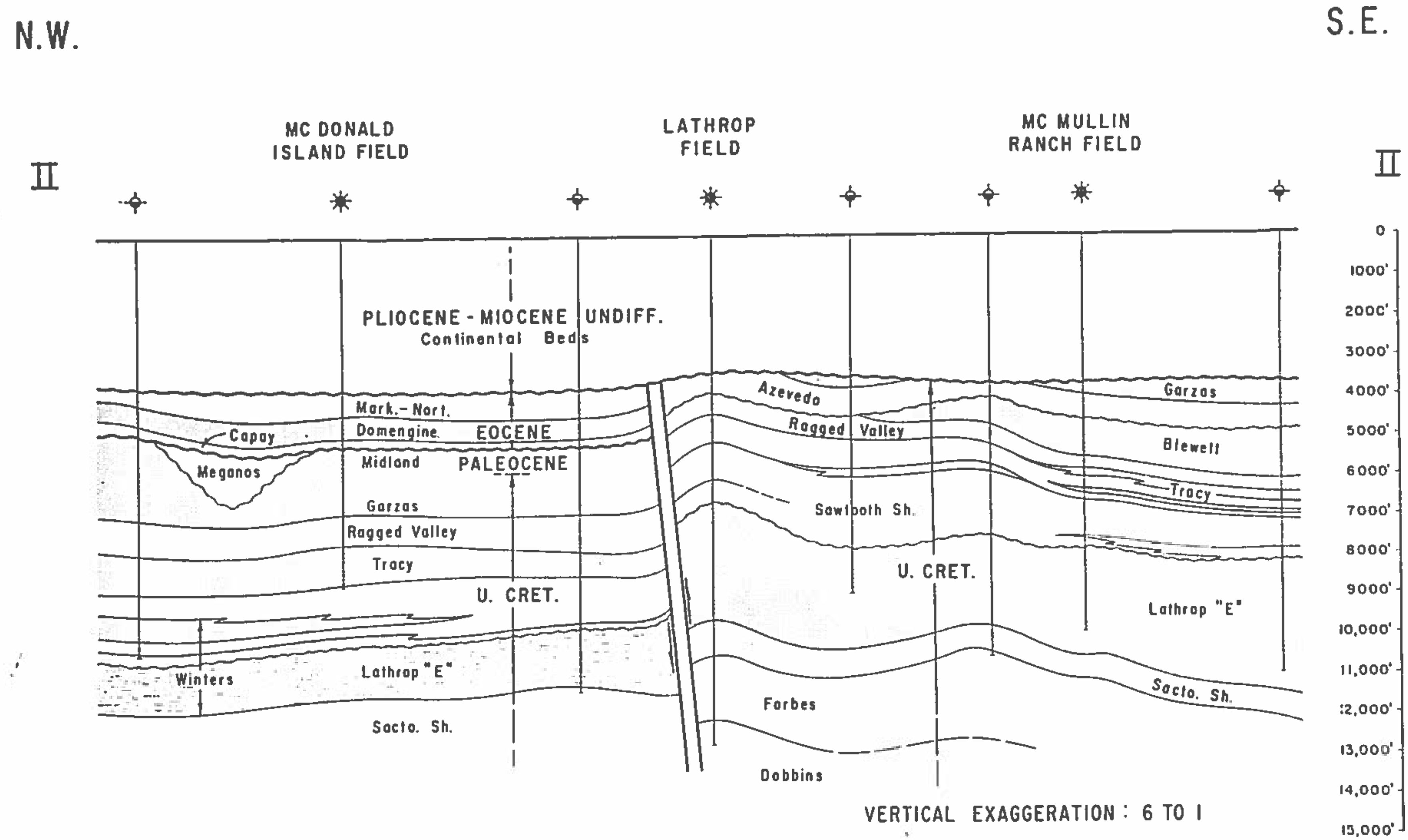


Fig. 3. Regional cross-section II-II'.

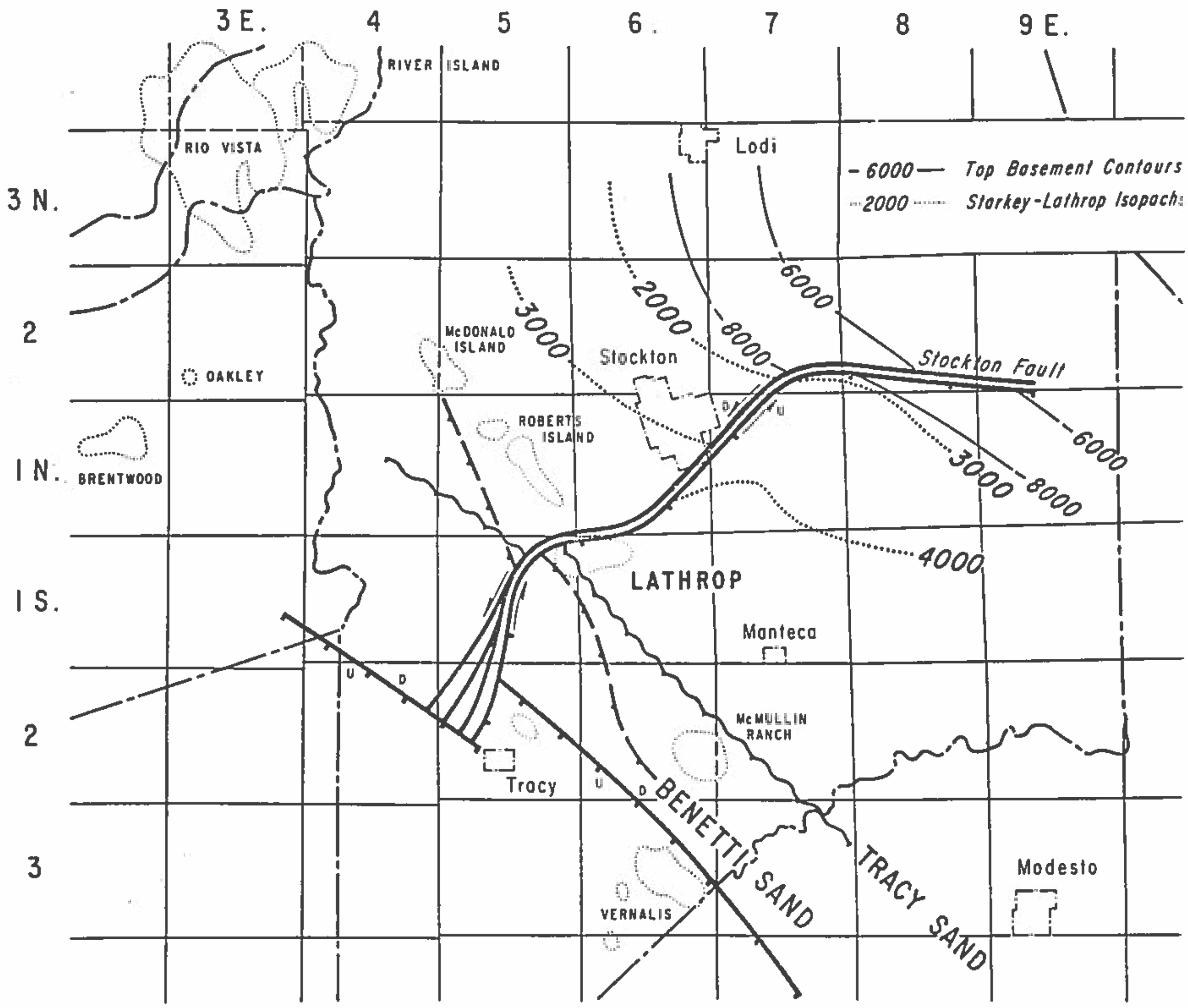
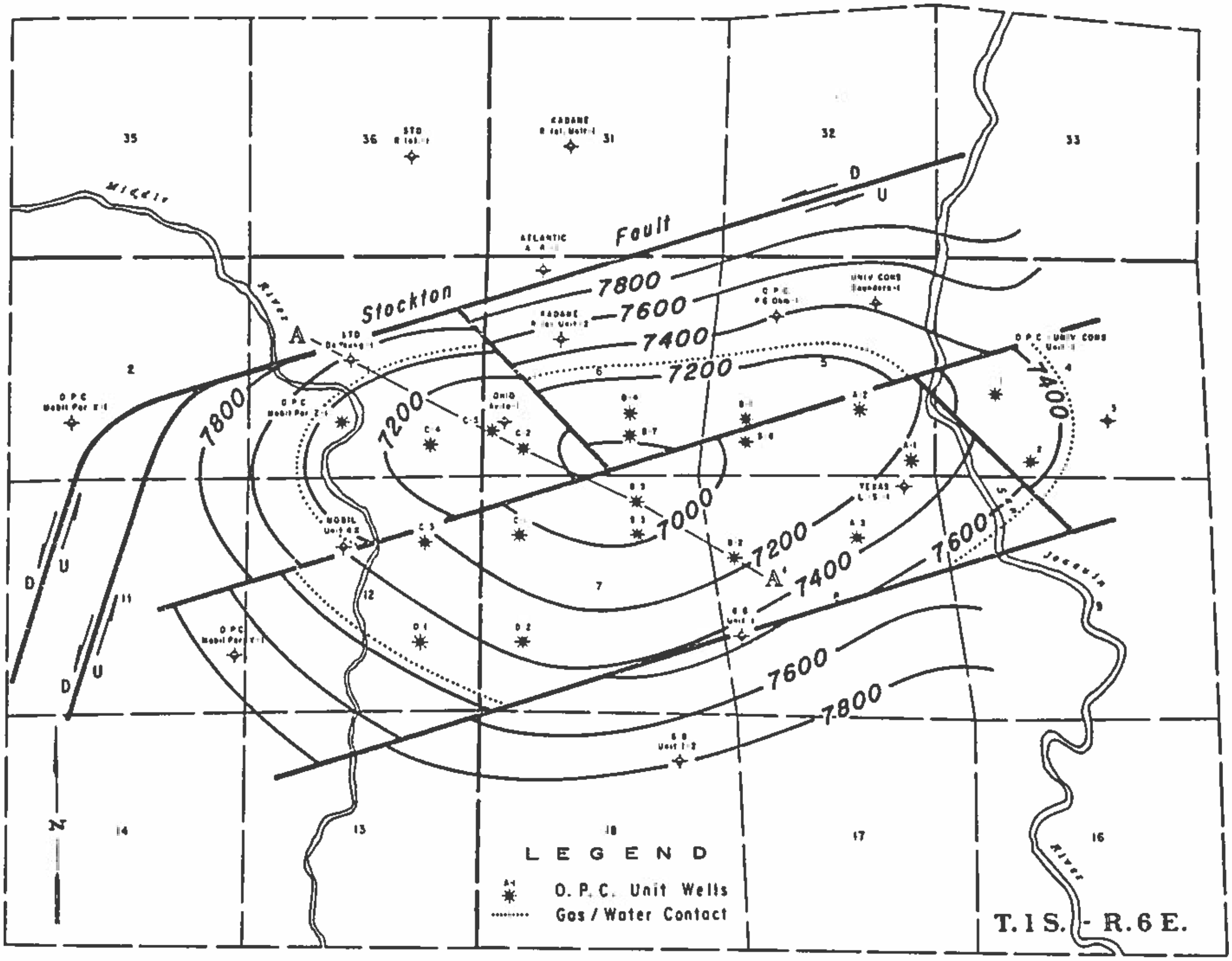


Fig. 4. Subsurface map of Stockton Fault.

GAS RESERVOIRS

Figure 9 is a high structure composite electric log showing the Lathrop "E" zone reservoirs only. Nine separate gas zones are seen to be stacked up vertically in this section. Wells on top of the structure record in excess of 600 feet of net productive sand. These various reservoirs have been named by their approximate original bottom hole pressure ranging from 3600 pounds to 4600 pounds. Thin shales down to 5 feet in thickness and colored black on the log, carry throughout the field and provide fluid and pressure barriers which trap the various gas reservoirs. The "3700 Pound" zone is the thickest and most extensive reservoir in the field and is comprised of a series of s which interfinger sufficiently to allow continuous gas-p continuity throughout the entire 550 foot section. In eral, the upper zones, "3600 Pound" through " Pound", are fine grained and silty with low resis electric log characteristics. The lower zones, "3900 Po through "4600 Pound", are medium grained and ma with high resistivity electric log characteristics. There three shallow minor gas zones in addition to the nine gas reservoirs. They are the Blewett equivalent at feet, the Upper Tracy equivalent at approximately feet and Upper "E" sand at 6325 feet. The Lathrop therefore contains a total of twelve distinct gas reser



LATHROP GAS FIELD

SAN JOAQUIN COUNTY, CALIFORNIA

STRUCTURE ON TOP 3700# ZONE

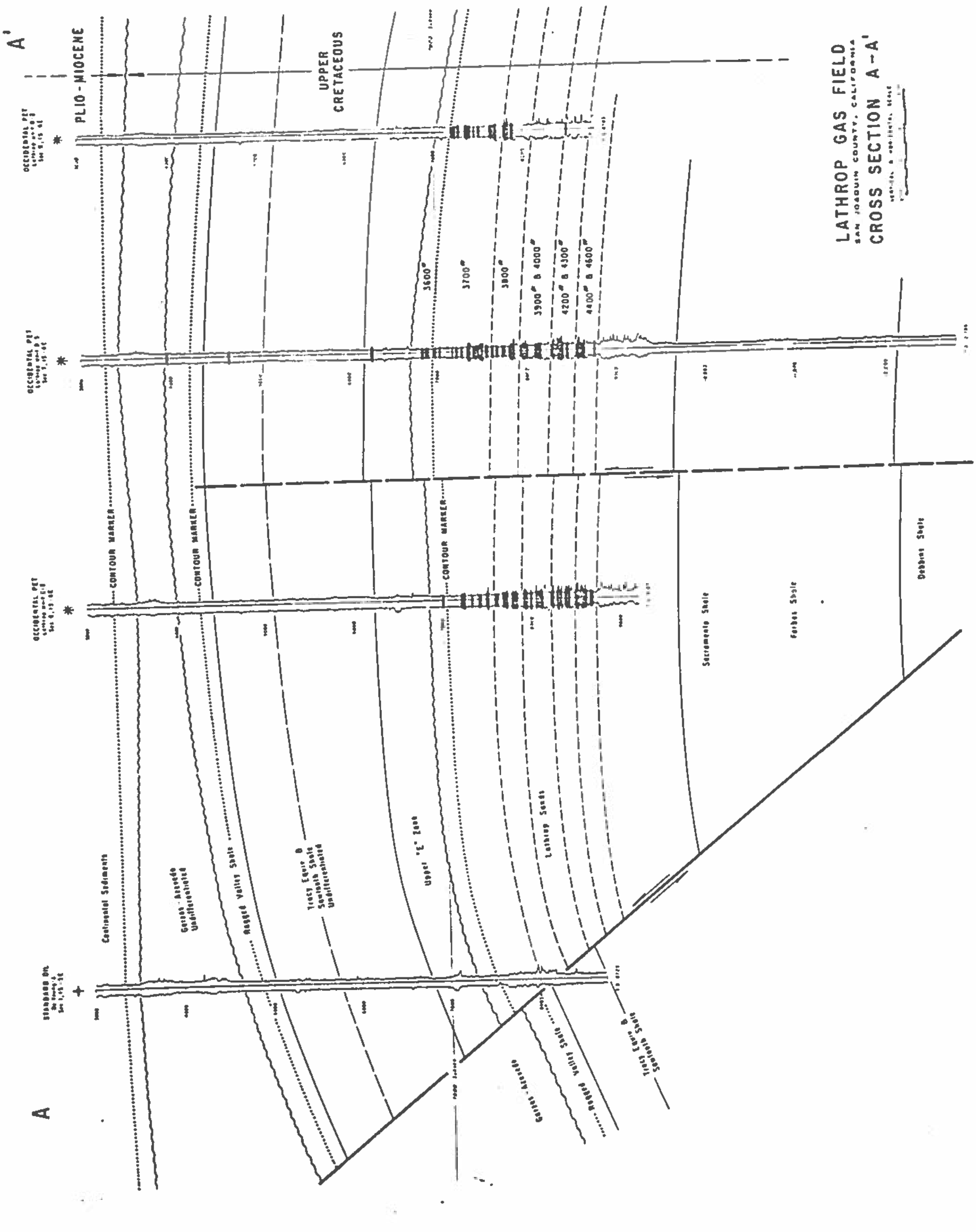
SCALE IN FEET

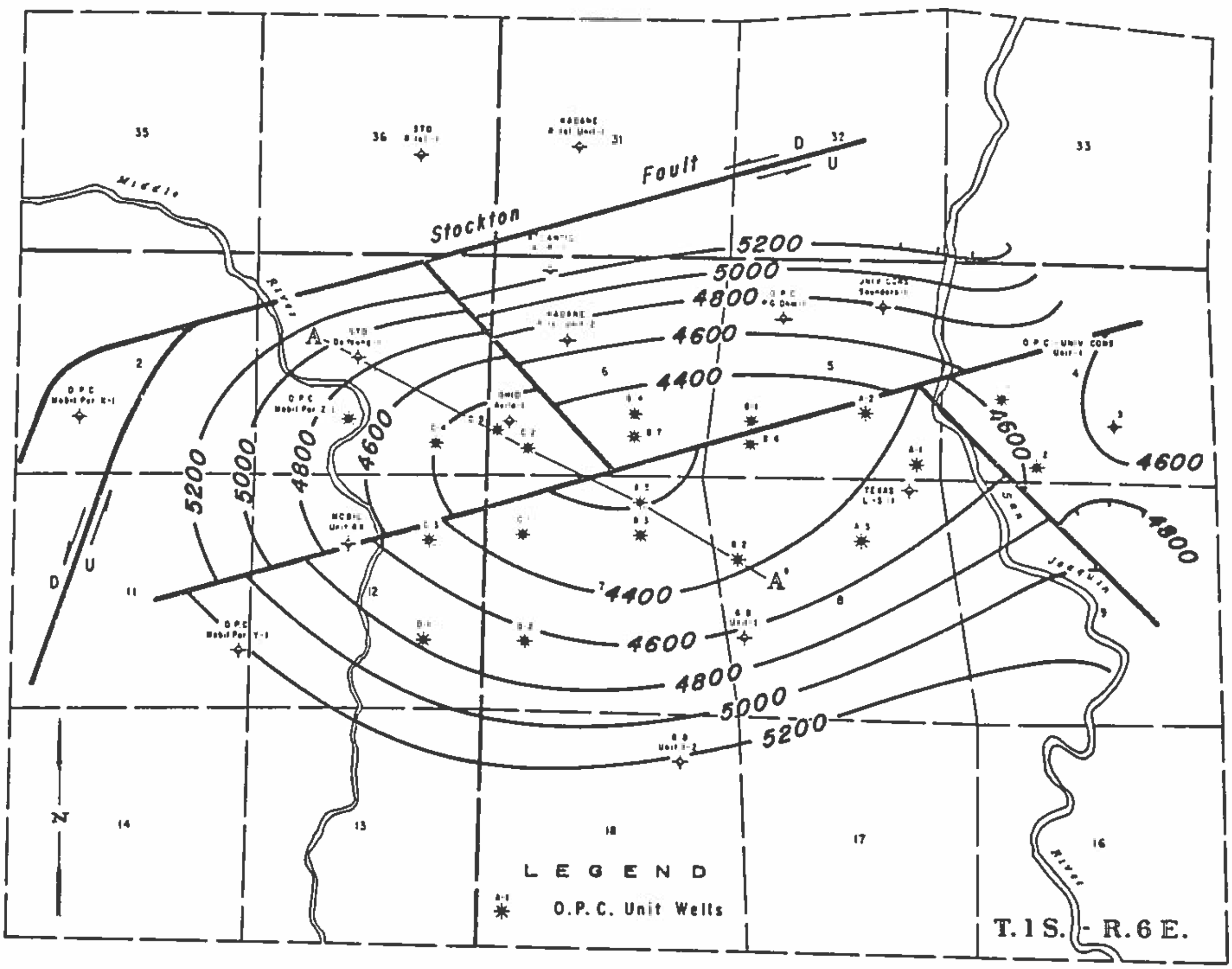
Fig. 5.

RESERVOIR DATA

During the course of rapid field development, large volumes of reservoir data were accumulated through mud logging, open hole testing, coring, electrical and acoustical well surveys. Usually two or three open hole tests were run per development well throughout the field. This technique not only provided formation evaluation but yielded pressure data critical in defining the various reservoirs as well as their productive capacity. Gas samples were routinely collected and analyzed for heating value. It is of interest that a wide range of gas compositions are found in Lathrop, generally decreasing with depth from a high of nearly 1000 Btu per cubic foot in the shallow zones to a low of approximately 760 Btu per cubic foot in the deepest zone. The total field volume-weighted average Btu is 875. Bottom hole pressures in the Lathrop sands exceed hydrostatic by approximately 600 pounds.

Several wells were selectively cored for reservoir data during the field development. Cores show porosities from 27% down to 23% generally decreasing with depth. Air permeabilities vary considerably throughout the field with an overall average of approximately 60 millidarcies. Restored state core analyses at 35 psi yield interstitial water saturations of between 35% and 40%. Formation water salinities in the Lathrop sands range from about 900 to 1600 grains per gallon.


LATHROP GAS FIELD
SAN JOAQUIN COUNTY, CALIFORNIA
CROSS SECTION A-A'
A
A'
PLIO-MIOCENE
UPPER CRETACEOUS
CONTOUR MARKER
CONTOUR MARKER
CONTOUR MARKER
Continental Sediments
Ragged Valley Shale
Upper "E" Zone
Lathrop Sands
Sacramento Shale
Forbes Shale
Dobbins Shale
3600#
3700#
3800#
3900# & 4000#
4200# & 4300#
4400# & 4600#



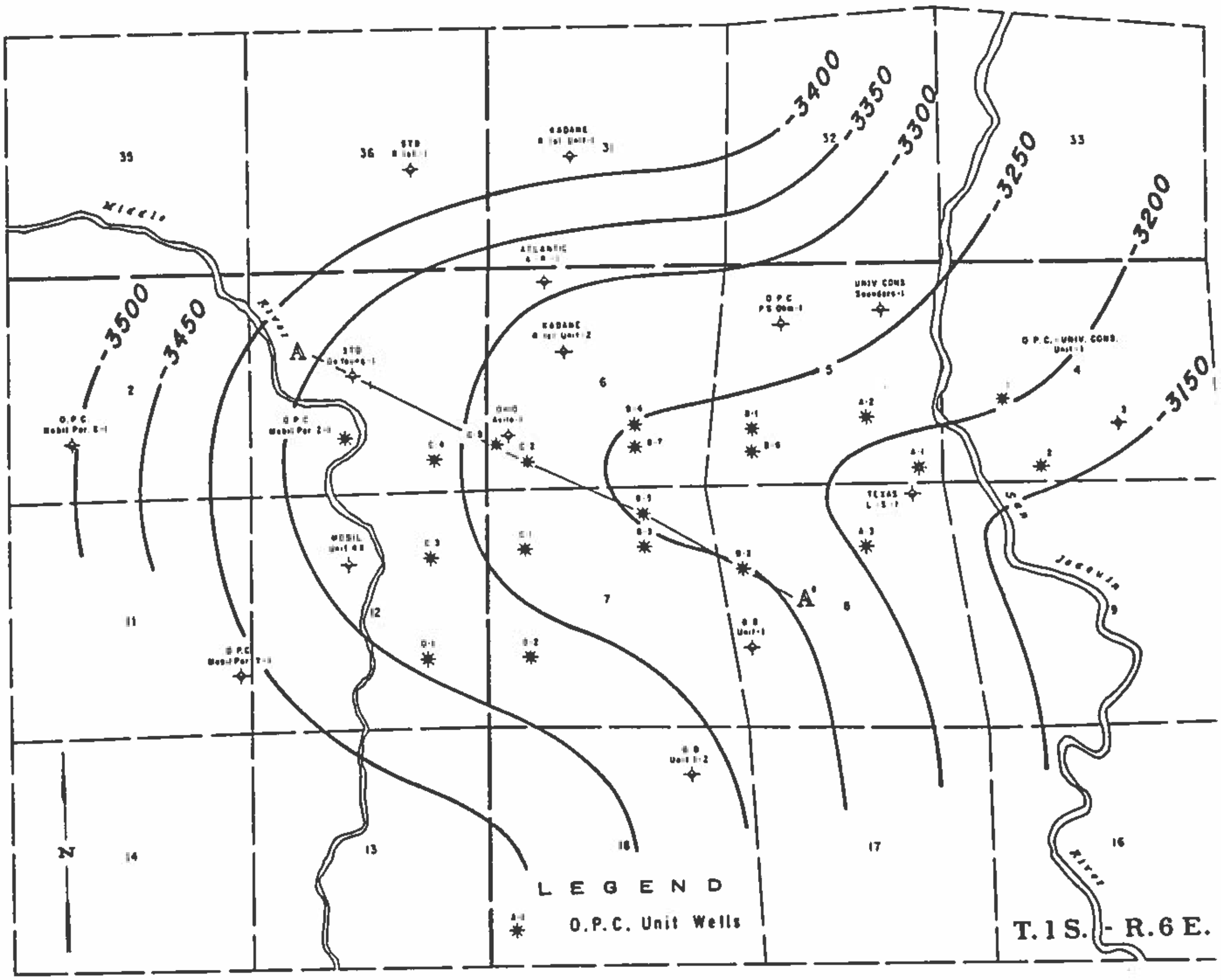
LATHROP GAS FIELD

SAN JOAQUIN COUNTY, CALIFORNIA

STRUCTURE ON RAGGED VALLEY SHALE MARKER

SCALE IN FEET

Fig. 7.



LATHROP GAS FIELD

SAN JOAQUIN COUNTY, CALIFORNIA

STRUCTURE ON BASAL CONTINENTAL MARKER

SCALE IN FEET

Fig. 8.

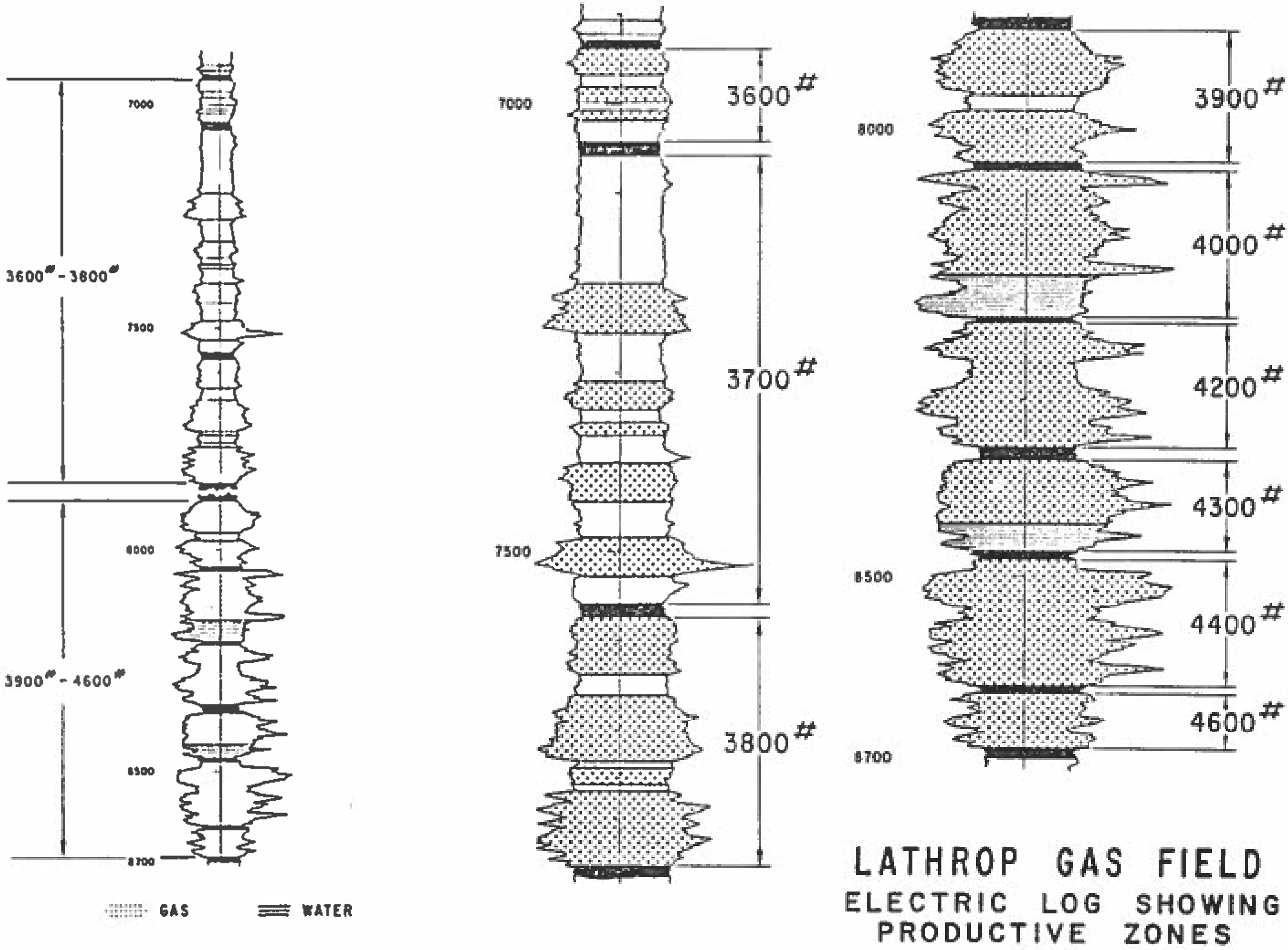


Fig. 9. High structure composite electric log at Lathrop.

Reserve estimates have been made by several independent organizations using the volumetric technique. These estimates range from 578 million Mcf to over 700 million Mcf of recoverable dry gas which, in either extreme, rank Lathrop as second in size in California only to the Rio Vista Gas Field. Such gas reserves as established at Lathrop will ultimately yield a gross income of approximately $175,000,000 assuming a static wellhead gas price thus equaling a 60 million barrel medium gravity oil field in terms of gross revenue.

DEVELOPMENT AND PRODUCTION

Wherever possible, development wells were programmed for dual zone completions using two strings of tubing hung side by side in 7" or 7⅝" casing with zones separated by a production packer. Currently there are 20 productive wells at Lathrop of which 13 have been dually completed. High initial wellhead deliverabilities have been obtained as a result of the thick productive gas zones and the dual zone completion program. Stabilized combined flow rates from 23,000 Mcd/D to 42,000 Mcf/D have been recorded per dual zone well. First deliveries of gas commenced into the Pacific Gas and Electric pipeline system during January of 1963 through a 12" line leading to the Tracy area. Daily gas production averaged approximately 50,000 Mcf during 1963 and reached a maximum of 100,000 Mcf/D during peak demand intervals. The maximum field production rate is currently limited by pipeline capacity since the field is capable of delivering approximately 400,000 Mcf/D on a sustained basis.

GEOLOGY OF THE NORTHERN SAN JOAQUIN VALLEY[1]

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ABSTRACT

The Northern San Joaquin Valley area includes Merced, Stanislaus, and the southernmost portion of San Joaquin Counties. Four commercial gas fields have been discovered within this area, with combined total reserves of approximately 965,000,000 Mcf of dry gas.

A thick section of Upper Cretaceous deposits overlies basement and is unconformably overlain by Plio-Miocene non-marine sediments. Paleocene and Eocene sediments overlie the Cretaceous and underlie the Plio-Miocene in the southern portion of the area.

The sediments occur in an asymmetrical northwest-southeast trending basin which has a steep west flank and a gentle eastern shelf area. Two faults of large displacement are present, the most important of which is the Stockton Arch Fault. The most prominent folds are the Tracy-Vernalis trend and the Lathrop structure.

Marine sedimentation was countinuous throughout late Cretaceous and Paleocene time, followed by a period of uplift at the end of the Paleocene. The Stockton Arch area was high through most or all of Eocene time, with only late Eocene marine beds deposited over the southern portion, or possibly all of the arch. Strong uplift and deformation at the close of the Eocene was followed by erosion over most of the area. Non-marine sediments were deposited during Miocene and Pliocene times. The area has undergone deformation during the Pleistocene.

The high level of exploratory drilling of the recent past is expected to continue, and it is probable that additional commercial gas discoveries will be made.

ACKNOWLEDGEMENT

The original presentation of this paper to the 1963 Annual Meeting of the Pacific Section of the American Association of Petroleum Geologists was made by Otto Hackel who should be given credit for many of the ideas expressed in this paper, as well as for his work in co-authoring the original talk.

LOCATION

The area discussed in this paper includes Merced and Stanislaus Counties and San Joaquin County south of the Stockton Arch Fault.

PRODUCTION HISTORY

The northern portion of this area has been historically important in the development of dry gas production in the Northern San Joaquin and Sacramento Valleys. The Tracy Gas Field, discovered in 1935 by the Amerada Petroleum Corporation, was the first commercial dry gas field in t northern part of the state. It was also the first commerc gas production from sediments of Cretaceous age. wells were completed in this field from a productive a of about 600 acres. The field is now depleted, with a cun lative production of 13,776,000 Mcf of 935 BTU gas fr the uppermost Tracy sand. No production has yet b obtained from deeper zones.

The Vernalis Gas Field was discovered in 1941 by Standard Oil Company. Only two wells were completed one additional well was abandoned by 1943. Signific development of the field began in 1958 with the com tion of the Porter Sesnon "T.L. & W. 13-23." The s operator's next well blew out and burned the drilling before being brought under control. This spectac occurrence can be considered the beginning point of current high level of exploration the Northern Califo gas province. By the end of 1963, 26 additional wells been completed and production established from at l 11 zones in the Miocene, Azevedo, Blewett, Ragged Val and Tracy sands. Cumulative production through 1962 33,898,000 Mcf and remaining reserves are estimate be in excess of 65,000,000 Mcf.

The renewed exploratory activity resulted in the covery of the McMullin Ranch Gas Field by Great Ba Petroleum Company in 1960. At least 9 separate ducing zones in the Blewett, Ragged Valley, Tracy, Lathrop sands have been established in this field. development of the most recently discovered Lathrop z still continuing.Cumulative production through 1962 8,601,000 Mcf with remaining reserves estimated at a 90,000,000 Mcf. It should be noted that three dry l were drilled within the limits of this field prior t discovery. Two of these wells penetrated productive s but their commercial value was not then recognized.

The outstanding gas find during recent years in Northern San Joaquin-Sacramento Valley gas provin the Lathrop Field, second largest gas field in Califo which was discovered in 1961 by the Occidental Petro Corporation. The field is not unusually large in area, 2400 acres proved productive, but the net pay thick which exceeds 600 feet in several wells, results in res estimated at 578,000,000 Mcf to 750,000,000 Mcf. T are 7 productive zones in the Lathrop sands and 3 sh zones of lesser importance.

In addition to these four commercial gas fields i Northern San Joaquin Valley, there are several commercial pools.

All four commercial gas fields are located on clinal structures and the accumulations are prim structural, although stratigraphic variation controls of the production. With the exception of the sub-con cial one-well Southwest Vernalis Pool no purely s graphic field has been found within this area. In p sands of known productivity elsewhere pinch out and out across structural noses, but are barren. Simi although several possible fault traps appear to be pr no fault traps not located on known anticlines have found productive.

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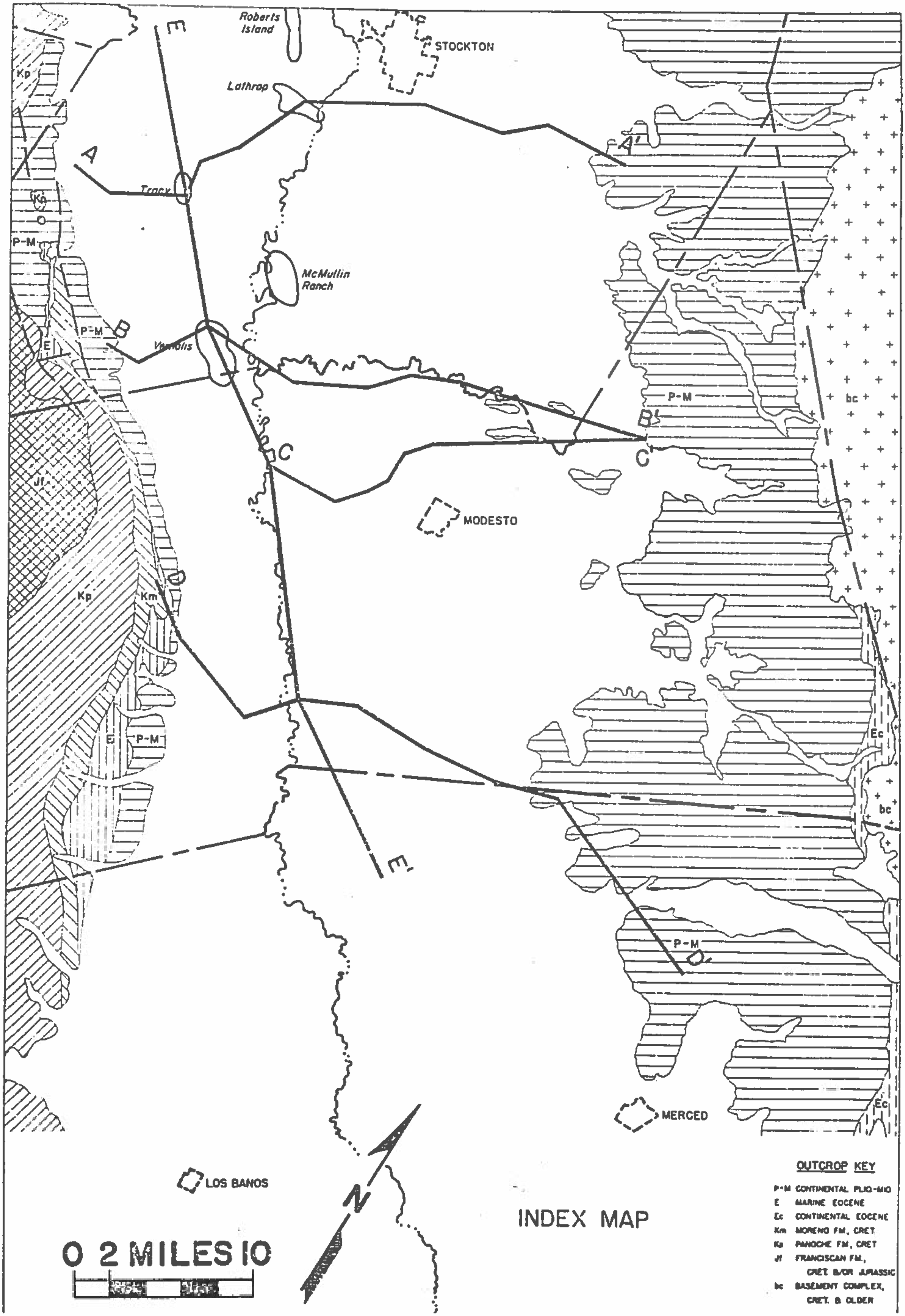
1. Presented to San Joaquin Geologist Society, May 14, 1963.
2. Consulting Geologist.



Roberts Island
STOCKTON
Lathrop
A
A'
Tracy
McMullin Ranch
Vernalis
B
B'
C
C'
MODESTO
D
D'
E
E'
P-M
Kp
Km
Jf
E
Ec
bc
MERCED
LOS BANOS
N
0 2 MILES 10
INDEX MAP
OUTCROP KEY
P-M CONTINENTAL PLIO-MIO
E MARINE EOCENE
Ec CONTINENTAL EOCENE
Km MORENO FM., CRET.
Kp PANOCHE FM., CRET.
Jf FRANCISCAN FM., CRET. &/OR JURASSIC
bc BASEMENT COMPLEX, CRET. & OLDER

STRATIGRAPHY

The Northern San Joaquin Valley Basin is filled with a series of sands and shales of late Cretaceous age lying on basement, and overlain throughout most of the area by non-marine Plio-Miocene sediments. In the southern portion of this area some Paleocene and Eocene marine sediments overlie the Cretaceous and underlie the Plio-Miocene.

Most of the Upper Cretaceous sand bodies have depositional trends parallel to the regional trend of the valley. There appears to have been an axis of sand deposition on both the west and east sides of the valley with source areas in the Sierra Nevadas on the east and the Coast Ranges on the west.

With the exception of the Starkey and Garzas sands, the Cretaceous sands of this area do not extend very far north of the Stockton Arch Fault into the Sacramento Valley. Similarly, the sands of the Sacramento Valley do not extend very far south into the Northern San Joaquin area. Thus it is apparent that the two areas represent different sub-basins of deposition for most of the Upper Cretaceous sands.

Basement Complex

In the subsurface the basement complex consists of grano-diorite, quartz diorite and granite. Basement crops out in the Sierra Nevada Mountains and is probably in excess of 20,000 feet at the deepest part of the basin. In the western portion of the basin the economic basement consists of sediments of the Franciscan formation which crop out in the Coast Ranges. No well in the area has reached the Franciscan and the location of the Franciscan-granitic basement contact can only be speculated on at this time.

Dobbins Shale and Older

Some beds belonging to the H Zone of Goudkoff are found in the outcrop on the west side of the valley. It is probable, however, that these do not extend into the subsurface to any appreciable distance.

The oldest formation found in the subsurface is the Dobbins shale of Goudkoff's G-1 Zone. This formation has been positively recognized only in the Occidental "Lathrop B-5," Section 7, T. 1 S., R. 6 E., where the section is entirely shale. The Rheem "Weaver-Cordes 1", Section 26, T. 2 S., R. 4 E., is also believed to have penetrated the Dobbins shale although the G Zone fauna has not been identified. Some sand was penetrated in the interval in the latter well.

The Dobbins shale is over 650 feet thick in the Occidental "Lathrop B-5" and thickens to the outcrop along the western side of the valley.

Forbes Formation

The Forbes formation, which carries the fauna of Goudkoff's F Zone, overlies the Dobbins shale. The few wells which have penetrated the Forbes in this area have encountered stratigraphic conditions similar to those of the younger Cretaceous formations. In the Rheem "Weaver-Cordes 1" (fig. 2), on the extreme west side of the valley, considerable sand is present in this formation. To the east, however, the Occidental "Lathrop B-5" and the Standard "Young Community 1", Section 34, T. 3 S., R. 8 E., (fig. 4) found no sand in the Forbes section. East of Lath along the Stockton Arch trend, the Occidental "Rodg 1", Section 7, T. 1 N., R. 8 E., and the Occidental "Arl 1", Section 13, T. 1 N., R. 7 E., encountered a moder amount of sand in a predominantly shale section (fig. Further east the Forbes shows an east side facies that predominantly sand (fig. 2, 3, 4, and 5). This east s sand series is probably separate from sands developed the west side. Correlation of these sands on section A (fig. 2) is questionable and may need revision wl additional wells are drilled.

No commercial production has been found in Forbes in the Northern San Joaquin Valley, although shows have been encountered.

The Forbes thins southward from the Stockton A Fault trend, where it is as much as 3000 feet thick, and becomes quite thin in the southern portion of the area.

Sacramento Shale

The Sacramento shale conformably overlies the Forl formation and carries the fauna of Goudkoff's E Zo The unit ranges from 200 to 700 feet in thickness. It recognized on the electric log by a resistivity break at top known as "the neck".

Lathrop Sands

The Lathrop sands, a thick series of sands with int bedded shales, conformably overlie the Sacramento sha They are the principal productive horizon at Lathrop a are also productive at McMullin Ranch. The Lathrop san are the primary objective of most wildcat wells drilled this area at the present time. They are thickest on the w side of the valley with maximum thickness in the surfa outcrop southwest of Vernalis. They thin to the east a southeast (fig. 7) and also thin and shale out rapidly the north along the trend of the Stockton Arch Fault. addition to easterly thinning the upper portion of the sands shales out to the east in the central portion of t valley (fig. 4 and 5).

E Zone Sands

There is sand development in the southeastern porti of this area (fig. 7), similar to that observed in t Forbes formation. These sands are distinct from t Lathrop sands (fig. 5) and represent a separate area sand deposition.

E Zone Shale

The Lathrop sands shale out basinward into a are conformably overlain by a shale body belonging to t E Zone of Goudkoff. This shale merges with the overlyi Sawtooth shale except to the west where the Winters sa lies between the two.

Winters Sand

The Winters sand is present only in the extreme we side of the northern portion of this area (fig. 8). This sa becomes thick and commercially important in the Del area of the Sacramento Valley. Although the southernmo extremity of this sand extends to the Northern San Joaqu Valley its source lies to the north and is different fro the source of most sands in this area.

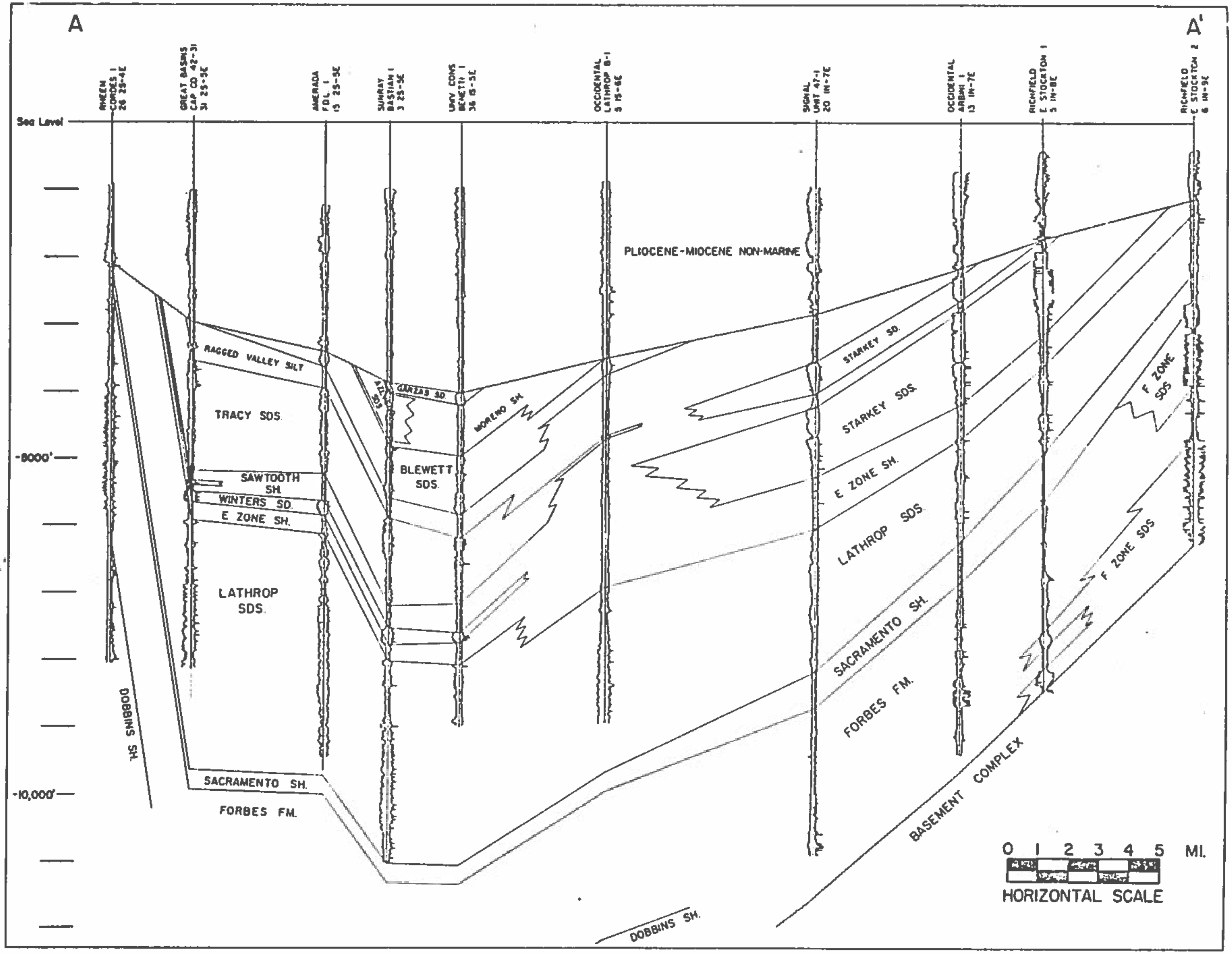


Fig. 2. Correlation section A-A'.

Sawtooth Shale

Named for its characteristic ragged appearance on the electric log, this shale overlies the Winters sand and has the fauna of Goudkoff's D-2 Zone. The Sawtooth shale merges with and becomes indistinguishable from both the E Zone shale below and the D-1 shale above in the central and eastern portions of the valley.

Tracy Sands

In the western portion of this area the Tracy sands of D-2 Zone age conformably overlie the Sawtooth shale. These sands are productive in the four commercial fields of the area but, except at Tracy, they account for only a small percentage of the production. Maximum thickness is developed just west of the Tracy field with the axis of maximum thickness trending northwest-southeast (fig. 9). The sands thin as well as shale out to the east and west of the axis of maximum thickness and to the northwest and southeast along the axis. A slight cross-valley arch may be indicated by the absence of Tracy sand near the south border of Stanislaus County in an area where regional trends indicate it should be present, and by a bowing in the outcrop band to the west.

Starkey Sands

A series of sands derived from an east side source and correlative to the Starkey sands of the Sacramento Valley are present on the east side of the valley where they occupy an interval corresponding to that of the Tracy sands on the west side. They are regressive sands and show the typical carrot shape pattern on the electric log (fig. 2). Maximum thickness is attained southeast of Stockton and the sands thin and shale out to the west and, apparently, to the east also. These sands have been eroded east of Stockton on the upthrown southerly side of the Stockton Arch Fault. To date no production has been obtained from them in the Northern San Joaquin Valley though they are productive in several fields in the Sacramento Valley.

Ragged Valley Silt

The Ragged Valley silt conformably overlies the Tracy sands in the western portion of the valley. This unit is about 350 feet thick and contains several widely-correlative electrical markers. The contact between Goudkoff's D-1 and D-2 faunal zones is near the top of this siltstone. To the east where the Blewett sand is absent, the Ragged Valley silt can not easily be segregated from the overlying unit. A local sand development within this unit is productive at Vernalis and is also the productive horizon at the sub-commercial Southwest Vernalis Pool.

Blewett Sands

Conformably overlying the Ragged Valley silt is a series of sands with interbedded shales carrying the D-1 fauna of Goudkoff. Like the Tracy and Lathrop sands these were derived from the Coast Ranges to the west. They reach maximum development in the northern portion of Merced County along the west side of the valley (fig. 10). The axis of maximum thickness trends northwest-southeast with thinning to the east and west and also to the north. Locally the Blewett sands cannot be separated from the overlying Azevedo sands, and for this reason the isopach map (fig. 10) includes both sands. In the no west part of the area, however, the two sands can segregated. Here the thickest portion of the Blewett ext along a line northwest and southeast of the McM Ranch field. The thicker area indicated on the isopach between the Tracy and Vernalis fields is due to exter development of the Azevedo along that trend.

At Tracy all of the Azevedo and much of the Bl have been eroded due to uplift on the Vernalis Fault. S of the Blewett section also appears to have been er from the Lathrop structure.

The Blewett sands are the most important produ formation in the Vernalis and McMullin Ranch fields. minor production has also been obtained from these s at Lathrop and the sub-commercial West Vernalis Po

D-1 Sands

In the southeastern area an east side D-1 sand s has been developed in a manner similar to the develop of older east side Cretaceous sands (fig. 10).

Panoche Sand

Panoche is a formational name used in early-day face mapping along the west side and in early subsu work. Sediments called Panoche include all west side l Cretaceous formations below the Moreno shale. Sin detailed map has been published that ties in ou lithology with foraminiferal zones and subsurface uni attempt has been made to subdivide the Panoche o outcrop area of the accompanying maps.

Moreno Shale

The Moreno shale conformably overlies the B sands and carries the fauna of Goudkoff's C Zone. shale interfingers with the Azevedo sands. Its max development is in the northern portion of the are of the Tracy-Vernalis Azevedo sand trend. To the in Stanislaus County, the unit is almost entirely re by the Azevedo sand but further south, in Merced C the shale again becomes predominent.

Azevedo Sands

The Azevedo sands are the sand facies of the M shale. Maximum development is reached in so Stainslaus County where they are indistinguishable the upper portion of the Blewett sands, and alo Tracy-Vernalis trend where they form a secondar of thickening (fig. 10). The Azevedo sands are a portant productive horizon in the Vernalis Gas

Garzas Sand

The Garzas sand is a fine grained, silty, carbon sand deposited in a shallow marine or brackis environment. Faunal development is very poor b sand probably belongs to Goudkoff's C Zone. I formaly overlies older formations and appears t been a blanket deposit over the entire Northern Sa quin Valley. At the northern end much of this sa been removed by erosion but it is correlative w lower portion of the Martinez formation in the Del of the Sacramento Valley.

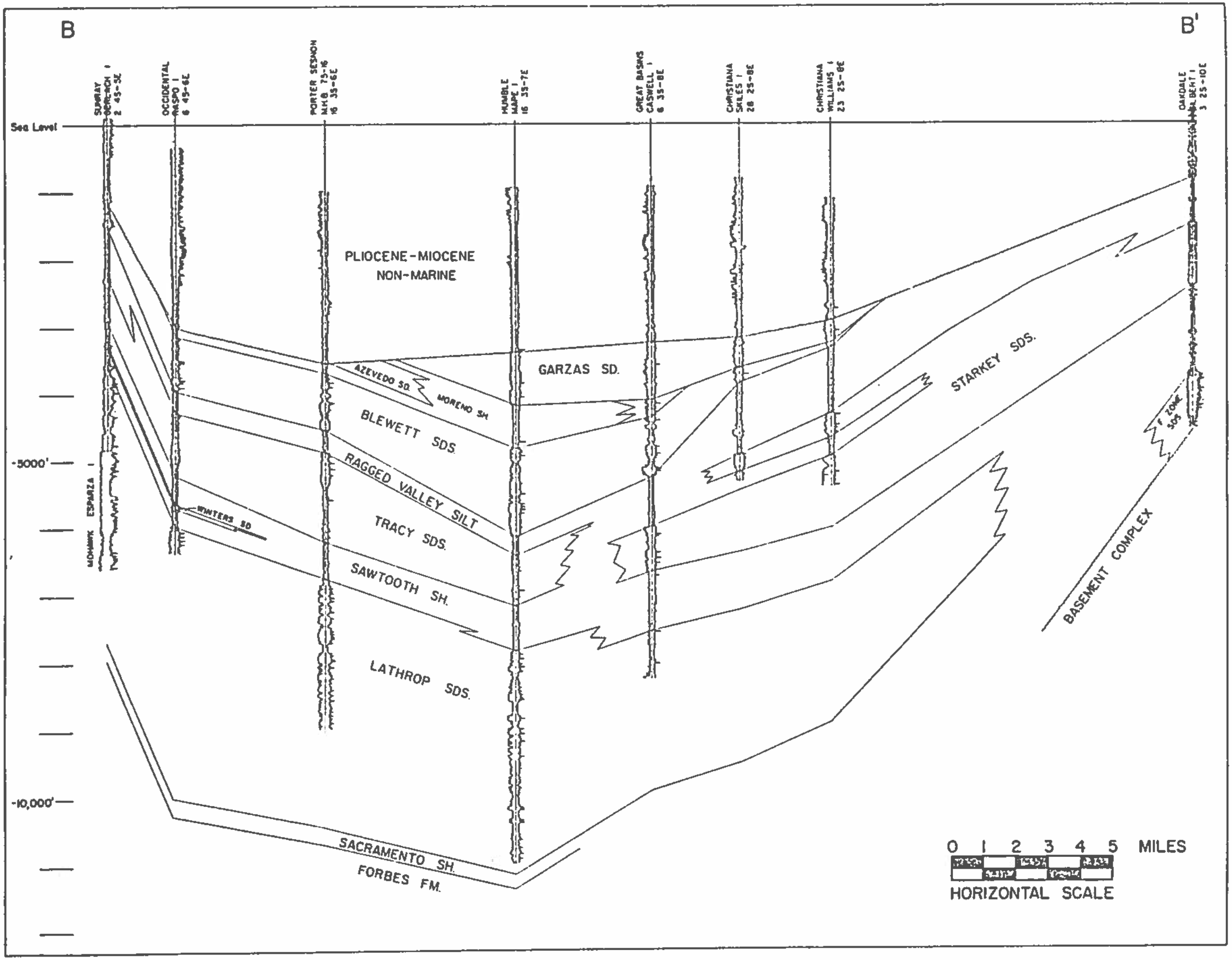


Fig. 3. Correlation section B-B'.

It appears that the earlier pattern of deposition with east and west side sands separated by mid-basin shale no longer existed, and the Garzas and subsequent deposition was continuous across the entire area. No isopach map of the Garzas is included, but in the southern area it ranges up to 1800 feet in thickness. The sand is not productive in the Northern San Joaquin Valley.

Hall Shale

The Garzas sand is overlain by a thin shale, herein called the Hall shale, after the Seaboard "Hall 1", Section 6, T. 2 S., R. 5 E. The unit is one of the better stratigraphic marker horizons in the southern portion of this area. It is usually barren, but late Cretaceous forams have been reported from this shale in several wells.

The Hall shale has been eroded from most of the northern portion of the area (fig. 6). It is present again on the northern side of the Stockton Arch Fault, and correlates roughly with the middle of the Martinez formation in the Delta area. The occurrence of this shale marker bed of probable Cretaceous age near the middle of what has been previously called the Martinez sand suggests that the lower portion of the Martinez in the Delta area is correlative to the Garzas sand and is Cretaceous in age.

Paleocene-Cretaceous Sands

Overlying the Hall shale is a series of shallow water, carboniferous, silty sands of Paleocene and/or Cretaceous age. They are present only in the southern portion of the area, having been removed by erosion in the north. No production has been obtained from these sands in the Northern San Joaquin Valley. They may be equivalent to the highly productive upper portion of the Martinez formation in the Delta area.

Kreyenhagen Shale

The Kreyenhagen is a brown foraminiferal shale of Eocene age that unconformably overlies the Paleocene-Cretaceous sands in the southernmost portion of this area (fig. 6). This shale is equivalent to the Nortonville shale of the Sacramento Valley, but it has been removed by subsequent erosion in the northern part of the area and it is not certain that deposition was continuous between the two areas. The Capay shale and Domengine sand were never deposited on the crest of the Stockton Arch. The Domengine sand reappears just south of this area where it is overlain by the Kreyehagen shale.

Eocene Sand

Overlying the Kreyenhagen shale in the southernmost portion of this area is a thin sand of probable Eocene age (fig. 6).

Pliocene-Miocene Non-Marine

Unconformably overlying all older formations is a series of non-marine sediments of Miocene and Pliocene age which range up to 4000 feet in thickness. At Vernalis several wells produce from the lowermost sand of this non-marine section. Presumably the gas has migrated into the non-marine from the underlying Cretaceous marine sediments.

STRUCTURE

The Northern San Joaquin Valley basinal area is an asymmetrical syncline (fig. 11), with a steep western flank in which the Upper Cretaceous sediments underlying the basin are exposed in a homoclinal outcrop band. The synclinal axis lies a few miles east of the outcrop, with the exact location of the axis migrating westward with depth due to the asymmetry of the basin. The east flank of the syncline is a broad shelf area, which rises gently to the Sierra Nevada foothills. The trend of the basin follows the northwest-southeast grain prevelant throughout most of California. The northern boundary is formed by the Stockton Arch Fault, a large reverse fault which trends across the regional grain. The southern boundary of the area covered by this paper is the Merced-Madera County line. The entire area has been uplifted and tilted to the south by movement on the Stockton Arch Fault.

Folds

Dips throughout the area are very low, ordinarly in the 1° to 3° range, and consequently most folds are of fairly low relief. The exceptions to this are the Tracy-Vernalis anticlinal trend, and the trend of nosing and roll-over that occurs along the length of the Stockton Arch Fault just south of the fault trace. Since both of these trends are in close proximity to major faults, it appears that the stronger folding is related to the large fault movement.

The Vernalis anticline has less relief that the Tracy anticline, and is situated at a point along the Vernalis Fault where movement has been considerably less than farther north. The long axis of the structure runs northwest-southeast, parallel to regional trends and the Vernalis Fault.

The McMullin Ranch anticlinal structure appears to be unrelated to faulting. It is nearly domal, with extremely low relief and is situated immediately adjacent to the basinal syncline. Although stratigraphic variations in the Blewett sand series accent the structure within that series, the anticline is nonetheless truly structural in origin, with the closure on most horizons unrelated to stratigraphic changes.

Both the Tracy and Lathrop structues are relatively high relief anticlinal folds. Tracy has its long axis parallel to the regional trend and the Vernalis Fault, but its northern plunge may be due, at least in part, to the roll over along the Stockton Arch Fault. Lathop is unique among the producing structures of the area in that its long axis runs east-west, a direction close to, but not exactly paralleling the trend of the Stockton Arch Fault. It is probable that the Lathrop structure owes its presence and its anomalous trend to the fault.

In addition to the anticlinal closures that have been proven productive numerous other anomalous features are present throughout the area, as demonstrated by subsurface well control and geophysical data.

Surface anticlines in the outcrop area west of the valley include the Altamont anticline, the Black Butte and Midway anticlines, and Bacon anticline.

Altamont anticline is a very broad, southeasterly plunging structure located just off the nothwest corner of the maps accompanying this paper. The Forbes formation is exposed over most of the anticline.

The Midway and Black Butte anticlines are smaller much sharper and steeper-flanked en echelon anticlines located near the edge of the outcrop area west of the Vernalis field. The Black Butte anticline appears to be closed, with Lathrop sands exposed in its core.

Both the Altamont and Black Butte anticlines have been tested by several wells; however, no production has been established on either anticline.

Bacon anticline is a steep-flanked southeasterly plunging structure projecting out from the homoclinal outcrop midway between the north and south lines of Stanislaus County. This feature has also been tested, but it apparently plunges into the valley and disappears without any closure being developed on it.

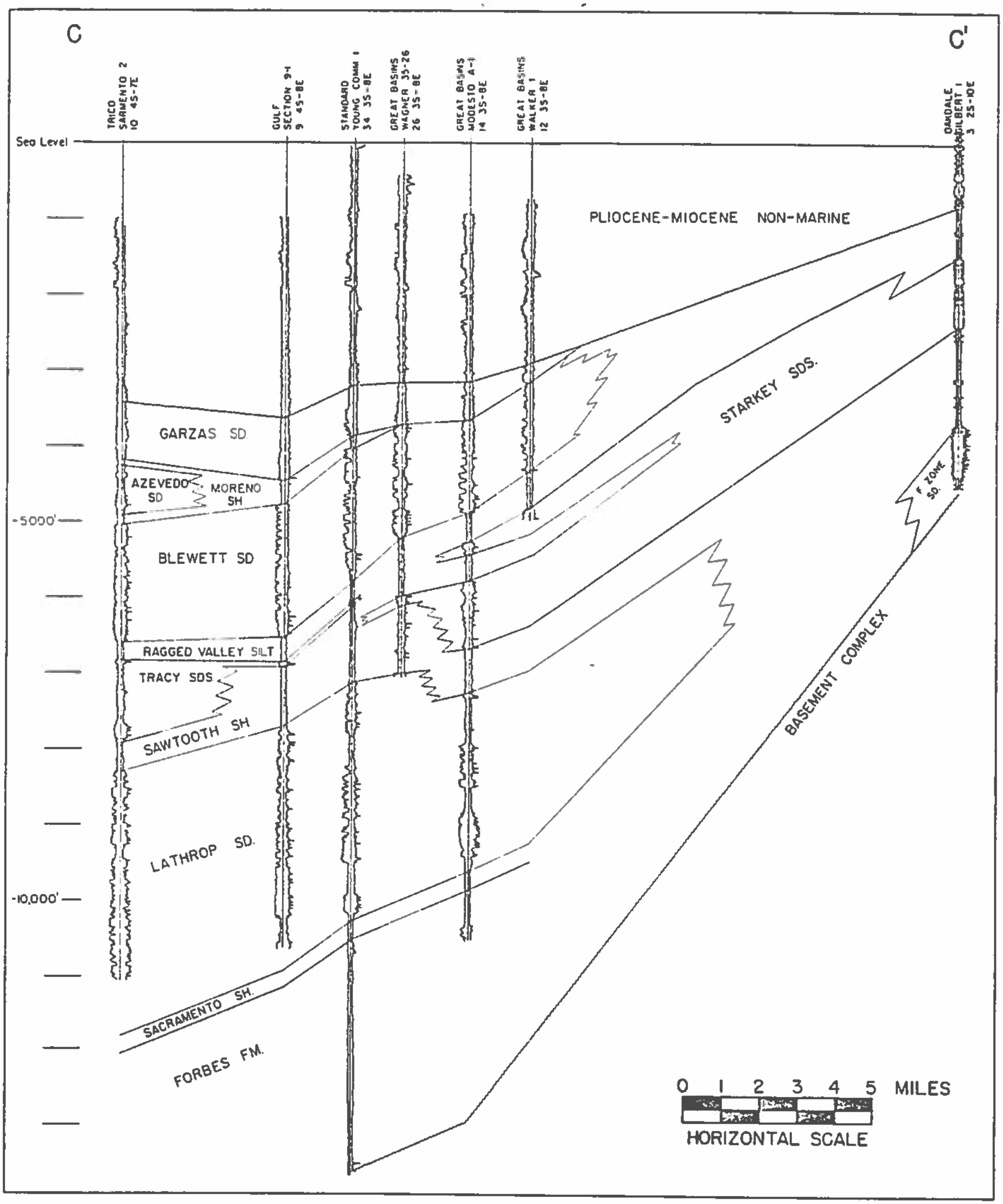


Fig. 4. Correlation section C-C'.

Faults

There are relatively few demonstrable faults in the Northern San Joaquin Valley, but those which are present have played an important part in the geological history of the area.

The Stockton Arch Fault is a large fault or fault zone running entirely across the valley in a direction at right angles to the regional strike. Movement on the fault has been up on the south, with measured displacements of at least 3600 feet. It is a reverse fault, as demonstrated by repeated section in a number of wells drilled through the fault plane. There is no evidence of any extensive lateral movement of the fault. Where stratigraphic trends can be followed across the fault there appears to be no lateral offset.

Although it has been called a fault in this paper, it is uncertain whether or not the Stockton Arch Fault is represented by a single fault plane anywhere along its length. Certainly the western portion of the fault bifurcates into at least three separate faults (fig. 11), each of fairly large displacement and each upthrown on the south. It is possible that two or more faults exist along the entire length of the trend, and it should more properly be considered a fault zone.

The fault apparently dies out prior to reaching the Cretaceous outcrop in the area west of Tracy. The trace of the fault east of the city of Stockton is less well established than on the west side, but it apparently carries at least as far as shown on the structure map, and probably considerably further. The fault bends fairly sharply at three places along its trace.

There has apparently been considerable drag along the fault on sediments lying just to the south, as shown by their comparatively sharp northerly dip. Sediments north of the fault have suffered only slight drag in a narrow area immediately adjacent to the fault plane.

Movement on the fault is predominately post-Eocene, since much of the Upper Cretaceous, Paleocene and Eocene sediments which were undoubtably deposited just to the south of the fault trace have been removed by erosion subsequent to movement. Some movement m... have occurred at the close of Paleocene time, however, since it seems likely that the area south of the fault did not receive any Capay shale or Domengine sand deposition. In addition, it appears that some subsequent movement may have taken place, since the Plio-Miocene non-marine sediments appear to be offset somewhat along the trace of the fault.

Basement appears to be higher on the north side of the fault and a pronounced basement high is present in the area to the north of the easternmost bend of the fault. The Lathrop sand isopach map (fig. 7) shows that stratigraphic changes of a very abrupt nature took place across the line of the fault during deposition of the Lathrop sands, with the sands thinning out and shaling out very rapidly to the north. The Starkey sands, which are continuous and correlative across the fault, show some thinning (fig. 9) to the north in the area immediately adjacent to the fault. In addition both the Tracy (fig. 9) and Blewett (fig. 10) sands thin and shale out to the north in the general area of the fault. Thus it appears that the area along the Stockton Arch Fault has been anomalous throughout much of late Cretaceous time. It seems probable that these abrupt changes in stratigraphy may have been responsible for, or at least reflect in some way, the localization of the Stockton Arch Fault along its trend.

The Vernalis Fault is a large reverse fault which parallels the regional strike and is located just east o Tracy-Vernalis anticlinal trend (fig. 11). It is unthrow the west side with displacement reaching a maximu 1500 feet adjacent to the Tracy field.

The Vernalis Fault probably buttresses agains Stockton Arch Fault zone just northwest of the field, and does not continue to the north. Moveme this fault may have been in part responsible for the f tion of the Tracy and Vernalis anticlines. Vernalis movement apparently took place at the same tim movements on the Stockton Arch Fault.

There is some subsurface evidence to indicate several other minor faults of fairly small displace may be present. In addition, some minor faulting is cated in three of the producing fields, but these have little regional importance.

The Black Butte Fault has been mapped in the ou west of the Tracy-Vernalis trend. It is apparently a r fault with small displacement, upthrown on the west located on the east side of the Black Butte anticline.

GEOLOGIC HISTORY

The sedimentary history of the Northern San Jo Valley began in late Cretaceous time with the depo of sediments of Goudkoff's H and G Zones in the w portion of the valley. The sea advanced eastward d deposition of the Dobbins shale and the overlying F formation. Deposition was continuous throughout Cretaceous time with sands being deposited on both of the valley. It is probable that the sands deposit the east side of the basin had their source in the Nevada Mountains, whereas the source for those o west was the Coast Ranges.

Near the end of the Cretaceous the sea had b quite shallow and the Garzas sand was deposited blanket shallow-water deposit over the entire area. S water deposition continued without interruption int Paleocene. It is likely that the Stockton Arch was u following the close of the Paleocene. This is indicat absence of the lower Eocene formations which occur Sacramento Valley. The sea advanced during th Eocene with deposition of the Kreyenhagen shal overlying sand extending northward, perhaps com covering the previously uplifted arch.

At the close of Eocene time movement on the St Arch and Vernalis Faults uplifted the Northern Sa quin area and tilted it to the south. A period of e followed during which Eocene, Paleocene, and a p of the Upper Cretaceous sediments were stripped the northern part of the area.

Throughout the Miocene and Pliocene, depositio entirely non-marine. During the Pleistocene the are been deformed by the orogeny which elevated and the Coast Ranges and which developed the present configuration.

It is concluded that most of the deformation place during the uplift at the close of Eocene tim that the folds and faults have been accented by Pleist movement.

FUTURE EXPLORATORY ACTIVITY

As previously noted, the Northern San Joaquin has been the scene of considerable exploration since and three gas fields, with a total estimated value c proximately $250,000,000 have been discovered. It that this high level of activity will continue for years for the following reasons:

1. There is a continuing interest by operato

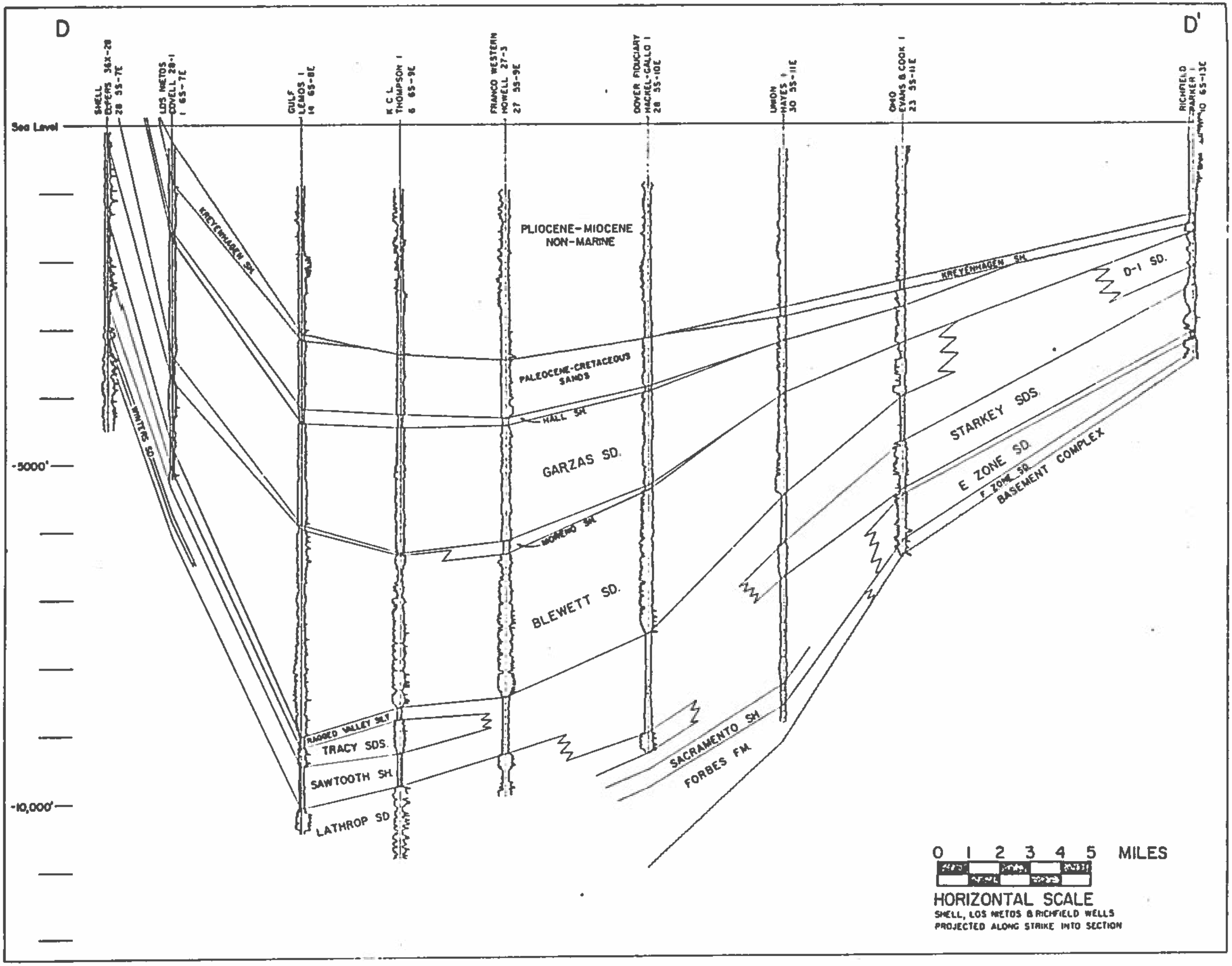
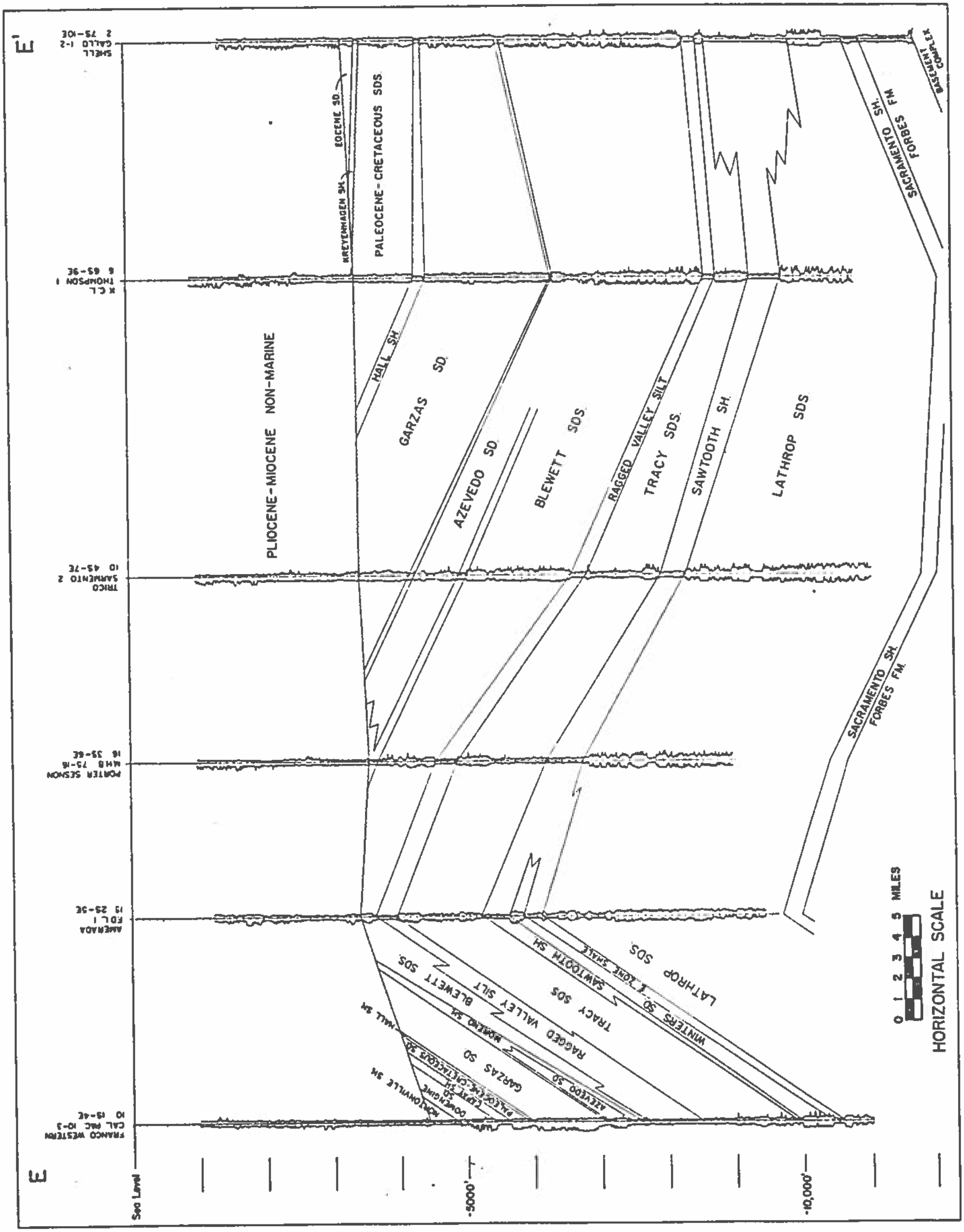
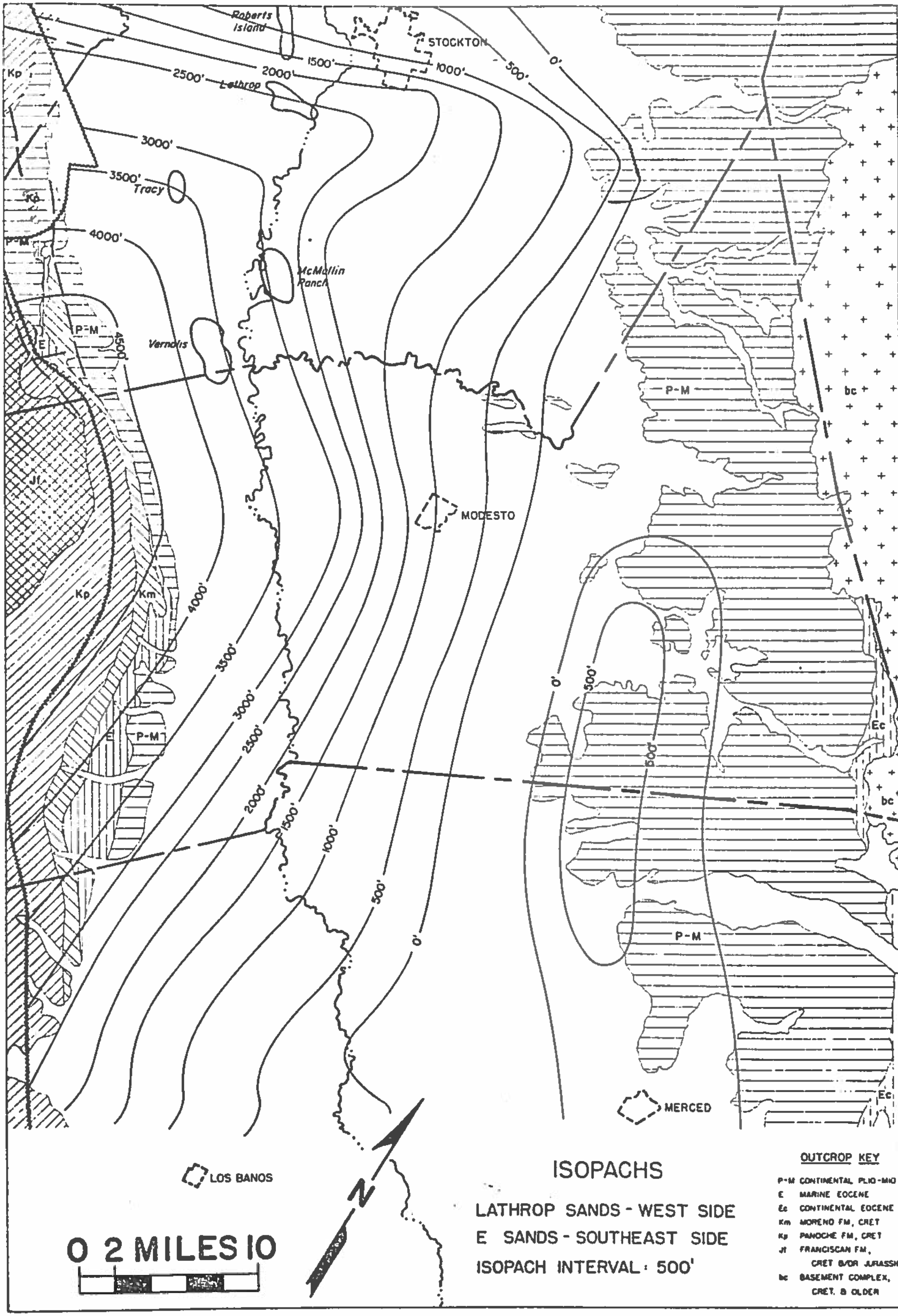


Fig. 5. Correlation section D-D'.


E
E'
SHELL GALLO 1-2
K C L THOMPSON 1
TRICO SARMENTO 2
PORTER SESNON MHB 73-16
AMERADA FDL 1
FRANCO WESTERN CAL PAC 10-3
Sea Level
-5000'
-10,000'
PLIOCENE-MIOCENE NON-MARINE
EOCENE SD.
KREYENHAGEN SH.
PALEOCENE-CRETACEOUS SDS
HALL SH.
GARZAS SD.
AZEVEDO SD.
BLEWETT SDS.
RAGGED VALLEY SILT
TRACY SDS.
SAWTOOTH SH.
LATHROP SDS
SACRAMENTO SH.
FORBES FM.
BASEMENT COMPLEX
MORENO SH
WINTERS SD
E ZONE SHALE
NORTONVILLE SH
DOMENGINE
0 1 2 3 4 5 MILES
HORIZONTAL SCALE



Roberts Island
STOCKTON
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Tracy
McMullin Ranch
Vernalis
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LOS BANOS
0'
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1000'
1500'
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2500'
3000'
3500'
4000'
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bc
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ISOPACHS
LATHROP SANDS - WEST SIDE
E SANDS - SOUTHEAST SIDE
ISOPACH INTERVAL: 500'
OUTCROP KEY
P-M CONTINENTAL PLIO-MIO
E MARINE EOCENE
Ec CONTINENTAL EOCENE
Km MORENO FM, CRET
Kp PANOCHE FM, CRET
Jf FRANCISCAN FM, CRET &/OR JURASSIC
bc BASEMENT COMPLEX, CRET. & OLDER

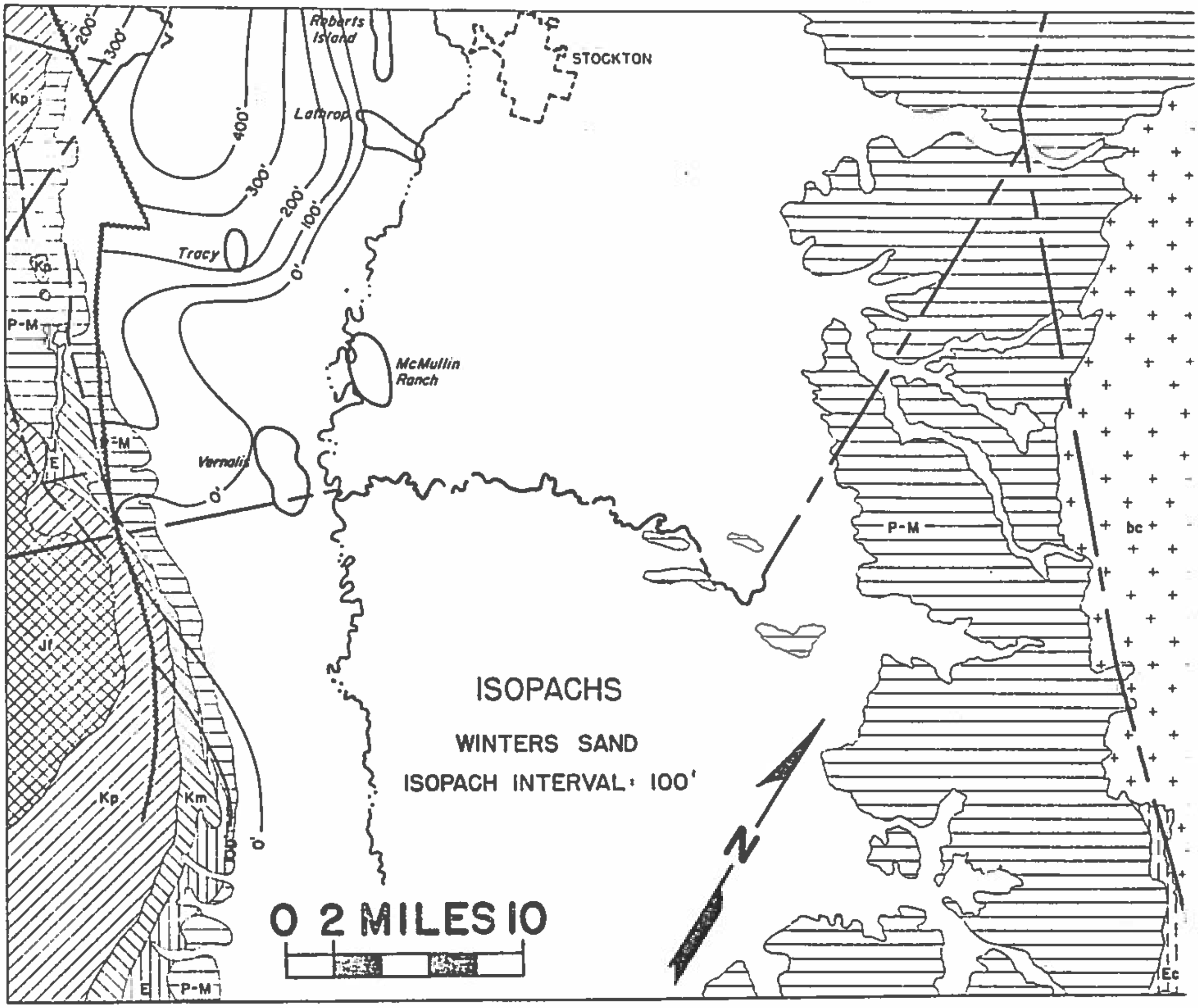

Fig. 8. Isopach of Winters sand.

natural gas exploration throughout the entire Sacramento-Northern San Joaquin gas province.

2. A thick marine section containing proven source and reservoir rocks is present.

3. Land costs are relatively low, averaging from two to five dollars an acre.

4. Drilling costs are extremely reasonable.

5. Much of the area, including the southern and eastern parts, has been only lightly prospected. Seventeen townships have yet to undergo exploratory drilling and as many more have only two or three wells.

6. Low relief structures similar to McMullin Ranch can be expected in the Stanislaus-Merced County area. Failure to find such structures to date is probably due to the extremely low dip prevelant throughout most of the area, and the failure of geophysical methods to adequately define such structures.

7. Producing horizons of the fields are present in the southern portion of the area where gas shows have been found in a number of wells.

8. Sufficient well data is now available in the Stanislaus-Merced County area to provide good subsurface control and a number of anomalous conditions are indicated.

9. Data from wells near the producing fields show that many anomalous conditions remain to be tested even in this more heavily-prospected area.

It is thus probable that continued exploratory eff will lead to the discovery of additional dry gas fields the Northern San Joaquin Valley.

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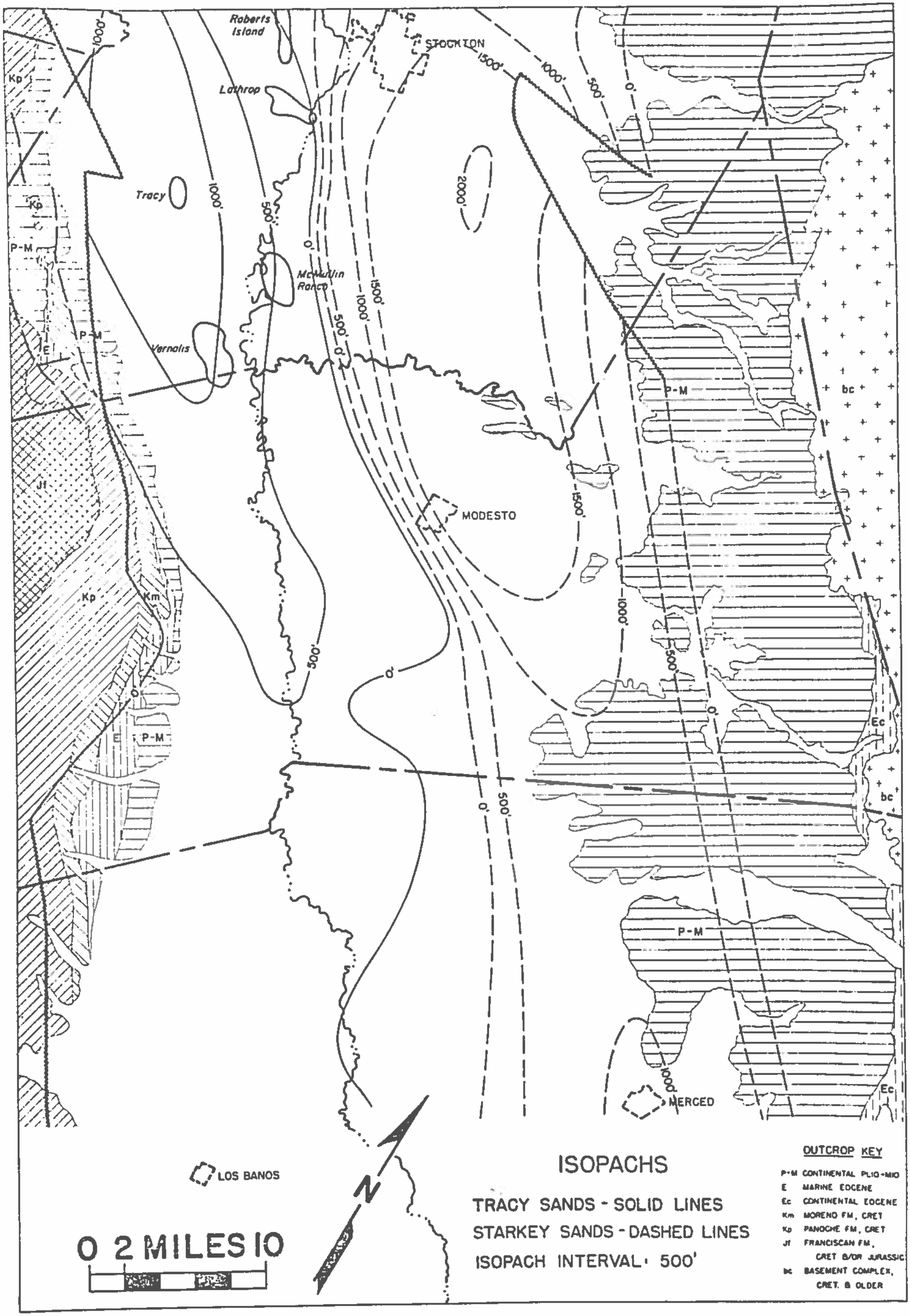

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Km
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1500'
500'
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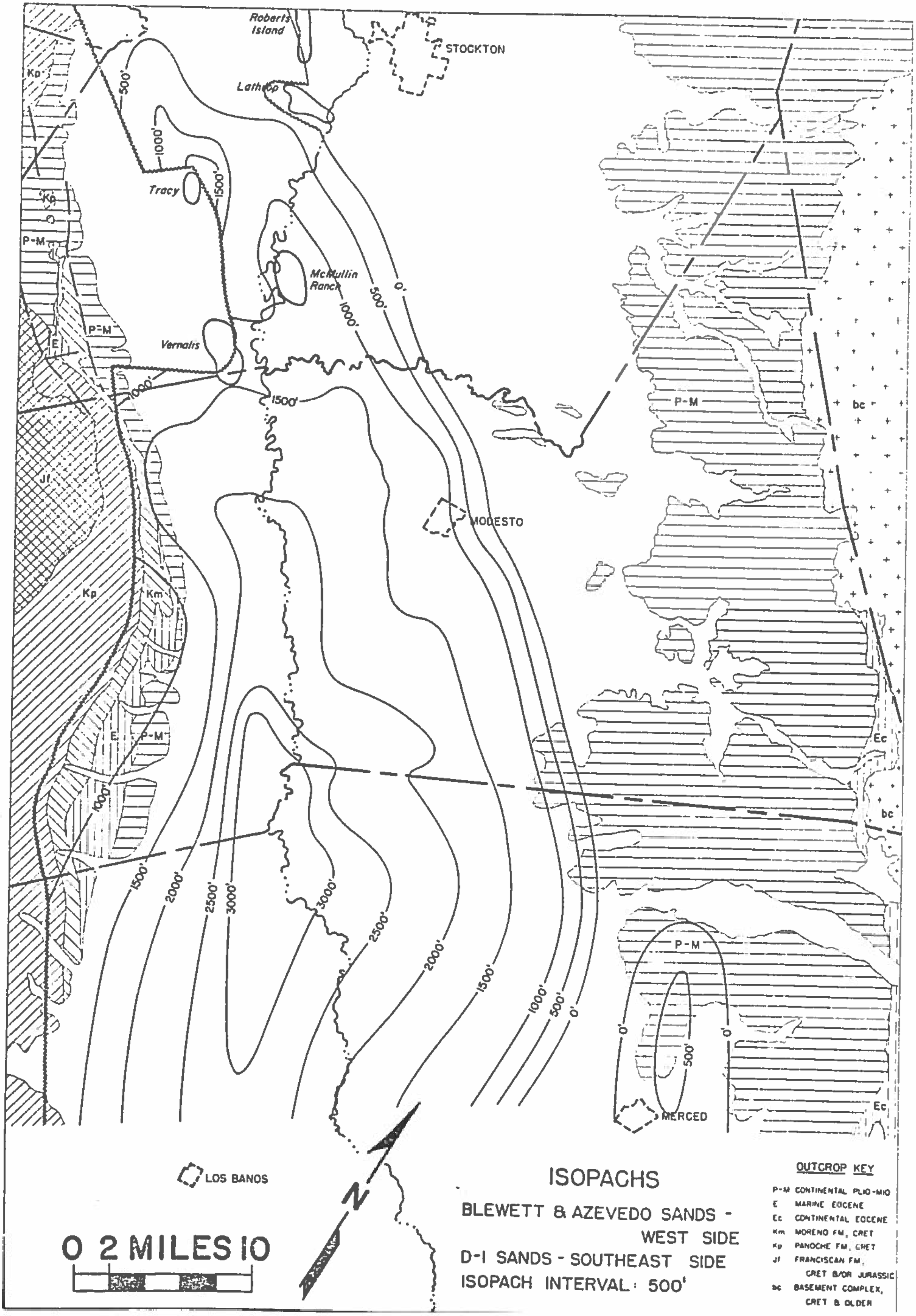
ISOPACHS
TRACY SANDS - SOLID LINES
STARKEY SANDS - DASHED LINES
ISOPACH INTERVAL: 500'
OUTCROP KEY
P-M CONTINENTAL PLIO-MIO
E MARINE EOCENE
Ec CONTINENTAL EOCENE
Km MORENO FM, CRET
Kp PANOCHE FM, CRET
Jf FRANCISCAN FM, CRET &/OR JURASSIC
bc BASEMENT COMPLEX, CRET. & OLDER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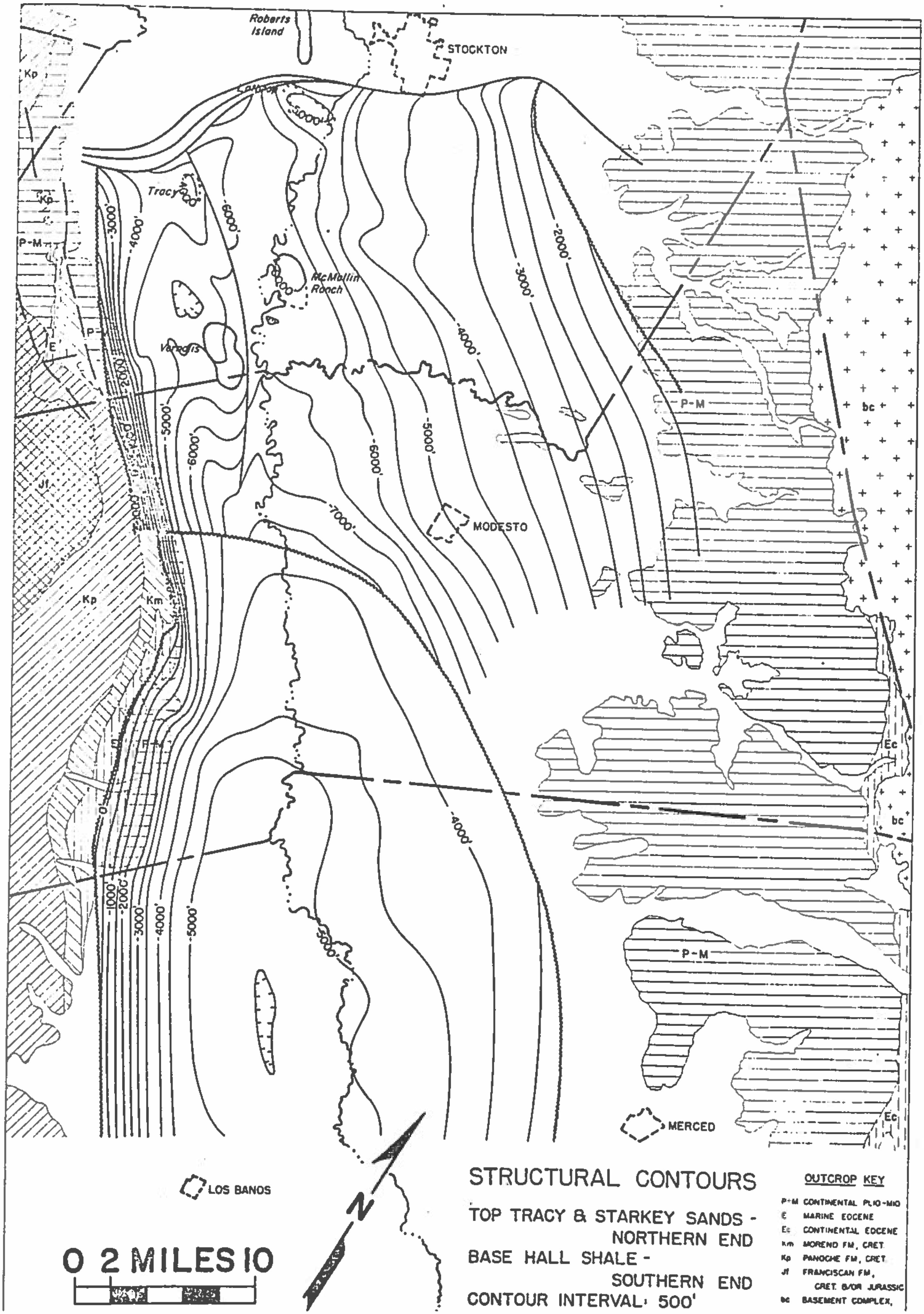
ISOPACHS
BLEWETT & AZEVEDO SANDS - WEST SIDE
D-1 SANDS - SOUTHEAST SIDE
ISOPACH INTERVAL: 500'
OUTCROP KEY
P-M CONTINENTAL PLIO-MIO
E MARINE EOCENE
Ec CONTINENTAL EOCENE
Km MORENO FM, CRET
Kp PANOCHE FM, CRET
Jf FRANCISCAN FM, CRET &/OR JURASSIC
bc BASEMENT COMPLEX, CRET & OLDER



STRUCTURAL CONTOURS

TOP TRACY & STARKEY SANDS - NORTHERN END

BASE HALL SHALE - SOUTHERN END

CONTOUR INTERVAL: 500'

KETTLEMAN HILLS AREA[1]

Hy Seiden[2], Bakersfield, California

ABSTRACT

The Kettleman Hills are a series of three elongate en echelon folds located on the west side of the San Joaquin Valley. They stretch for a distance of 50 miles and consist of North Dome, Middle Dome and South Dome, which latter is believed to be continuous with the Lost Hills structure.

The most prolific oil producer, the Temblor formation of North Dome, was discovered by the Milham Exploration Company "Elliot-1", Section 2, T. 22 S., R. 17 E., on November 7, 1928. Production was subsequently established in the Vaqueros and Eocene McAdams sands. Cumulative production to January 1, 1961 was 427,495,000 barrels of oil and 2,456,375,000 Mcf of gas. Ultimate reserves have been estimated at over 2 billion barrels of oil.

Middle Dome, the smallest structure, has been of lesser importance while South Dome-Lost Hills, the largest structure, has been disappointingly barren in the horizons that produce at North Dome.

The Kettleman Hills derived their greatest expression from the mid-Pleistocene orogeny that produced most of the structures in the San Joaquin Valley. The vast accumulations in the lower Eocene and Miocene at North Dome seem anomalous, but can be explained by an examination of the regional history and stratigraphy.

Two areas of future possibilities are fractured Kreyenhagen shale and the thicker northeast flanks of Kettleman North Dome.

INTRODUCTION

The Kettleman Hills consist of three elongate en echelon domes trending northwest-southeast on the west side of the San Joaquin Valley. They are part of a major structural trend that extends for approximately 90 miles from Joaquin Ridge through the Coalinga-Kettleman-Lost Hills area to Semitropic and Buttonwillow. North Dome is 17 miles long. Middle Dome 6 and the South Dome-Lost Hills structure, believed to be continuous, is 27 miles long.

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HISTORY AND PREVIOUS WORK

According to historical sources, the hills were named for David Kettleman, a cattle drover who pastured his sheep in the hills and sold beef to the Forty-niners during the Gold Rush. W. L. Watts described the hills in 1894 and first used the name Kettleman Hills in the literature. In 1908, Arnold and Anderson made a preliminary report on the Coalinga area and followed it in 1910 with a more complete report on Coalinga in which they covered the Kettleman area in a few pages. After the discovery of oil in 1928, the California Division of Oil and Gas published a series of reports on the field. G. C. Gester and John Galloway published a study of the stratigraphy, structure and occurrence of oil in 1933. The most recent work is that of W. P. Woodring, Ralph Stewart and R. W. Richards who wrote in 1940 a comprehensive report on the stratigraphy, structure and paleontology of both the surface and subsurface of the Kettleman Hills. Since that time, nothi additional has been published on the area.

Numerous wells were drilled in the Kettleman Hi prior to the discovery in 1928, but very few exceeded 10 feet. The discovery was made by the Milham Explorati Company "Elliot-1" in Section 2, T. 22 S., R. 17 E., n well No. 88-2P, abandoned (fig. 1). The well was spudd March 21, 1927 and drilled to 7236 feet where pipe w lost. It was redrilled to 7108 feet where a blowout occur on October 5, 1928 which continued out of control un completed on November 7, 1928 for 3670 BD of 6 gravity oil and 80,000 Mcf of gas. At first production w thought to be coming from 7200 feet but later drilli proved the top of the zone was at 6250 feet.

Lost Hills production in the Pliocene Etchegoin w discovered in 1910, and one well on Middle Dome obtain a little production from the Etchegoin in 1927. Tembl production was not established on Middle Dome until 19 with about six wells finally making up the field. These ha since been abandoned. Deeper drilling on both North Do and Middle Dome eventually established production in t lower Miocene Vaqueros and lower Eocene McAdams North Dome, and in the lower Eocene McAdams and upp Eocene fractured Kreyenhagen shale at Middle Dome. present all horizons are producing at North Dome but on Kreyenhagen shale produces from 2 or 3 wells at Midd Dome.

The Milham discovery at North Dome set off an boom in the area. Rigs and equipment were rushed o night and day and drilling reached a feverish pace. On one additional well was started in 1928 but over thir were started in 1929. Big land deals were consummate mergers of interest were common and innumerable la suits resulted from the frenzied activities. Some holde of prospecting permits had failed to comply with the lett of the law and others filed on the land, partners failed split royalties, and heirs to land found themselves embroil in questions of legal title.

In 1929, the Department of Interior arranged a cu tailment agreement whereby operators drilled and co pleted their wells and then suspended operations and on offset wells to the discovery were allowed to produce. return for suspending, all operators were to share in t oil produced. This slowed down activity for a time, un the Superior "Huffman-1" in Section 29, T. 21 S., R. 17 and the Petroleum Securities "Felix-1" in Section 35, 21 S., R. 17 E., came in. They were not bound by t agreement and produced wide open. Offset drilling w forced in these areas and the race was on once again. did not slacken until April, 1931 when the Kettleman Nor Dome Association (KENDA) took over operation of government and most small fee lands. It cooperated wi Standard Oil Company of California in an orderly develo ment of the field, until, in 1952, the Kettleman North Do Unit (KNDU) was formed with Standard Oil as operato

The early practice of multizone completions in t Temblor and Vaqueros has contributed to the productic of water with the oil. No effort was made to segregate t producing zones and consequently it is impossible today isolate the source of the water. Correction of the wat problem would be an enormously expensive task so t water is produced and injected into the Etchego formation.

Development of the Lower McAdams on the northea flank is continuing and production is extending beyon

1. Presented to the San Joaquin Geological Society, January 9, 1962.
2. Consulting Geologist.

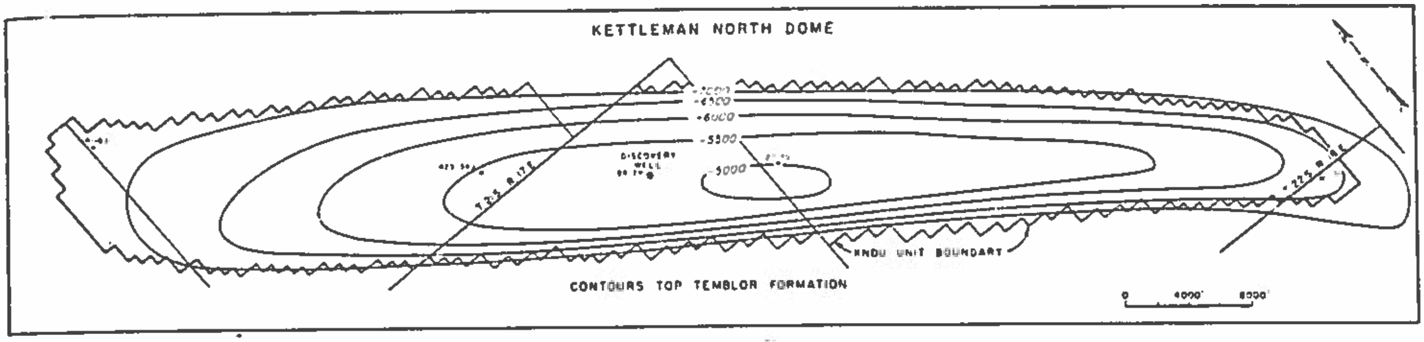

Fig. 1a. Structural contour map on top of Temblor formation.

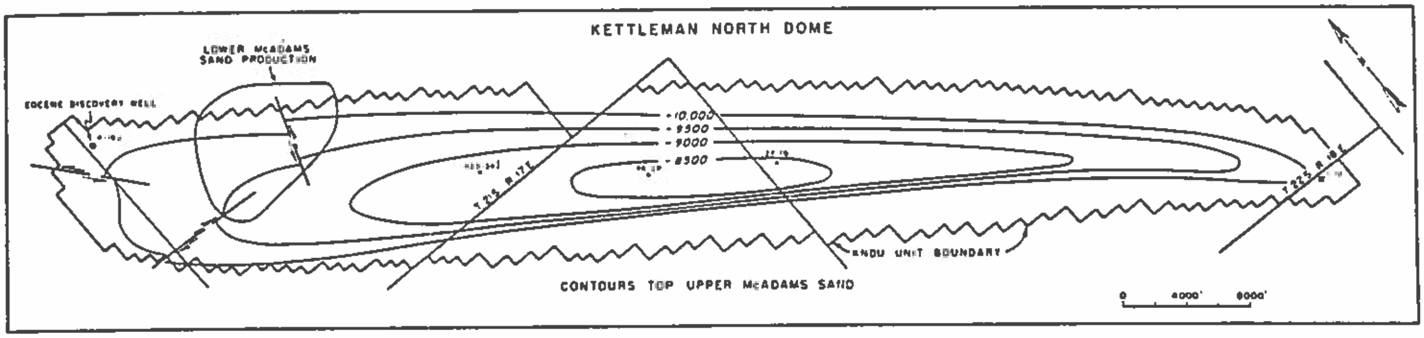

Fig. 1b. Structural contour map on top of Upper McAdams sand.

present unit boundaries. Agreements have been completed and a new Lower McAdams Unit is being formed.

Cumulative production to January 1, 1961 was 427,495,000 barrels of oil and 2,456,375,000 Mcf of gas. Ultimate reserves have been estimated at over 2 billion barrels of oil and astronomical volumes of gas (Gester and Galloway, 1933).

STRUCTURE AND STRATIGRAPHY

The Kettleman Hills are comparatively recent structures having received their present relief in the mid-Pleistocene orogeny. Tulare beds fringe the structure at 35 degree dips. In addition, stratigraphic thicknesses show no evidences of any strong structural growth in the Eocene or Miocene. On the contrary, isopachs show that the area was usually basinal. For these reasons, the vast accumulations of oil and gas at North Dome seem anomalous at first glance. To attempt to explain them, the geologic history of the San Joaquin Valley must be examined.

During lower Eocene time, the San Joaquin Valley was an asymmetrical basin sloping gently to the Sierras on the northeast and climbing steeply up to the Diablo high on the southwest (fig. 2). This high paralleled the ancestral San Andreas fault zone. A promontory of the high protrudes into the basin in the Coalinga area, and the Kettleman area was in the basinal deep paralleling the southwest shoreline. The Vallecitos area afforded a channel to the open ocean and strong currents through the channel distributed coarse and fine material over most of the west half of the basin in the thick and varied sequences of Gatchell-McAdams sands. Interference of the Coalinga promontory resulted in stratigraphic complexities in the Coalinga Nose, Polvadero and North Dome areas and probably assisted in the formation of coal beds, novaculites, kaolinitic deposits and other types of permeability barriers found in this area. The Cantua sand lens was deposited southward from the Vallecitos channel and east side sources contributed thin sand stringers on the Sierran slopes.

By upper Eocene time (fig. 3), the basin had shifted southward and a broad shelf was developed in the Kettleman area. Any oil which had accumulated in the Gatchell-McAdams sands remigrated updip to the sand edge and into the Coalinga area. The writer has concluded that accumulation was extensive enough to include the North Dome area. The thick sequence of Point of Rocks sand on the west side and the Famosa and Tejon sands on the east and south were deposited through the rather thick, homogenous and widespread brown clay that makes up the Kreyenhagen shale. The basin was still confined on the west by the Steep Diablo-San Andreas shoreline.

In the lower Miocene (fig. 5), both borders of the basin were uplifted and the deep migrated far to the south to the vicinity of Maricopa. The uplifted areas provided vast amounts of detritus which formed the thick sections of Temblor-Vaqueros-Phacoides-Carneros sands on the west side and the Vedder-Jewett-Olcese sands on the east side. Non-marine sediments encroached on the basin in the north, and for the first time, the seas breached the steep San Andreas barrier over a broad area on the west. The Diablo uplift was strongly positive in the Coalinga-Kettleman sector. Oil accumulations in the lower Miocene and lower Eocene horizons still stretched far enough south to include the Kettleman North Dome area.

During the middle Miocene (fig. 6), the Diablo high continued positive with a long broad nose developing in the Coalinga-Kettleman North Dome area. Thick sections of sand and shale were deposited in the basin from sources on all sides. The basinal deep migrated somewhat north to the Raven Pass area.

In the upper Miocene (fig. 7), the basin deep returned to the Maricopa area. At this time any oil that may have accumulated in the South Dome-Lost Hills area probably migrated northward into the Coalinga-Kettleman North Dome area and left only residual pockets in Middle Dome and South-Dome-Lost Hills. Depending on stratigraphy, contemporaneous faulting and/or time of folding, the north plunge of South Dome could have preserved an accumulation. Only further drilling can determine this.

Thus, it is apparent that all through Tertiary time from its inception until lower Pleistocene time, the Kettleman North Dame area has been in a favorable position to accumulate large amounts of oil and with the Coalinga area to maintain its updip position until the mid-Pleistocene

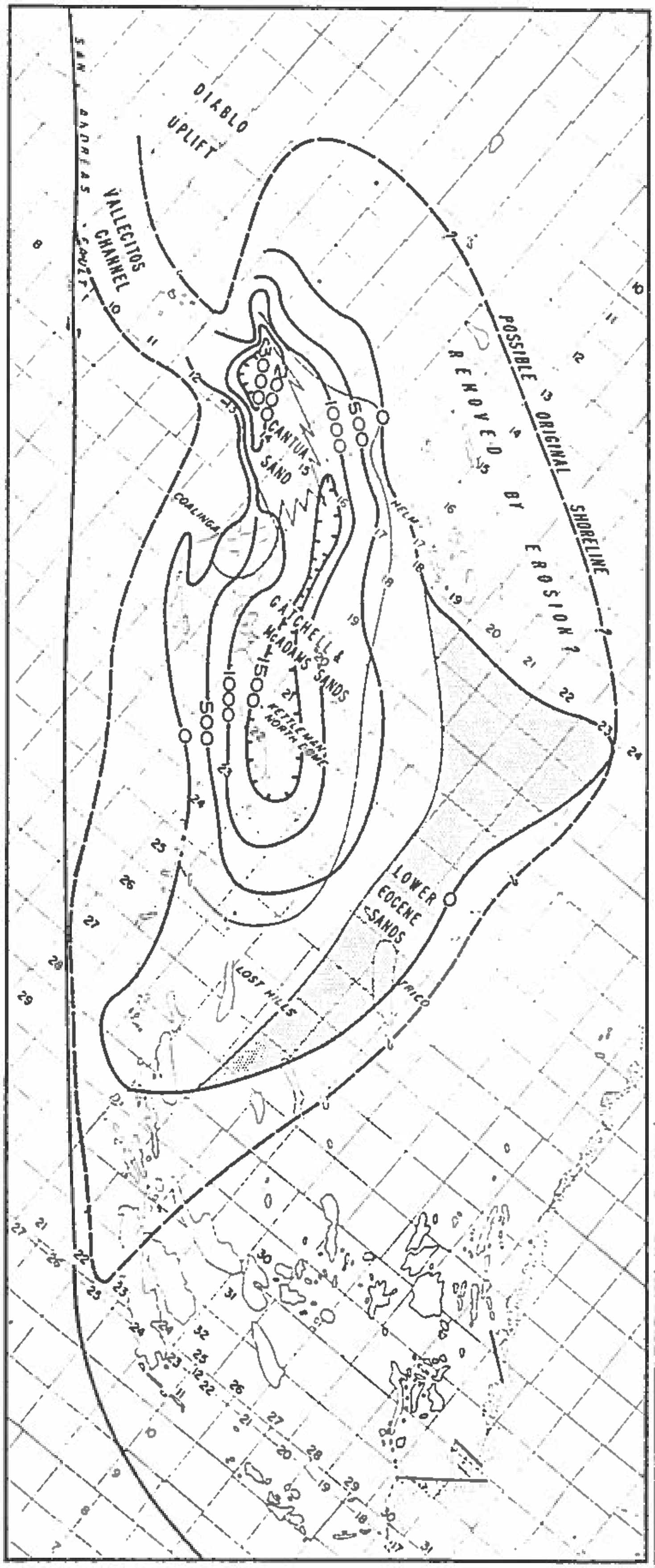

Fig. 2. Isopachs of Lower Eocene.

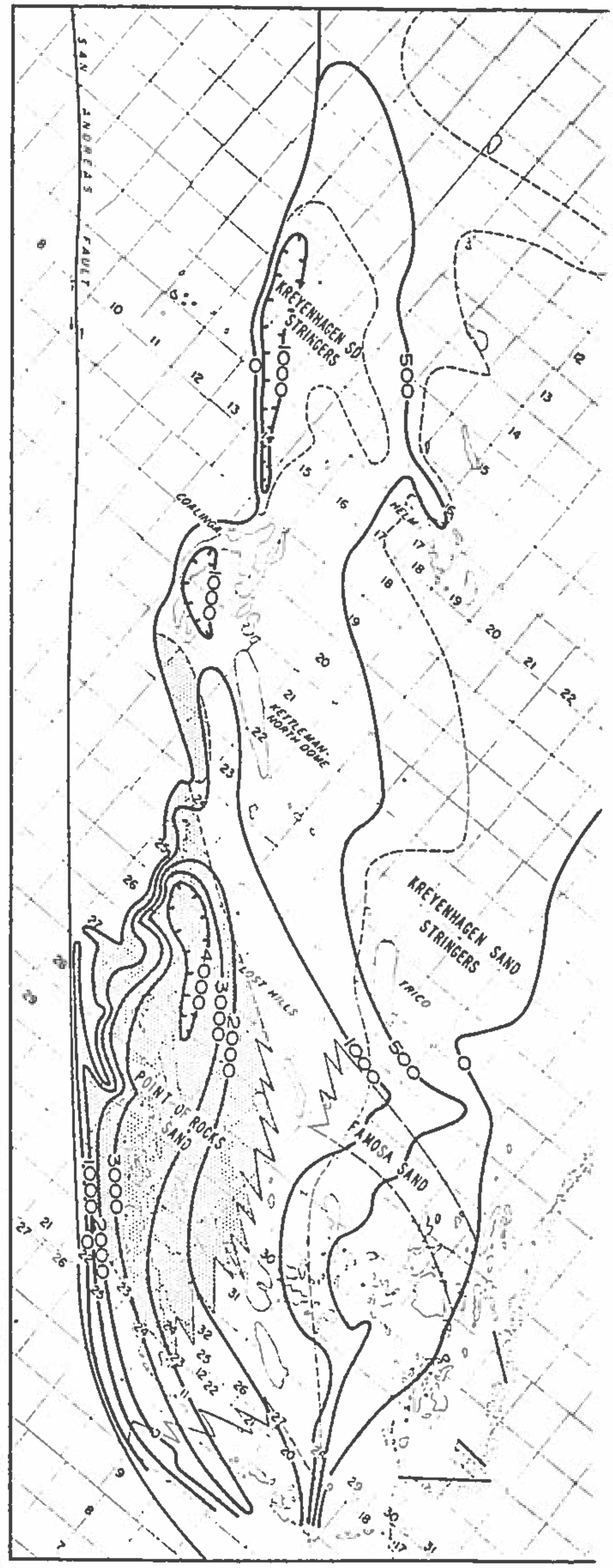

Fig. 3. Isopachs of Upper Eocene.

orogeny superimposed the closed domes we see today. Middle Dome was probably near the downdip edge of the accumulation and couldn't trap much oil, but South Dome-Lost Hills was beyond the accumulation entirely except for possible stratigraphic or fault interruptions which are undetermined as yet.

By reconstructing the geologic history it can be demonstrated that during the upper Miocene oil migrated on a vast scale into the Coalinga-North Dome area. Accumulations in the Gatchell-McAdams sands were originally purely stratigraphic, as were those in the Temblor-Vaqueros, and despite truncation and exposure of the Temblor to the surface where much oil must have been lost, an effective asphaltic seal was formed which preserved the tremendous accumulations first tapped by Milham Exploration's discovery in 1928.

The present structure of North Dome is asymmetrical to the southwest, similar to that of the Coalinga structure. Some workers have concluded it is a drape fold over a deep-seated basement shoulder at the contact of granitic basement on the northeast with the Franciscan. Earlier folding, if any, may have been this type, but it is believed the main structure produced by the mid-Pleistocene orogeny was caused by compression resulting from strong uplift in the Diablo-Temblor high and along the San Andreas fault.

The Middle Dome fold is long, narrow and tight. It appears to be symmetrical. The South Dome-Lost Hills structure, at least where control exists, seems to be asymmetrical to the northeast, the opposite of North Dome and Coalinga. The reason for this is not readily apparent except that it may be related to faulting present on the northeast flank.

FUTURE PROSPECTS

One of the prospects, the north plunge of South Dome, has been probed a number of times by Occidental Petroleum Corporation but thus far without success. Fractured Kreyenhagen shale on North Dome affords a very good possibility of future production since it already produces at Middle Dome. In addition, thickening in the Temblor and lower Eocene sections coupled with the complex stratigraphy of the area makes the northeast flank of North Dome an interesting area for exploration. Drilling, however, would be very deep and expensive.

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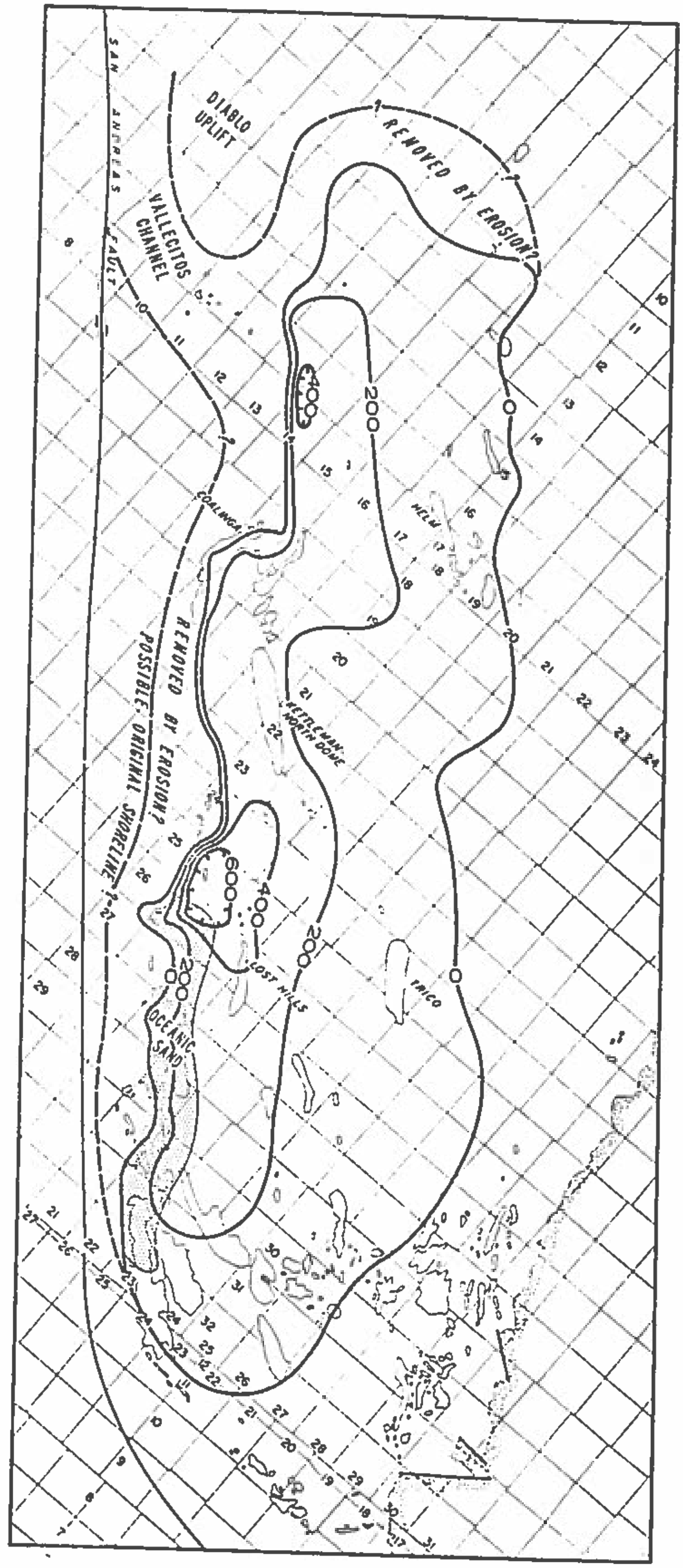

Fig. 4. Isopachs of Oligocene.

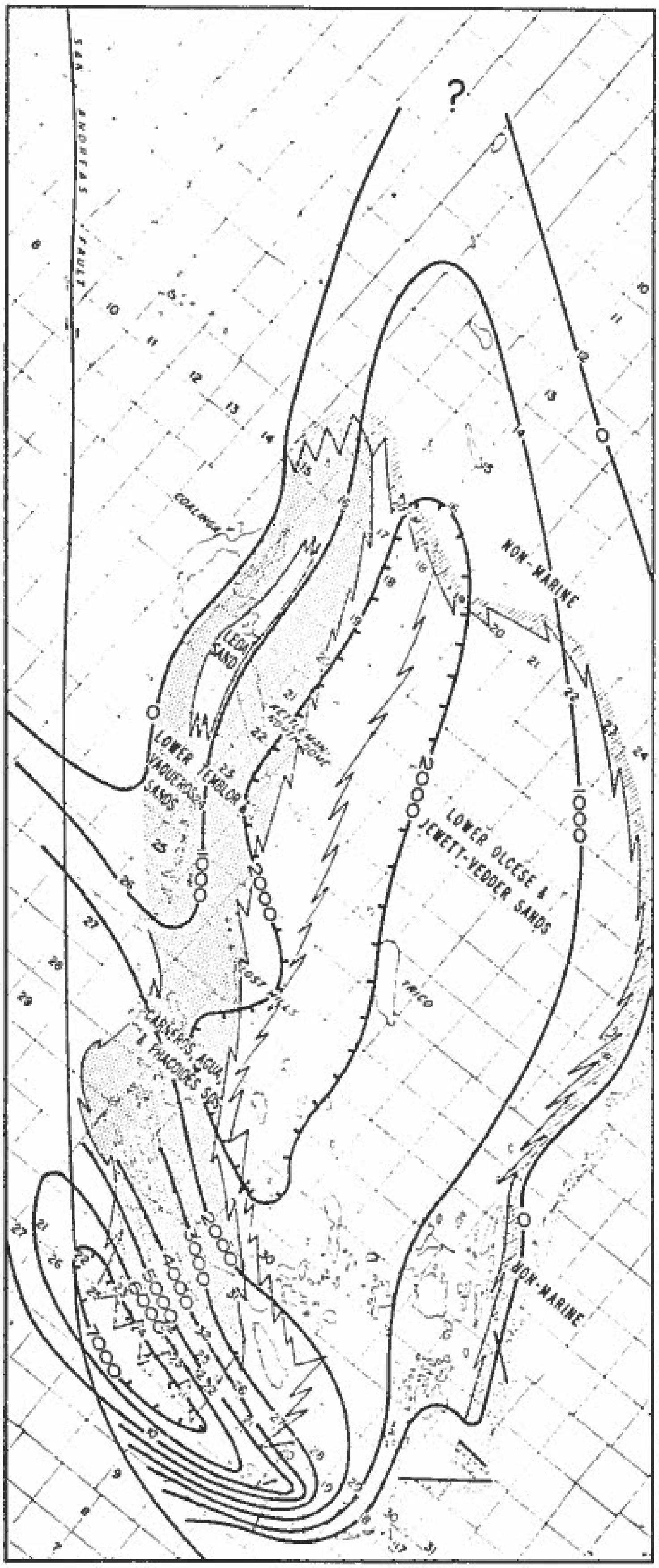

Fig. 5. Isopachs of Lower Miocene.

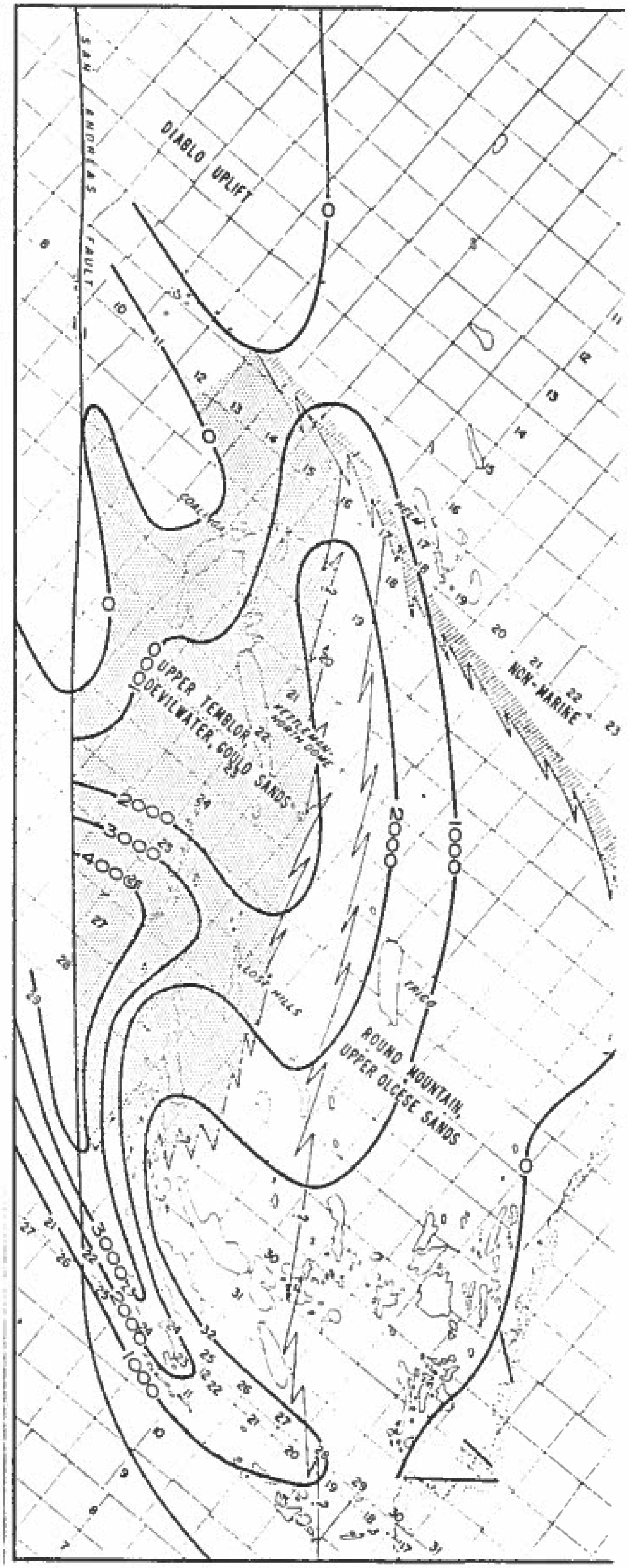

Fig. 6. Isopachs of Middle Miocene.

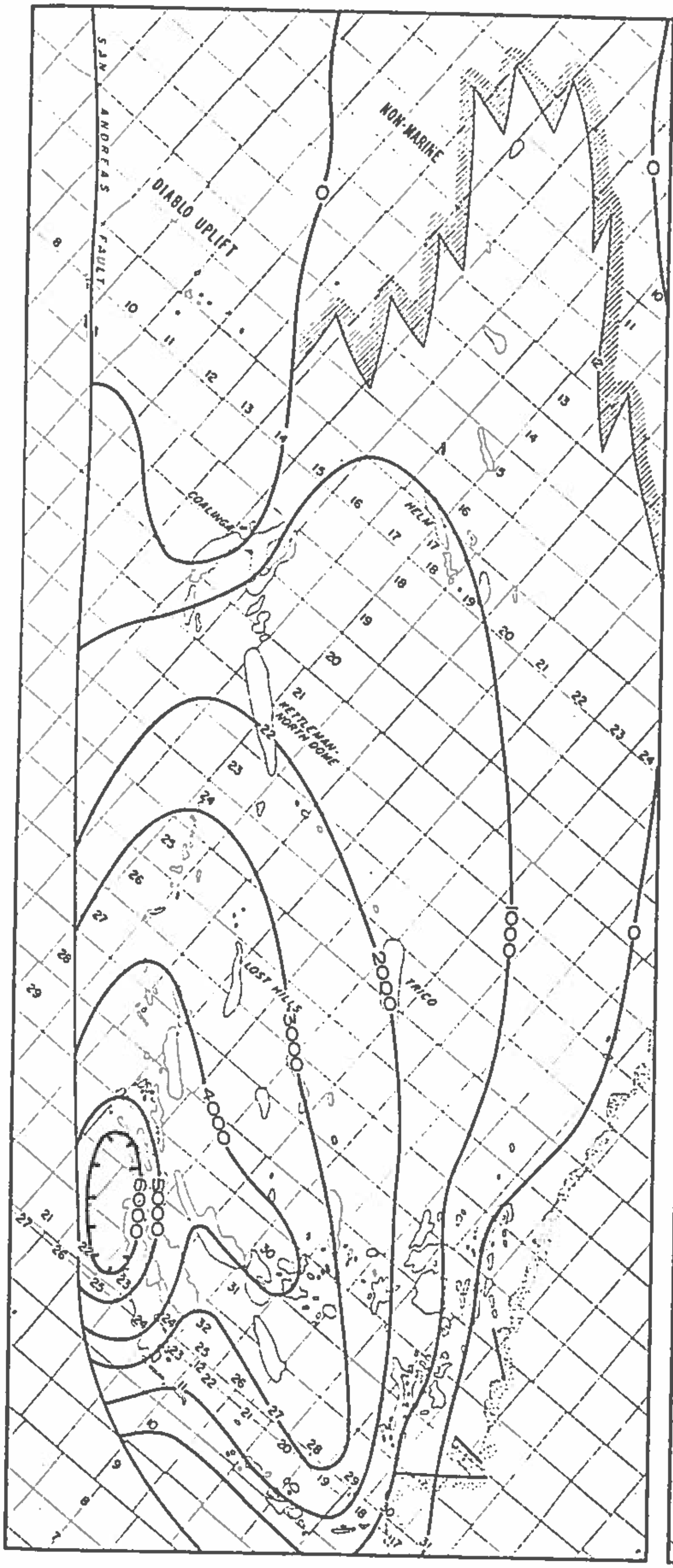

Fig. 7. Isopachs of Upper Miocene.

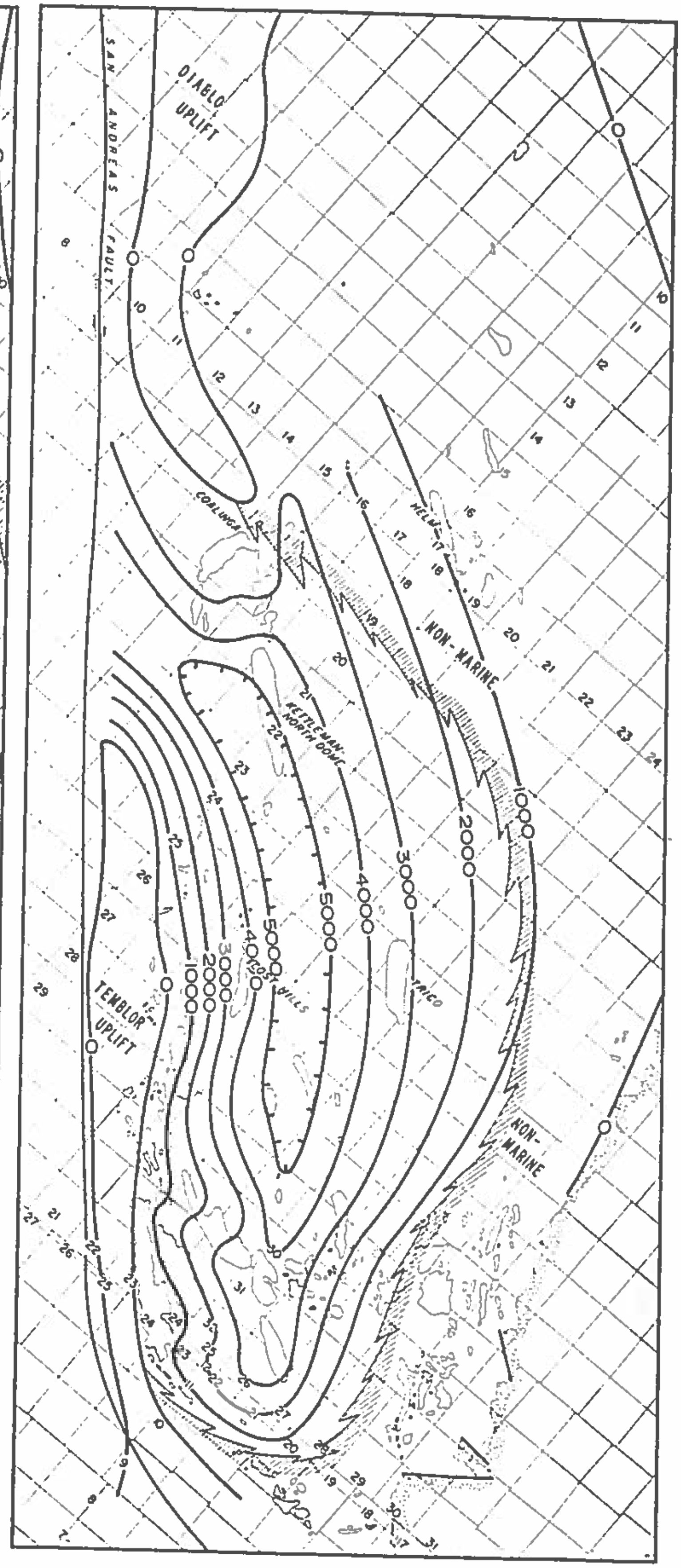

Fig. 8. Isopachs of Pliocene and Lower Pleistocene.

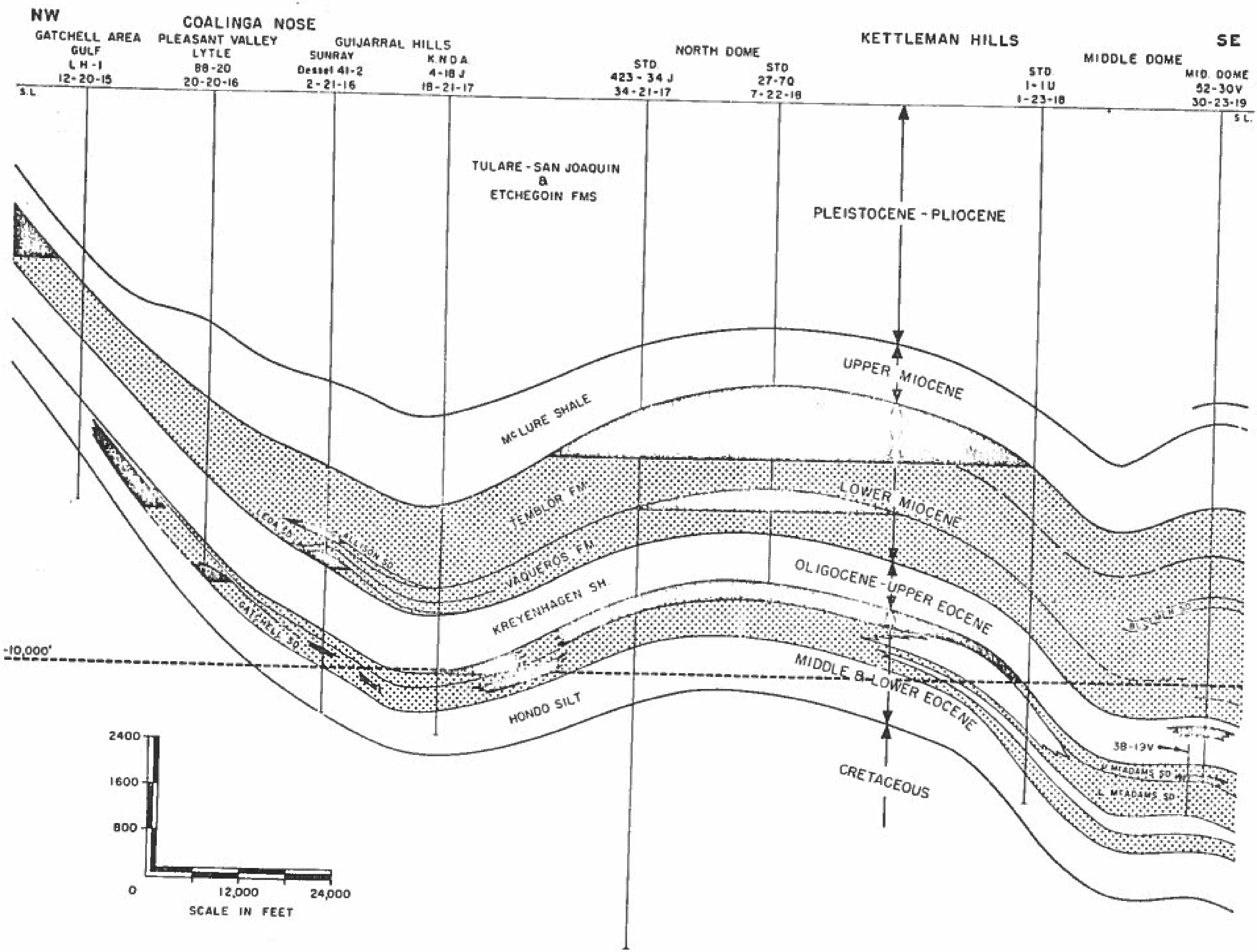

Fig. 9a. Structural cross-section Coalinga to Lost Hills—northern portion.

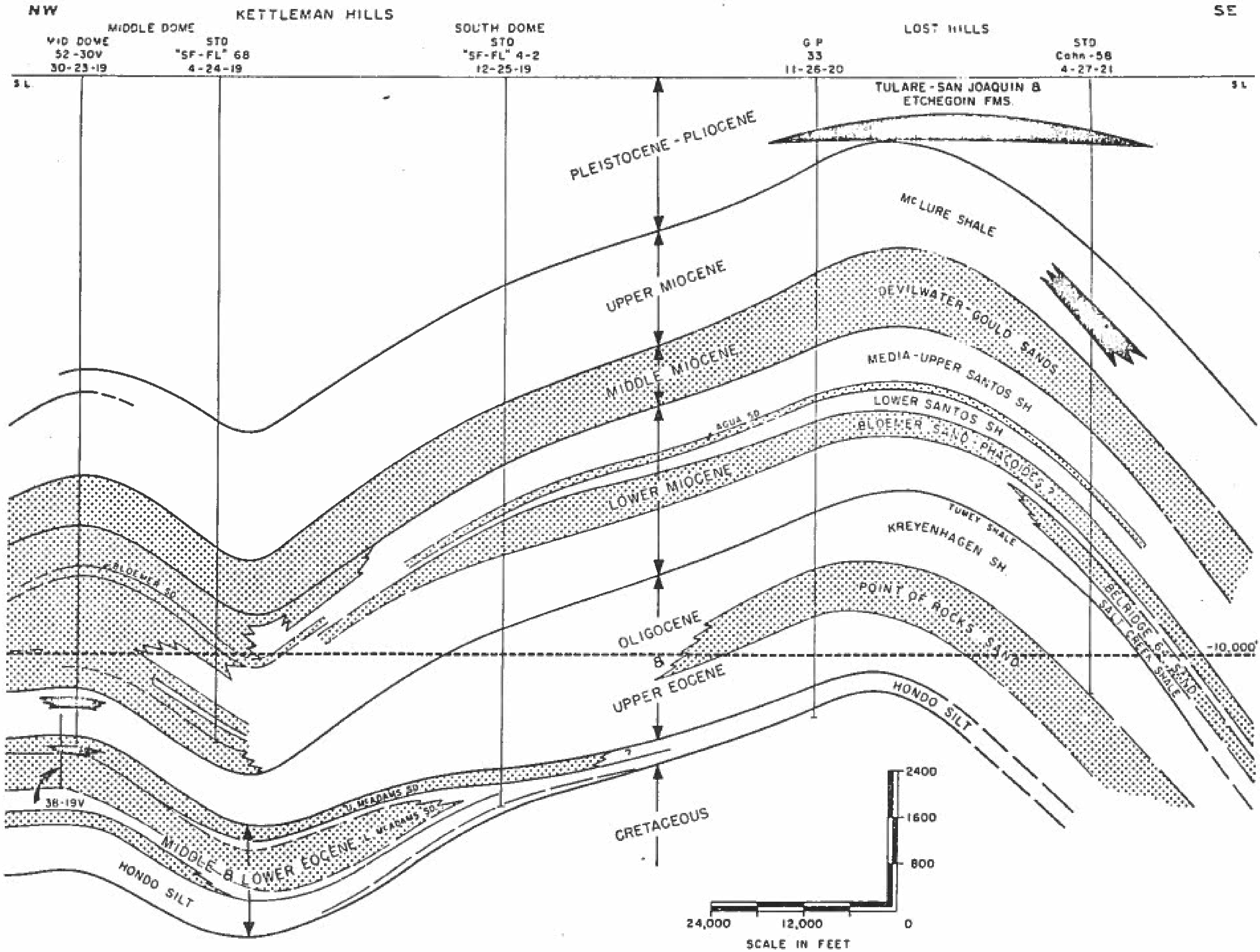

Fig. 9b. Structural cross-section Coalinga to Lost Hills—southern portion.