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LATE MESOZOIC STRATIGRAPHY OF THE SACRAMENTO VALLEY [1]

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ABSTRACT

More than 60,000 feet of marine sediment accumulated in the Sacramento basin during the Late Jurassic and Cretaceous. For the most part, the beds are dark gray mudstones with interbedded discontinuous sandstones and conglomerates. Sediments of a deep marine geosynclinal environment dominate, although basal Lower Cretaceous (Valanginian) and basal Upper Cretaceous (Cenomanian) beds reflect a shallowing of the basin.

Based on the uniform organic carbon content and relative volatility of the late Mesozoic section, the hydrocarbon potential of strata older than the Forbes formation (F zone) is as good as those presently producing beds provided adequate reservoir rocks can be located.

INTRODUCTION

The purpose of this paper is to discuss late Mesozoic sedimentation and geologic history of the Sacramento basin as inferred from outcrop and subsurface information. A large amount of pre-existing written and verbal information has been digested for use in this report.

The methods of study include a literature review, field work, and subsurface investigations. A complex terminology problem involving Cretaceous stratigraphic nomenclature is revealed by a survey of the literature. Popenoe and others (1960) have reviewed and discussd this problem at length. Surface studies are especially applicable in the Upper Jurassic, Lower Cretaceous and lower part of the Upper Cretaceous on the west side of the Sacramento Valley. More than a hundred miles of continuous outcrop demonstrates the physical nature of the exposed section. Sedimentary and faunal characteristics of the rocks are abundantly available for detailed investigation. Subsurface studies in the Sacramento Valley are limited mainly to G zone or younger strata because of the shallow penetrations. Interpretations of lithology and correlation were made from electric log studies and foraminiferal zonations.

Figure 1 shows the regional location of the Sacramento Valley; figure 2 indicates the salient geographic features of the area. For the purposes of this report the Sacramento Valley is arbitarily divided from the San Joaquin Valley at the Stockton arch. The Sacramento Valley contains roughly five million acres and is bordered by the northern Sierras on the east, by the southern Cascades and Klamath mountains on the north, and by the Coast Ranges on the west.

PRE-UPPER JURASSIC HISTORY

The complex paleozoic and pre-upper Mesozoic geologic history of northern California is not well known. In the Redding and Taylorsville areas more than 22,000 feet of Paleozoic and pre-Upper Jurassic strata have been described (Diller, 1906, 1908). Recently Irwin (1960) has compiled and synthesized a vast amount of data in this region.

Although there is no evidence of pre-Silurian deposition in northern California, strata of every other period are represented. Detrital sediments predominate in the section, and limestone was laid down in the Permian and Triassic. Rhyolites comprise the Lower Devonian, and tuffs and volcanic conglomerates are present in the Carboniferous, Lower Triassic and Jurassic. Several unconformites occur within this thick stratigraphic sequence.

The pre-Upper Jurassic rocks were uplifted, folded, faulted, crushed and regionally metomorphosed near the close of the Jurassic. Accompanying this were synorogenic and postorogenic intrusions of granitic batholiths. These granites have been dated radiogenically between 134 and 143 million years, (Curtis and others, 1958, pp. 5-7), and they are Late Jurassic or Early Cretaceous on the absolute time scale. This event has been called the Nevadan orogeny. The metamorphosed and intruded area extended as far south as Sacramento, probably as a large land mass. Simultaneously the Sacramento Valley was formed to the southwest and began to receive marine deposits.

As shown on figure 3, the Nevadan orogney should not be confused with later mountain building for which there is widespread evidence in the central and southern Sierras. As many as seven granitic intrusions have been dated between 76 and 95 million years in the Yosemite area. This second intrusive episode has been named the Santa Lucian orogeny (Idem, 1958, p. 10). The granitic rocks of the Nevadan orogeny apparently are separated from those of the Santa Lucian by the Melones fault zone (Clark, 1960, p. 486). There are a number of small batholiths in the Coast Ranges of California which are contemporaneous with the Santa Lucian granites of the central Sierras.

STRATIGRAPHY

Figure 3 illustrates the stratigraphic terminology used in this report. It includes the commonly referred to formation names, the equivalent time-rock or faunal classifications based on Foraminifera or ammonites, and approximate absolute ages in millions of

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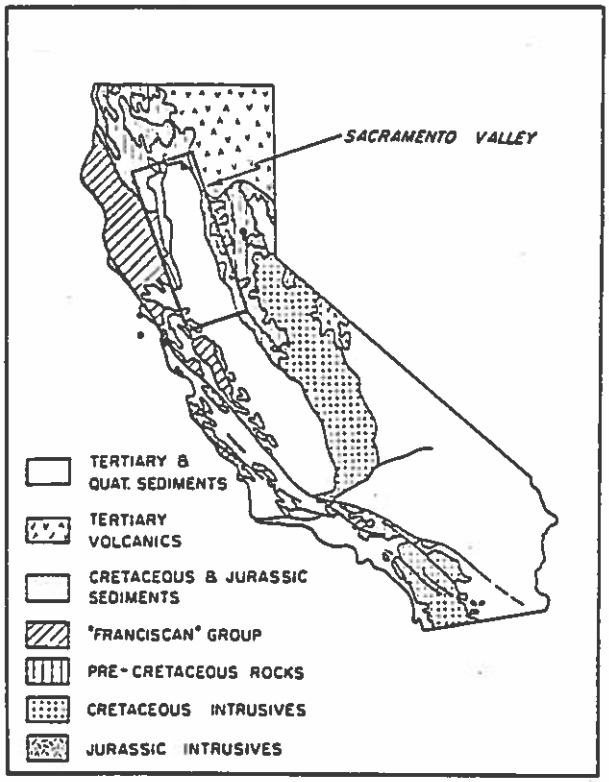


FIG. 1. Regional location map showing late Mesozoic sediments of the Sacramento Valley.

years. The pre-F zone strata have been divided arbitrarily into four units which could be delineated either by their litho- or biofacies and isopached with some accuracy. They are (in ascending order): 1) Upper Jurassic "Knoxville" Series, 2) Lower Cretaceous "Shasta" Series, 3) Upper Cretaceous H zone, and 4) Upper Cretaceous G zone.

Upper Jurassic ("Knoxville") Series

C. A. White (1885, p. 19) first proposed the term Knoxville beds as a subdivision of the Shasta group. The strata at the type area near Knoxville in Napa County were at that time believed to be entirely Cretaceous in age. F. M. Anderson (1932, p. 315) referred to the Knoxville group and placed it properly in the Upper Jurassic. Since then the term Knoxville has been changed to a series (Anderson, 1933), a stage (Dibblee, 1950) and a formation (Irwin, 1957). Except for the wide acceptance and broad connotation of the word "Knoxville" to mean Upper Jurassic Series, the term could better be abandoned in favor of bona fide formation names and true time-stratigraphic stages.

Lithologically, the "Knoxville" includes all varieties of clastic sediment ranging from shale to cobble conglomerate. Dark gray to black, concretionary, brittle, hackly-fracturing shale or mudstone predominates in the section. Massive-bedded, lenticular conglomerates up to 5,000 feet thick are erratically distributed in the mudstones. Well-rounded, many-colored cherts comprise as much as 90 percent of the clasts in the conglomerates. The associated sandstones are dark gray, poorly sorted, and typical of the impervious graywacke suite. A few sands in the uper "Knoxville" are well sorted, fine grained and porous.

A maximum Upper Jurassic thickness of about 20,000 feet probably exists south of Paskenta where there is a large structural embayment. Measured thicknesses of 15,000 feet or more are recorded from numerous areas north of the Elk Creek quadrangle. To the south the preserved Knoxville section diminishes in thicknesses; this may be caused by basal faulting or reduced sedimentation or both. The isopach map (Fig. 4a) shows the "Knoxville" surface outcrop and inferred subsurface limits.

The "Knoxville" fauna includes prolific Buchias, scattered belemnites and ammonites, and rare Foraminifera. Frequently concretions within the mudstones, especially in the upper "Knoxville", contain myriads of *Buchia piochii*. Anderson (1933, 1945) has described a large ammonite and belemnite fauna collected on McCarthy Creek. Goudkoff has obtained Radiolaria, *Dentalina* cf. *nana*, *Lagena* sp., *Robulus* sp., *Trochamina* sp., and *Dictyomitra* from 13,000 to 15,000 feet above the "Knoxville" base along and south of Grindstone Creek, Glenn County. Associated ammonites indicate the Portlandian stage of the Upper Jurassic.

Contact relations of the "Knoxville" are: 1) generally faulted against ultrabasic or Franciscan rocks at the base, and 2) accordant but probably disconformable with overlying Lower Cretaceous sediments. Unconformable lower contacts have been reported (Lachnbruch, 1962, p. 58) but not described in detail. At the north end of the Sacramento Valley, Lower Cretaceous strata overlap the "Knoxville" and rest on basement.

The Upper Jurassic depositional environment was always marine but of a unique type. Some special ecologic condition such as turbid, brackish, or unusually cold water is suggested by the limited fauna. Most of "Knoxville" deposition apparently took place below wave base preserving the delicate turbidite features so clearly seen in the section. Submarine slumping occurred frequently and accounts for the pebbly mudstones and distorted beds described in the lower part of the "Knoxville" (Crowell, 1956, pp. 995-1000).

Source of the Upper Jurassic sediments was apparently to the north and northwest. Sedimentary structures indicate a deposition slope to the south and southeast in the Elk Creek area. The chert clasts in the "Knoxville" conglomerates were probably derived from the western Paleozoic and Triassic belt of Irwin (1960, p. 22) where chert is the second most abundant sedimentary rock. Upper Jurassic Nevadan intrusives were emplaced before and during "Knoxville" deposition, creating a land mass-source area to the north.

Lower Cretaceous ("Shasta") Series

Gabb and Whitney (1869, pp. xii-xiv and p. 129) proposed the name Shasta group for the fossiliferous Lower Cretaceous section exposed along Cottonwood Creek, Shasta County. The term always has had a time-rock connotation (Gault to Neocomien in the or-

iginal usage), and its present general acceptance as a series seems justified. For the purposes of this report it is applied in this sense. Unfortunately, the value of the word "Shasta" is greatly diminished by its misuse and frequent redefinition in the literature. Murphy (1956) studied the Lower Cretaceous strata in the type area and detailed eight faunal zones; however, some of the Lower Cretaceous stages are absent. He proposed the names Ono and Rector formations for the rock units exposed in the region.

Gray-green, concretionary mudstones make up the bulk of the Lower Cretaceous strata, but dark-colored lenticular conglomerates and gray or brown, poorly sorted, argillaceous sandstones occur in limited amounts. Several areas contain porous sandstone in the lower part of the section. An occasional thin limestone bed (two to five feet thick) can be traced a few miles along strike. Generally speaking, the "Shasta" can be distinguished lithologically from the "Knoxville" in the three ways: 1) mudstones are less brittle, fracture conchoidally, and have a greenish cast; 2) sandstones have a dark brown to tan cast and are cleaner, and 3) conglomerates contain a diverse clast mixture of granite, volcanics and ultrabasics.

The thickest Lower Cretaceous section is exposed on Cottonwood Creek along the Shasta-Tehama county line. Here at least 22,000 feet have been measured (Anderson, 1938, p. 22 and Marianos, 1958). Outcrops varying between 12,000 and 16,000 feet thick exist along the west side of the valley from Putah Creek to Elder Creek. The isopach map (Fig. 4b) outlines "Shasta" distribution and the inferred eastern limit.

Lower Cretaceous sediments include a moderately abundant and diversified fauna. Murphy (1956, p. 2114) shows 80 molluscan species, and Anderson (1902, 1938) indicates many more. Although the ammonite fauna is sparse in some areas, every stage of the Lower Cretaceous is represented except the lowermost or Berriasian. Foraminifera have been zoned preliminarily (Marianos, 1958, 1961) but these data have not been published. Compared to the rest of the "Shasta" section, the microfauna are numerous in the upper part (Albian stage) where Goudkoff (in Chuber, 1961, p. 115) identified 16 genera and 28 forms. At the base of the Lower Cretaceous there is a persistent horizon characterized by prolific *Buchia crassicollis* beds. The north end of Lower Cretaceous outcrop contains a more varied and abundant fauna than any exposure on the west side of the Sacramento Valley.

Although the Lower Cretaceous beds accordantly overlie Upper Jurassic strata, there are some good indications of a hiatus: 1) the missing Berriasian fauna, 2) conglomerates sporadically developed at the base of the "Shasta", and 3) reworked Belemnites and Buchia piochii in the lower "Shasta" beds. Detailed surface geologic studies should clarify the exact position and nature of the probable disconformity.

The Upper-Lower Cretaceous boundary occurs in a conformable rock sequence and cannot be mapped accurately in the field. Along Stony Creek the Albian-Cenomanian boundary exists near the top of a thick mudstone unit. In the Ono area Murphy and Rodda, (1960, p. 835) indicate that the boundary occurs near the base of their Bald Hills formation, a conglomerate-

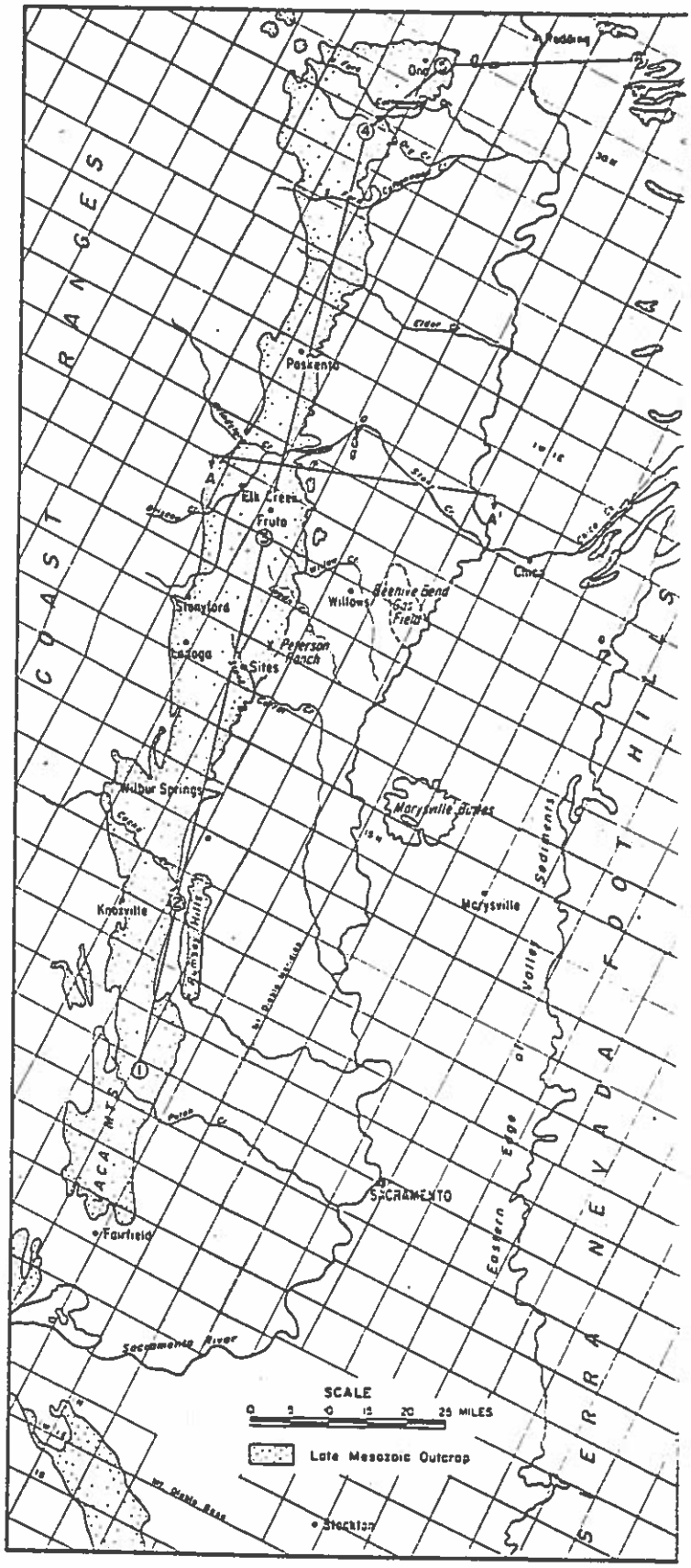


Fig. 2. Detailed Sacramento Valley location map Mesozoic outcrop areas and geographic names referred to in text.

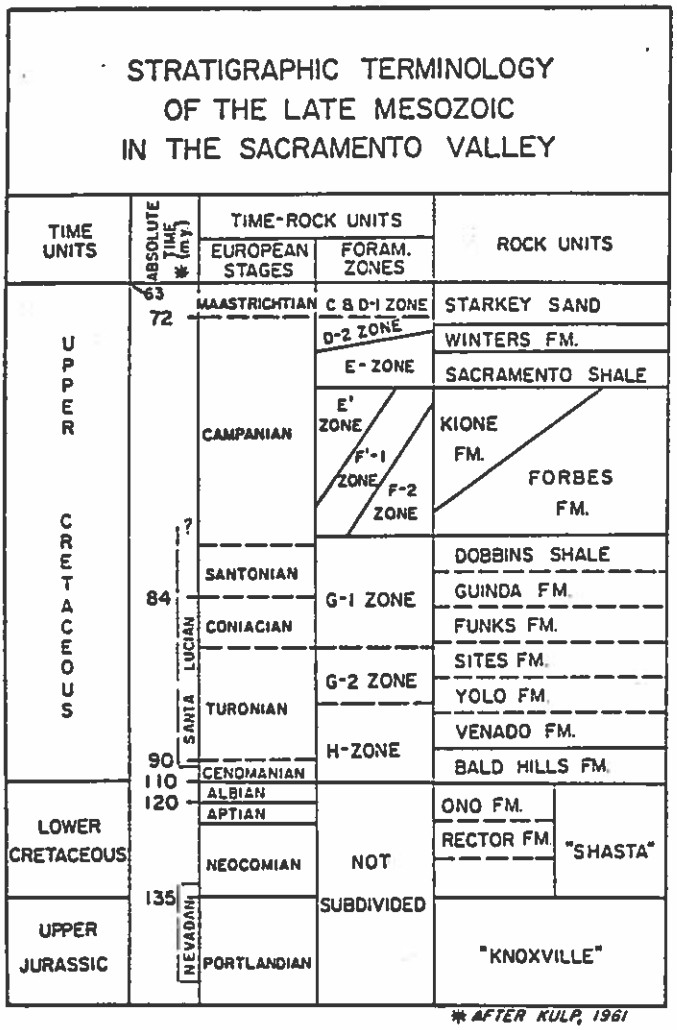


FIG. 3. Late Mesozoic terminology in the Sacramento Valley.

sandstone rock unit. However, the presence of reworked Lower Cretaceous fossils in basal Upper Cretaceous beds has been reported by Murphy and Rodda (1960, p. 838), Brown and Rich (1960, p. B319,) and Chuber (1961, p. 44). These occurrences suggest that somewhere in the Sacramento Valley, probably in the subsurface east of present outcrops, the Upper Cretaceous rests unconformably on the Lower Cretaceous. This is indicated on the cross section (Fig. 6b)

As interpreted from the outcrop, there are two predominant depositional environments found in Lower Cretaceous beds. At the north end shallow marine deposition is defined by coarse lithology and an abundant fauna. Southward, the paucity of organic remains, the predominant mudstone lithology, and the preservation of turbidite sediments points to deposition below wave base for the bulk of the section There is one exception: the basal *Buchia crassicollis* beds which are frequently associated with massive conglomerates and thick-bedded, coarse sandstones with carbonized wood fragments. These suggest a shallow marine environment.

There is supporting evidence to show that the Lower Cretaceous section was derived from a source area to the north or northeast: 1) the thinner section and coarse clastics of the north end outcrops compared to west side exposures, 2) sandstone sedimentary structures in NW/4, sec. 13, T. 21 N., R. 6 W., indicating a north to south depositional slope, and 3) an eastward increase in conglomerate of an upper rock unit in Fruto quadrangle, Glenn County, (Chuber, 1960, p. 40).

Upper Cretaceous H Zone

This time-rock unit is delineated because it represents a compromise between the available subsurface and surface paleontologic data. The term was proposed by Goudkoff (1945, p. 993) who assigned to it the "lowest part of the Upper Cretaceous column." Based on the associated megafauna it includes the Cenomanian and part of the Turonian stages of European usage (Muller and Schenck, 1940, fig. 6., p 272). In the subsurface the top of this unit is the base of G-2 zone foraminiferal fauna which generally occurs at, or about 100 feet above the Venado-Yolo formational contact. The lower contact is drawn between the lowest occurrence of Cenomanian fossils and highest occurrence of Albian fossils.

Several rock units have been described and defined within the H zone or basal Upper Cretaceous section. They include most of the Bald Hills formation of Murphy and Rodda (1960, pp. 835-838), the Salt Creek Conglomerate and the pre-empted "Antelope Shale" referred to by Jennings (1954), the Venado and lower part of the Yolo formations of Kirby 1943, p. 282), and Popenoe's Member I (1943, p. 307) in the Redding area. In recent years Lawson (1956, P. 121) and Chuber (1961, p. 41) have used unpublished formation names for beds of the same age.

Lithologically, the H zone beds are similar to the underlying and overlying strata. Massive lenticular conglomerates and tan, gray or brown sandstones characterize the lower beds. These interfinger with the surrounding gray and gray-brown mudstone and siltstone Reworked Lower Cretaceous fossils have been described from these conglomerates in the Ono area. They also occur in the Lodoga quadrangle in the east half of secs. 19, 30 and 31, T. 19 N., R. 4 W. (a strike ridge conglomerate). Some well-washed, porous, thick, light gray sandstones exist in the lower part of the section.

The upper part of the H zone section includes Kirby's Venado formation and about 100 feet of the Yolo formation. The Venado, a predominantly sandstone rock unit, is persistent and easily identified for 85 miles along strike from Fairfield on the south, to Williows on the north. It is dark gray to brown, fine grained, impervious sandstone with minor amounts of siltstone and shale. At or near the base there are some lenticular conglomerate beds. Massive, slump-distorted beds are exposed in the Putah Creek section and near Peterson Ranch (Brown and Rich, 1960) at the base of the Venado formation. Albian ammonites, Rudistids and quartz diorite blocks occur within the distorted strata. The Venado formation grades into the overlying Yolo formation which includes gray-green or tan siltstones and mudstone.

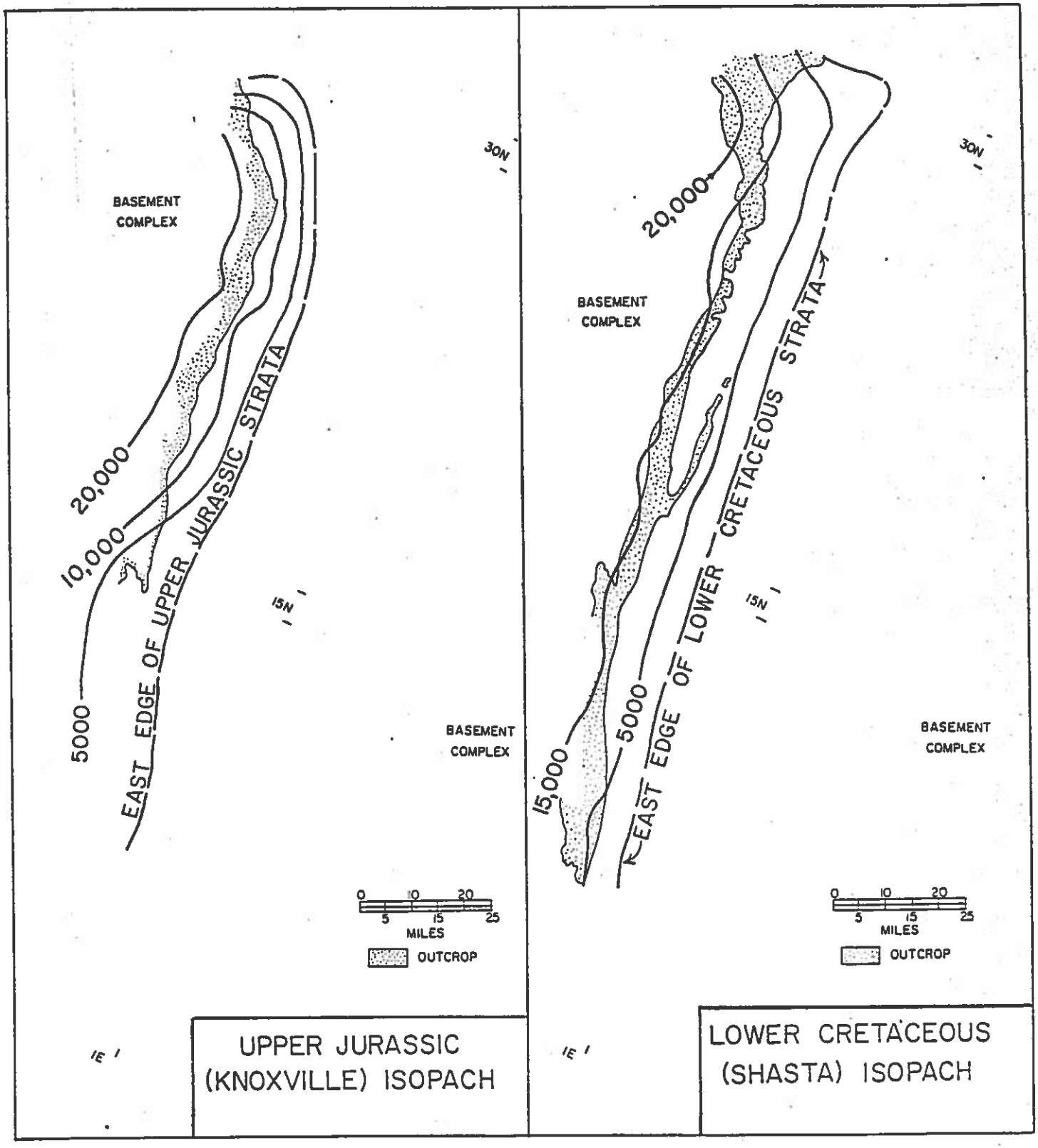


FIG. 4a. Upper Jurassic ("Knoxville") Isopach map and inferred eastern limit.

Fig. 4b. Lower Cretaceous ("Shasta") isopach map and inferred eastern limit.

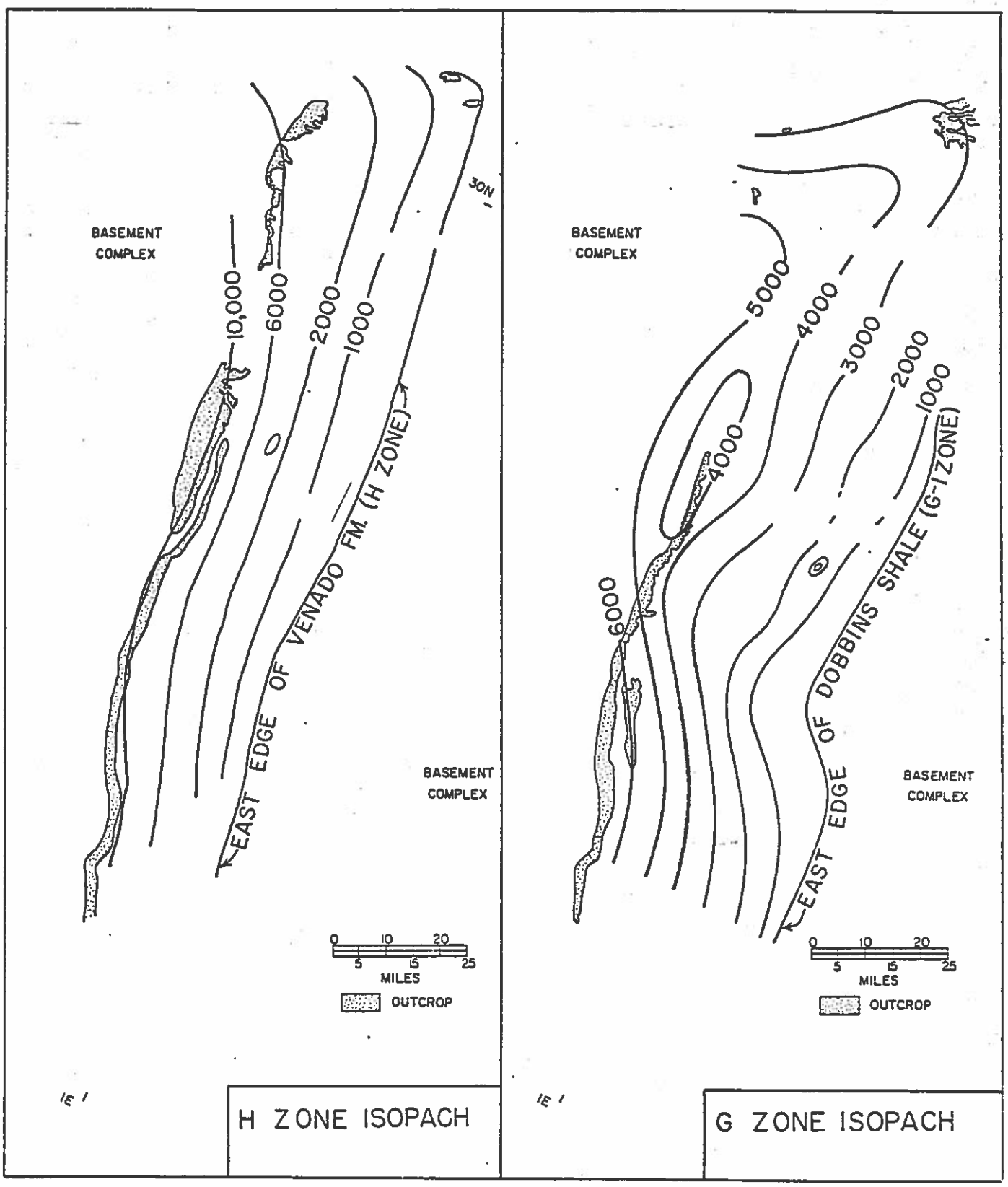


FIG. 5a. H Zone isopach map with eastern limit of Venado formation.

FIG. 5b. G zone isopach map with eastern limit of "Dobbins Shale."

Isopachs of the H zone strata are shown on Figure 5a, indicating a maximum of more than 8000 feet in and south of Fruto quadrangle. Northward the exposed strata of this interval thin and onlap toward Redding where 750 feet of H zone beds rest directly on basement (Popenoe, 1943, p. 310). Figure 6a illustrates this relationship. This transgression is also seen in the subsurface, as shown on the cross section (Fig. 6b). The eastern limit of the H zone is drawn along the eastern edge of the Venado formation as controlled by subsurface penetrations. In this region both the G zone and the H zone foraminiferal fauna are sparse, and the rock unit limit gives the only consistent approximation of eastern extent.

Except in the north end outcrops, the megafauna of this timerock interval are meagre, but more control exists than for the Lower Cretaceous and Upper Jurassic Series. Murphy and Rodda (1960, p. 837, fig. 2) have tabulated 30 genera of Mollusca, some in good abundance (more than 10 specimens) in the Ono area. Matsumoto (1960, pls. 1 and 2) indicates the diagnostic ammonites, baculites, and inocerami and their positions in the Sacramento and San Joaquin Valley sections. Rudistic fragments occur abundantly in Cenomanian sandstone beds exposed in center E/2, sec. 6, T. 20 N., R. 5 W.

The Cenomanian portion of the basal Upper Cretaceous contains some diagnostic Foraminifera. These were described by Kupper (1953, pp. 40 and 41) in the Lodoga quadrangle. Marianos (1959) indicates five planktonic genera and their species distribution in the Cenomanian and lower Turonian of Dry Creek. Goudkoff (1945, p. 994) states that "the H zone beds have furnished only a meager fauna of poorly preserved and indeterminate species of arenaceous Foraminifera, with some associated limonitized Radiolaria."

As previously mentioned, the Upper-Lower Cretaceous boundary occurs frequently within a conformable sequence of mudstone and siltstone. The contact of the H zone with the overlying G-2 zone is also conformable. However, uplift and erosion of Lower Cretaceous beds probably took place during the early Late Cretaceous somewhere east of the west side outcrops. Evidence for this is the reworked Lower Cretaceous fossils and large scale slump structures noted in H zone beds of several areas. These events might coincide chronologically with the early phases of granitic emplacement in the High Sierras.

A variety of depositional environments are suggested from the litho- and biofacies of the H zone or basal Upper Cretaceous sediments. The molluscan fauna of the Ono area and the coarse lithology clearly indicate shallow marine conditions. In Fruto quadrangle the abundant Rudistid fragments and conglomerate or sandstone lithology imply a clear, shallow, possibly warm water environment. However, the upper part of this interval exhibits numerous indications of turbidity including large scale slump structures, massive beds (up to 50 feet) without stratification, graded bedding, and the absence of a molluscan fauna. These suggest deposition below wave base.

There are several indications of an eastern source for the basal Upper Cretaceous section: 1) eastward overlap and coarse lithology at the north end of the Valley, 2) northwestward thinning and decrease in grain size of the Venado formation in the Fruto quadrangle (Chuber, 1961, p. 55), and 3) blocks of quartz diorite (which occurs only to the east and north in the Sierra and Klamath mountains) in basal Venado slump-distorted beds. An eastern or southeastern source seems likely because of the emplacement of Santa Lucian batholiths in the Sierra Nevadas during the early late Cretaceous.

Upper Cretaceous G Zone

The terms G-1 and G-2 zones were proposed by Goudkoff (1945, p. 991-992) for foraminiferal subdivisions in the surface and subsurface of the Great Valley. They were included by him in the Cachenian stage, a name which has not received the popular usage of practicing California geologists and paleontologists.

Kirby's (1943, p. 282) Yolo, Sites, Funks, Guinda, and lowermost type Forbes formations (now "Dobbins Shale") comprise the exposed G zone section, in ascending order. The formations have been properly defined at type localities and traced in the field by Kirby. They are at present the best Upper Cretaceous rock units available for field mapping purposes in the Sacramento Valley. Near Redding, Popenoe (1943) described a numbered sequence (Members I through VI in ascending order) of Upper Cretaceous strata. The upper five units are G zone in age and roughly equivalent to some of Kirby's formations.

In the subsurface the G zones of Goudkoff as originally defined (Idem, p. 991-993, and Table 7, p. 968-969) for the most part are not difficult to distinguish. No modifications of this early faunal study have been published although there have been some changes in its use. As shown on the recent Sacramento Valley Cross Section (Am. Assoc. Petroleum Geologists, 1960), the G zones include equivalents of the Yolo, Sites, Funks, and Guinda formations. Also, the "Dobbins Shale" has been separated from the Forbes formation because of its distinctive faunal, lithologic, and electric log characteristics (Idem, note 1). It is G-1 in age.

Lithologically, in both surface exposures and subsurface penetrations, G zone rocks are an alternation of sandstone units with siltstone-mudstone units. The Sites and Guinda formations include massive tan, brown, or light gray, fine- to medium-grained sandstones with small amounts of interbedded gray mudstone. Guinda sandstones are more porous and clean than those of the Sites and often are characterized by spherical concretions. The Yolo, Funks, and "Dobbins Shale" formations are predominantly dark gray, massive to thin bedded, mudstones and siltstones. In the subsurface the formation boundaries are not difficult to define, even through the Sites and Guinda sandstones appear to have large amounts of interbedded mudstone and siltstone. Electric log markers in these units can be correlated over long distances with fair certainty.

Isopachs and surface distribution of G zone strata are shown on Figure 5b. The thickest outcrop sections are preserved in Putah and Cache Creeks where about 6500 feet have been measured. Gradual northward thinning takes place toward Willow Creek

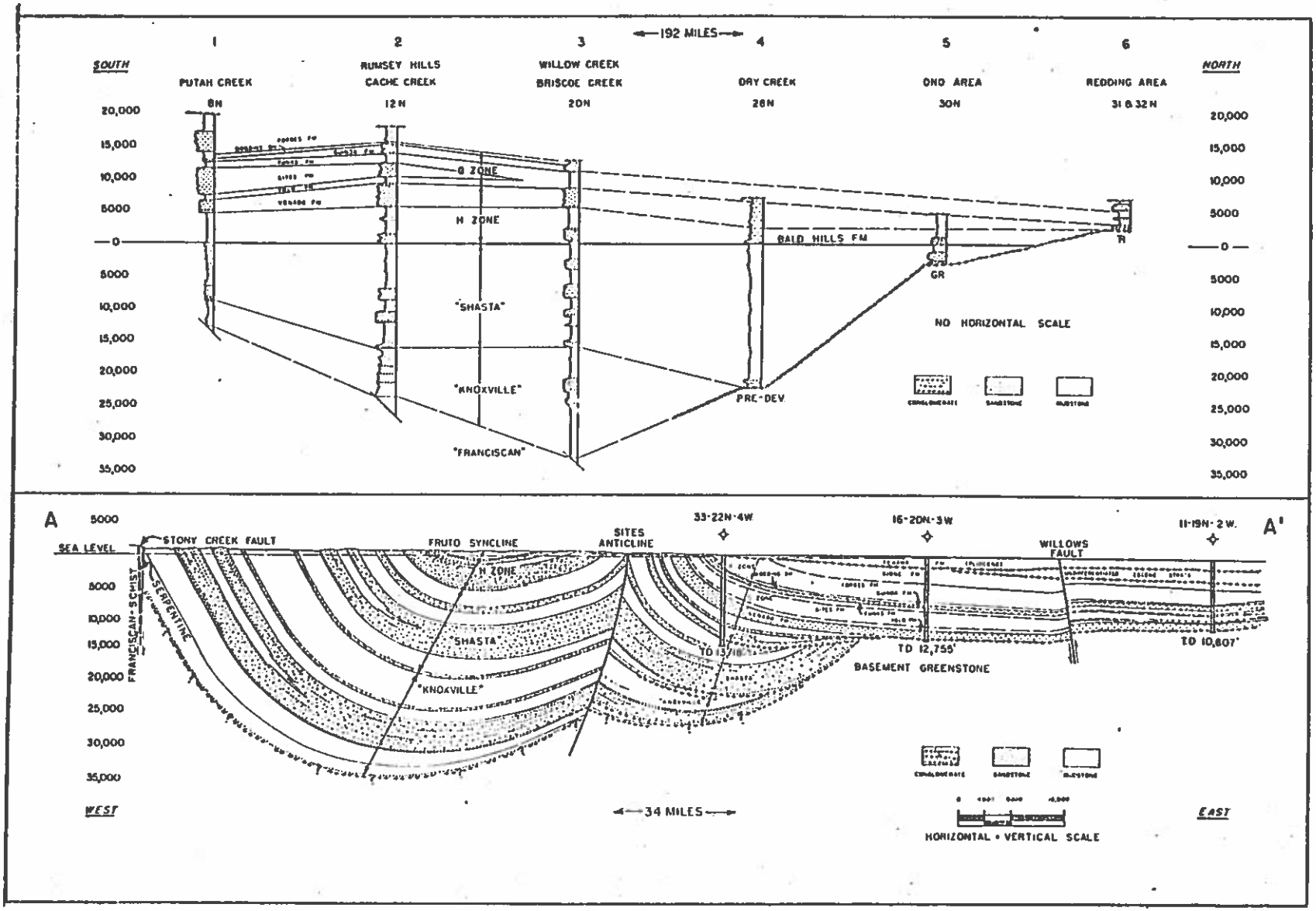


FIG. 6a. North-South correlation of outcrop sections. Fig. 6b. East-west surface—subsurface correlations along section A-A'.

where 3200 feet crop out. Along the south fork of Cottonwood Creek 4700 feet of G zone beds were measured (A. A. Almgren, oral communication) in an incomplete section beneath the Pliocene. In the Redding area 3200 feet of G zone strata were delineated by Goudkoff (1945, p. 966). These surface measurements, combined with the subsurface penetrations, outline a uniform, westward-thickening G zone section in every area except west of Beehive Bend. Here the data indicate an isopach thin of 4000 feet along the Sites anticline, possibly caused by early movement on the structure. The eastern edge of G zone sediments is drawn at the point where F zone beds overlap the "Dobbins Shale" and rest on basement. This line is controlled by many well penetrations and one surface exposure at Chico Creek. A near-shore sandstone facies without diagnostic Foraminifera is exposed in Chico Creek. At least half of this section has been equated by megafossil correlations to the G zone (probably G-1) of the Redding area (Matsumoto, 1960, plate 2).

The G zone microfauna listed by Goudkoff (1945, p. 968-969) were described as "the richest and most diversified in the whole Upper Cretaceous column of the Great Valley." (Idem, p. 991). More recently Trujillo (1960) published a detailed study of the Foraminifera from the shale members of the Redding section. He indicates a correlation with the European stages and also shows the inferred paleoecology.From this study and the one of Matsumoto (Idem), the G zones of Goudkoff appear to represent the upper Turonian, Coniacian, Santaonian, and lower Campanian stages of the Upper Cretaceous Series.

Along the west side G zone outcrop, the collected megafauna are not prolific. Ammonites, baculites and inocerami are common in "Dobbins Shale" concretions and also in thin fossil bands of the Guinda formation. The G zone outcrops of Redding and Chico Creek, on the other hand, contain an abundant molluscan fauna. These have been described by Matsumoto (Idem) and Saul (1959).

Although the G zone section is structurally accordant with adjacent beds in most west side outcrop areas, there are indications of possible disconformity. Near Redding, Matsumoto (Idem, plate 2) suggests a hiatus at the base of Member IV on the basis of missing megafauna. Popenoe (1943, p. 311) indicates an unconformity at the base of Member V because of the abrupt lithologic change (shale to conglomeratic sandstone) and the apparent change of strike across the contact.

To the east in the subsurface, the F zone unconformably overlies the G zone. Electric log correlations in the Willows area show the loss by erosion of several upper "Dobbins Shale" markers at the base of the F zone. Also the abrupt change in subsurface lithology and microfauna indicate a widespread hiatus in the central and eastern parts of the Sacramento Valley.

A "fairly deep water" environment for the G zone is postulated by Goudkoff (1943, p. 1003). The presence of turbidite features in west side exposures of the Sites and Guinda formations indicates deposition below wave base. Using the percentage abundance of planktonic Foraminifera as a key to depositional site, Trujillo (1960, p. 300) suggests inner to outer sublittoral for the Redding area shale members. The same depositional environment existed in the Chico Creek area according to Saul (1959) who studied the molluscan assemblage.

The G zone strata contain heavy minerals indicative of the Sierran belt, pointing to an eastern or southeastern source. Andalusite and staurolite first appear, and garnet tourmaline become common (one grain in 30-50) in the Funks, Guinda, and Forbes formations in the Vaca Mountains (Day, 1948). This eastern source is in accord with the chronolgy established by Curtis and others (1957) who indicate emplacement of the Santa Lucian batholiths in the High Sierras at the approximate G zone absolute time interval. Also the presence of an eastern shoreline is demonstrated by the lithology and fauna of the Redding and Chico Creek areas.

GEOLOGIC HISTORY

Figures 7 and 8 show: 1) the combined Upper Jurassic-Lower Cretaceous isopach, 2)) the combined Upper Cretaceous isopach, 3) the total late Mesozoic isopach, and 4) the eastern subsurface limits of definitive rock units. During the late Mesozoic the Sacramento Valley received a nearly continuous succession of marine sediments totaling 60,000 feet along its western margin. Simultaneously there was a progressive eastward overlap. Subsequent Late Cretaceous sedimentation (C,D, and E zones) was regressive in the Sacramento Valley, and marine seas never again extend as far to the east or north as during G and F zone time.

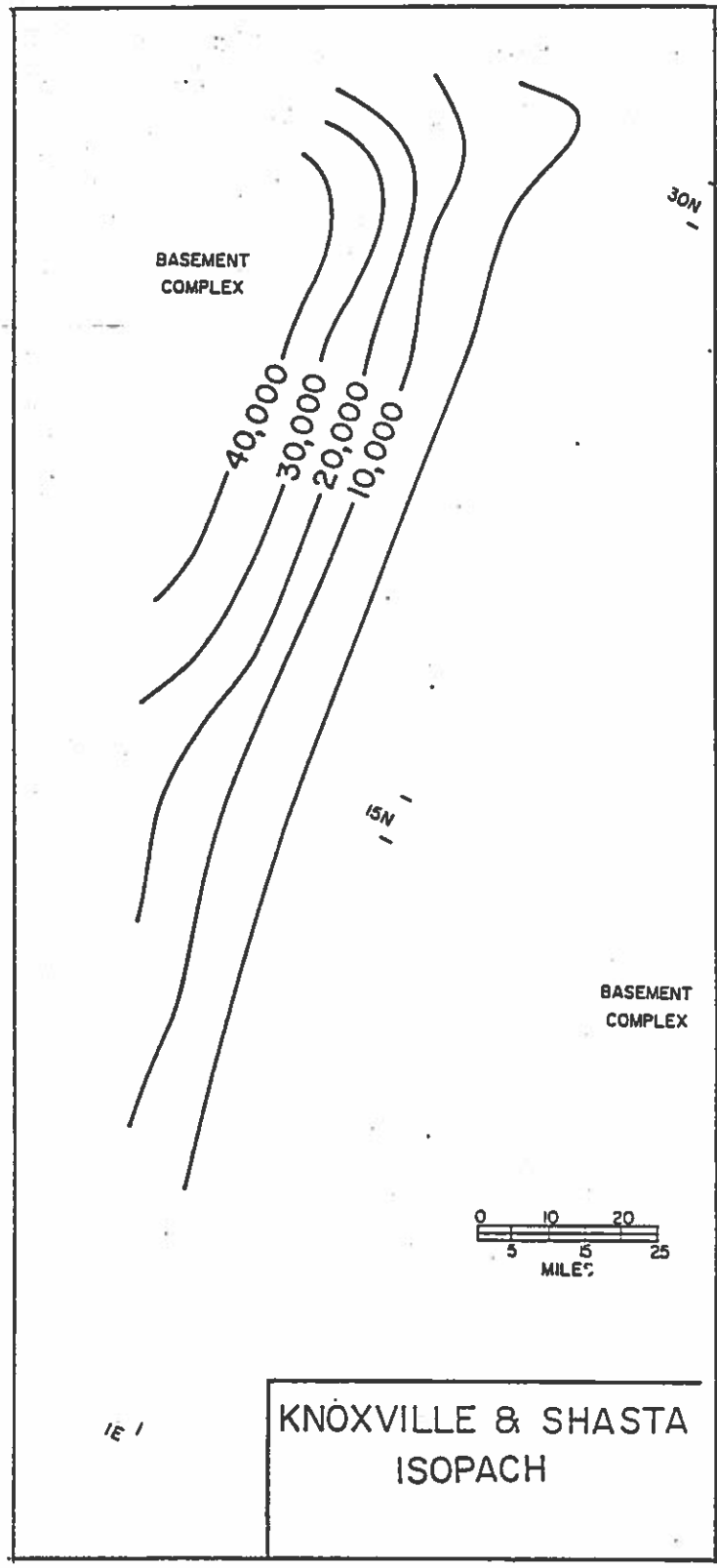
Upper Jurassic

"Knoxville" beds aggregating more than 20,000 feet were laid down in the trough formed as a result of the Nevadan orogeny. Postorogenic granitic intrusions took place in the Klamath mountains and northern Sierras contemporaneous with Late Jurassic deposition. Cool, deep water, marine conditions prevailed in all but the shelf areas, but shoaling occured near the end of the period. Possibly a special or unique environment caused the predominance of an essentially one-element (Buchia) fauna. The major source area was to the north and northeast.

Lower Cretaceous

The earliest Lower Cretaceous beds contain evidence of shallow marine conditions. Uplift and erosion or nondeposition is suggested by the missing Berriasian age fossils. This may have been the result of a late intrusive phase of the Nevadan orogeny in the Klamath Mountains and northern Sierras. Deep water conditions returned and subsequent Lower Cretaceous seas transgressed eastward.

Lower Cretaceous conglomerates contain a more diverse suite of rock types than those of the Late Jurassic, suggesting that erosion had penetrated deep into the provenant area to the north or northeast. As much as 15,000 feet of Lower Cretaceous sediments were laid down in the Sacramento basin. The sparse fauna and predominant fine grained lithology indicate an outer shelf depositional environment during most of Early Cretaceous time.



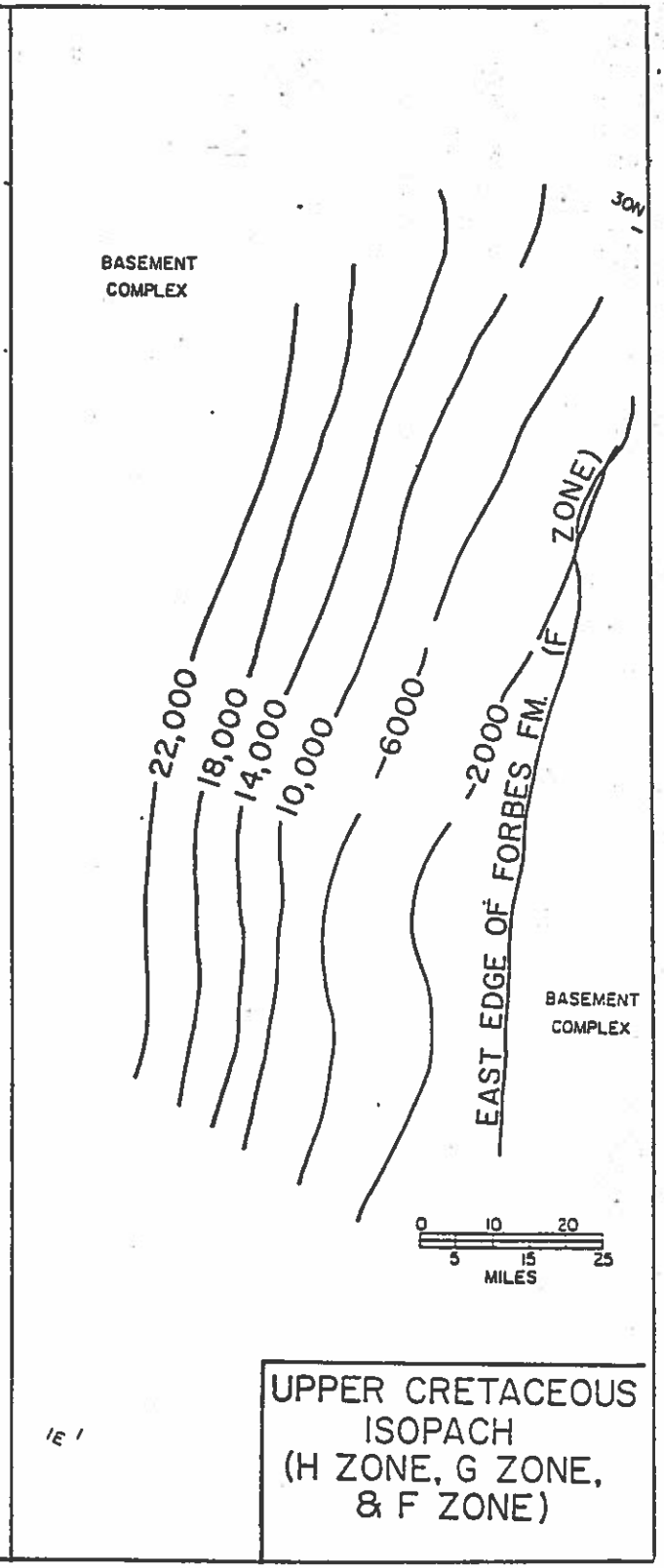


FIG. 7a. Combined Upper Jurassic and Lower Cretaceous Isopach map.

FIG. 7b. Combined Upper Cretaceous Isopach map, including H zone, G zone, and F zone.

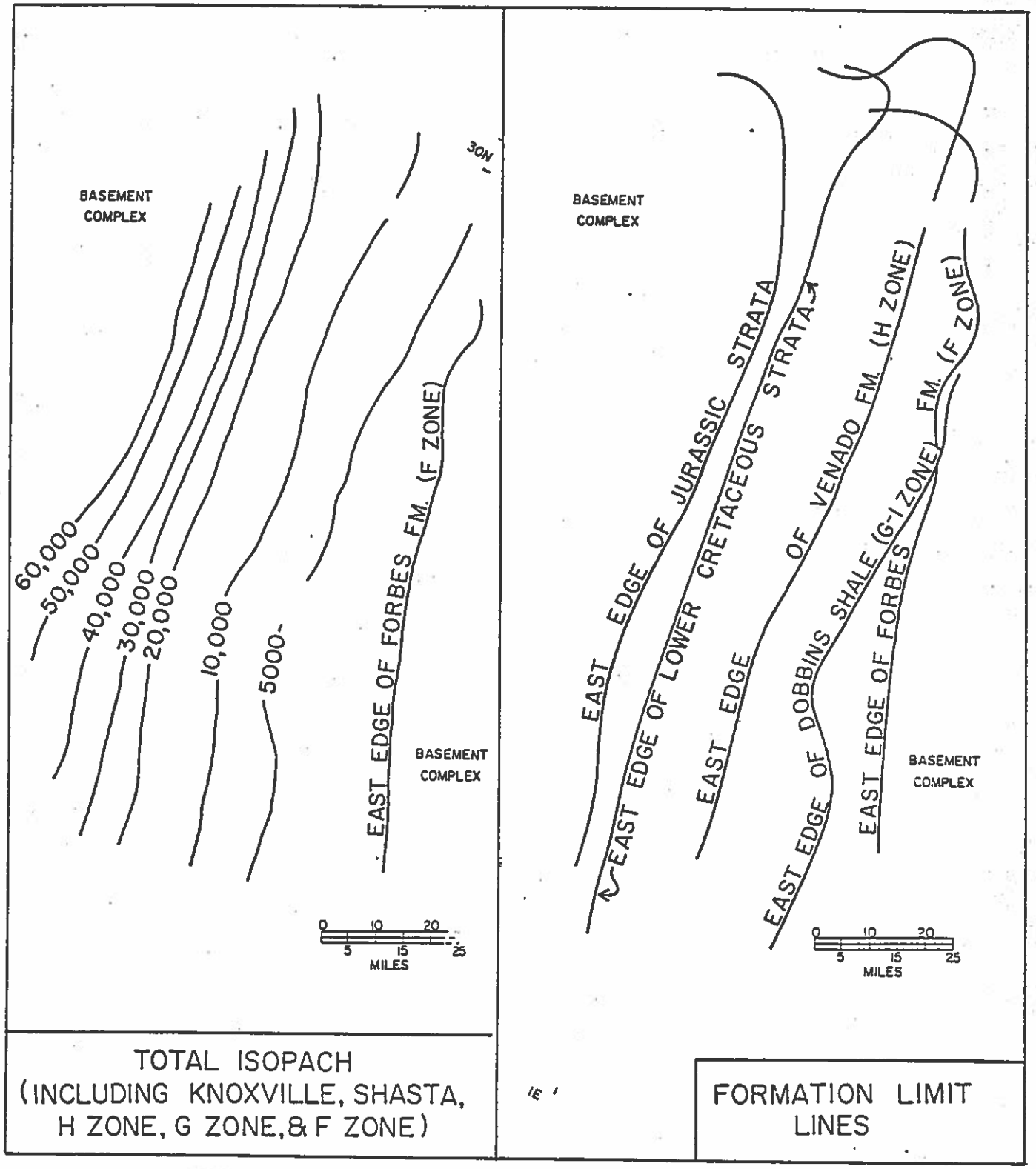


FIG. 8a. Total late Mesozoic isopach map including Upper Jurassic, Lower Cretaceous, and Upper Cretaceous.

FIG. 8b. Subsurface formation limit lines.

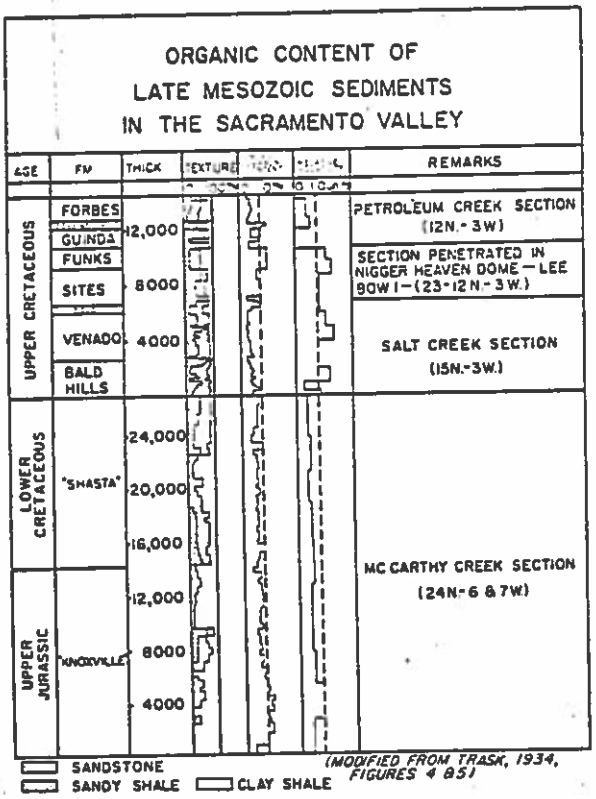


FIG. 9. Texture, organic carbon contents and relative volatility of late Mesozoic sediments in the Sacramento Valley.

Upper Cretaceous H Zone

Near the beginning of Late Cretaceous time a second period of uplift occurred. It caused withdrawal of the seas in some areas and the deposition of conglomerates and coarse sands in the H zone section. This uplift represents the first pulse of regional metamorphism and granitic emplacement in the High Sierras during the Santa Lucian orogeny. Shallow water conditions in some areas allowed the growth of Rudistids, possibly in clear, warm seas. Erosion of Lower Cretaceous beds probably took place east of present outcrop areas and caused the reworking of Albian fossils into Cenomanian strata. Renewed submergence was again interrupted regionally by tectonic uplift to the east, causing widespread slumps and conglomerate deposition at the base of the Venado formation. These events probably reflect another pulse of the Santa Lucian orogeny, possibly one accompanied by additional granitic intrusion. Subsequently, eastward transgression took place and Venado sandstones overlapped all older rocks to rest on basement in a wide area of the central Sacramento Valley. Maximum H zone thickness reaches nearly 10,000 feet in the west side outcrops.

Upper Cretaceous G Zone

Marine seas continued to advance easterly on the Sierran landmass, overlapping the eastern edge of H zone sediments. Except along the eastern shoreline, the indicated depositional environment was cool and deep. Shoaling, or rejuvenation in the eastern source area may have occurred twice because the Sites and Guinda formations contain fine- to medium-grained sandstones. The adjacent rock units (Yolo, Funks and "Dobbins Shale" formations) are predominantly siltstone and mudstone. More than 6000 feet of G zone beds were laid down on the west side of the Valley. Some of these are represented by a thin, near-shore facies exposed along Chico Creek. Heavy mineral analysis of the G zone strata indicate a Sierran metamorphic suite.

There is good evidence for an unconformity between F zone and G zone sediments, especially in the northern, central, and eastern subsurface parts of the basin.

Post G Zone

Although the F zone overlaps the G zone from Chico Creek southward, the scattered surface and subsurface control shows an offlap relationship to the north. These conflicting events can be explained by the unconformity between the F and G zones. There may have been withdrawal of the seas after the late G zone time and either non-deposition of, or erosion by, the lower F zone before transgression began again. The early F zone transgression was shortlived and, in some areas, did not reach the eastern limit of previous G zone seas. Subsequently a gradual withdrawal of marine seas began in late F zone time and continued until the end of the Cretaceous.

Although there were marine invasions during the Tertiary, none of them covered as extensive an area as those of the Late Cretaceous.

HYDROCARBON POTENTIAL

Source Beds

Figure 9 is modified from Trask's study on source beds in the Mesozoic rocks of the Sacramento Valley (1934, figs. 4 and 5). Significantly, Trask concluded that almost any part of the late Mesozoic section, excepting some of the sandy intervals, offered the same possibilities as source beds as any other part.

Since 1934 gas in substantial amounts has been discovered in Upper Cretaceous beds. Following Trask's line of reasoning one can postulate that similar economic deposits could occur in older sediments provided adequate reservoir rocks and suitable traps can be located.

Seeps

Considering the great thickness of late Mesozoic sediments with hydrocarbon generating capacity, the paucity of oil seeps is anomalous. It is not surprising to note a lack of gas seeps, for without a water media to pass through and be observed, gas from outcrops is impossible to detect. Carlson (1962, p. 25) and Lachenbruch (1962, in text) recently have compiled data on the location and age of beds containing the seeps. One additional is added: numerous gas seeps occur in fractured Upper Jurassic mudstones along the south fork of Elk Creek in sec. 13, T. 20 N., R. 7 W. The

following summary shows in a general way that each part of the stratigraphic column has generated hydrocarbons:

Upper Jurassic	Lower Cretaceous	Cenomanian	G zone & younger
3 oil	2 oil	2 oil	2 oil
1 gas		4 gas	5 gas

Reservoir Rocks

Generally speaking, compared to the older sandstones, the younger contain higher porosity and permeability. However, sandstones capable of producing hydrocarbons (especially gas) occur in every part of the exposed sedimentary column in limited thickness. Since the presence of eastern shorelines has been adequatly demonstrated, it is not difficult to visualize a higher proportion of clean sandstones in the subsurface eastward from the outcrops.

CONCLUSIONS

Isopach maps of the different time-rock units show that the Sacramento basin was formed in the Late Jurassic and received deposition of marine sediments totaling 60,000 feet until the end of the Cretaceous. There was onlap eastward toward the Sierran landmass from which most of the sediments were derived. Although almost continuous sedimentation occurred along the western margin of the Valley, widespread uplift and erosion took place on the eastern shelf during the Late Jurassic and Early Cretaceous, and periodically in early Late Cretaceous time.

The overall lithologic similarity of the late Mesozoic section suggests that the environment remained almost constant during its deposition. Turbidites abound in the strata. This, combined with a dearth of fossils, implies accumulation along the outer shelf or upper slope (lower neritic or upper bathyal) below the reach of waves and bottom currents.

Based on the presence of thick sourcebeds and potential reservior rocks, the pre-Upper Cretaceous section offers good possibilities for large hydrocarbon reserves. These will be expensive to locate, drill and complete; therefore, economics will play an important role in their exploration.

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STRATIGRAPHY OF THE LATE UPPER CRETACEOUS IN THE SACRAMENTO VALLEY [1]

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Abstract

Except for a lower member, which is essentially parallel to the underlying Dobbins Shale, the F Zone section was deposited with progressive eastward onlap onto older formations and basement. The Kione Sands and the accompanying E′ fauna are a shallow water facies of the F Zone. Sand development elsewhere in the F Zone is characterized by rapid facies changes which account for considerable stratigraphic gas accumlation. The Sacramento Shale and the Winters formation were deposited above the F Zone without any break in sedimentation. Deposition of the Winters formation closed with a transgression of the sea followed by a series of regressions and transgressions which resulted in deposition of seven regressive sand bodies which are the Starkey Sands, the youngest Upper Cretaceous formation in the Sacramento Valley.

Introduction

During the late Mesozoic an extensive series of Upper Jurassic and Cretaceous marine formations were deposited in a rapidly subsiding geosynclinal basin in northern and central California. To date only the late Upper Cretaceous formations have yielded hydrocarbons, all natural gas, in significant commercial quantities. This paper will be limited in scope to the occurrence of these late Upper Cretaceous formations in the Sacramento Valley. These formations have limited surface outcrop and this paper is based almost entirely on subsurface well data. In age they embrace the Campanian and Maestrichtian European stages. The Mount Diablo base and meridian are used for the geographical frame or reference.

F Zone

F Zone Deposition: The name F Zone as used in this paper includes formations commonly referred to as the Forbes Shale, Kione Sands, and Wild Goose sands. The F Zone unconformably overlies the Dobbins Shale (sometimes called "G" Shale) and is conformably overlain by the Sacramento Shale. Its present surface and subsurface extent is shown in Figure 1. The eastern limit very nearly coincides with the original limit of deposition; the western limit is that of surface outcrop and truncation by Tertiary formations. The original northern limit was probably between the present occurrence and basement outcrop. The original F Zone basin as well as present occurrence extends far south of the area shown in Figure 1.

Isopachs of the total F Zone deposited are shown in Figure 2. Reconstructed isopachs, shown by dashed lines, are used in the northern part of the valley where the upper portion has been eroded off. The westward swing of the isopachs to the south is the expression of a gentle high which formed during the early portion of F Zone deposition. This does not represent a southern limit to the basin since this trend reverses further south where thick sections are again encountered.

Lower Member of the F Zone: In the Colusa Basin area (approximately T 12N to T 15N and R 2 W to R 1 E) the F Zone has a lower member which is about 800 feet thick that is not present at Beehive Bend and northward. This unit has not been recognized (possibly because of insufficient well control) south of T 12 N. A minor unconformity exists between it and the underlying Dobbins Shale though there is no significant onlap except near the 4500 foot F Zone isopach (Fig. 2) where it goes out to the east, primarily by onlap onto the Dobbins Shale. This lower member has an F-2 fauna that locally shows some G-1 zone affinities. Sand development is generally poor but at Grimes there is good sand development and several gas wells have been completed from these sands. This lower member is separated from the rest of the F Zone by an unconformity.

The rapid eastward loss of F Zone section is due to onlap at its base onto the Dobbins Shale and onto basement further east. In areas where the lower member of the F Zone is present this onlap occurs at the unconformity which separates the bulk of the F Zone (Fig. 4) from its lower member.

Figure 3 shows an area where there is little significant onlap of the F Zone onto the Dobbins Shale and where these two formations would appear conformable. This area extends from T 18 N to near Red Bluff. Horizons which overlie the Dobbins Shale throughout this area of no significant onlap are at about the same stratigraphic level as those at Grimes which overlie the lower member (Fig. 4) of the F Zone at a reduced rate of onlap.

Faunal Zones: There are three fauna zonules within the F Zone, namely Goudkoff's E′, F′-1 and F-2. Relationship of these zonules to each other is shown in

1. Presented before the San Joaquin Geological Society, Dec. 12, 1961.

2. Consulting Geologist. Partner, Reynolds and Edmondson.

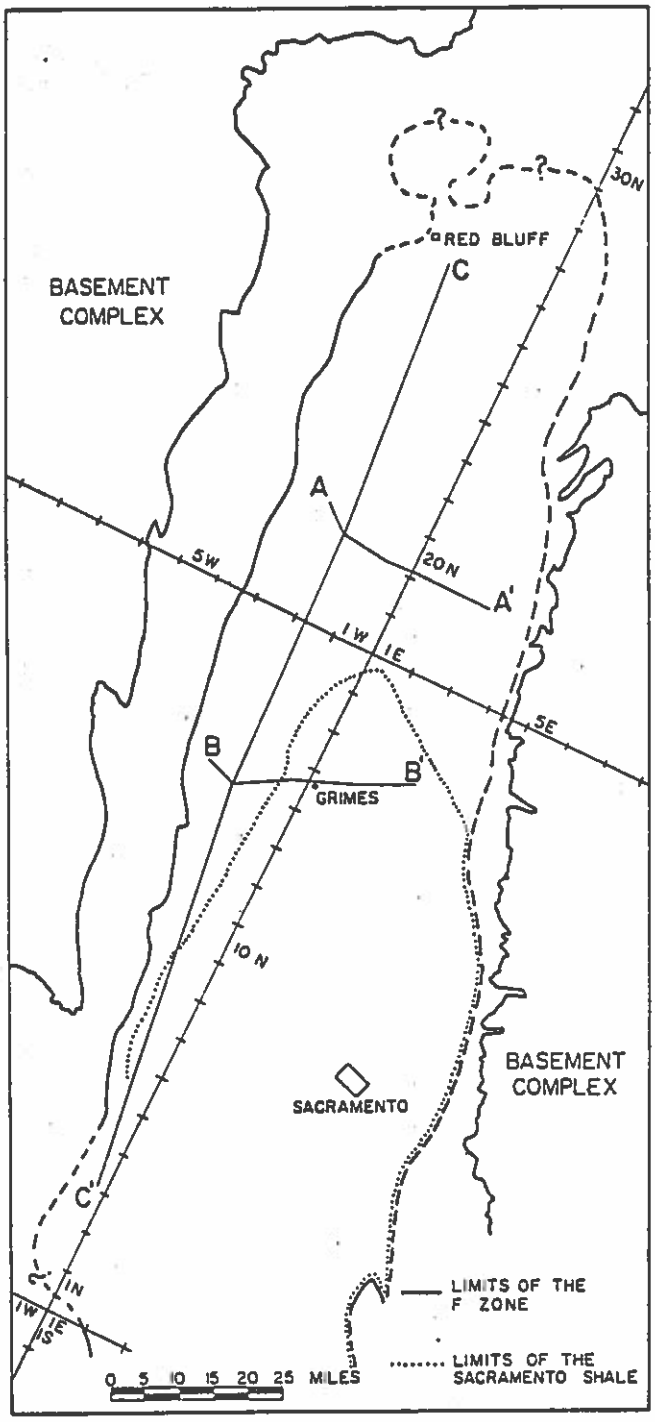

FIG. 1. Present extent of Zone and Sacramento Shale.

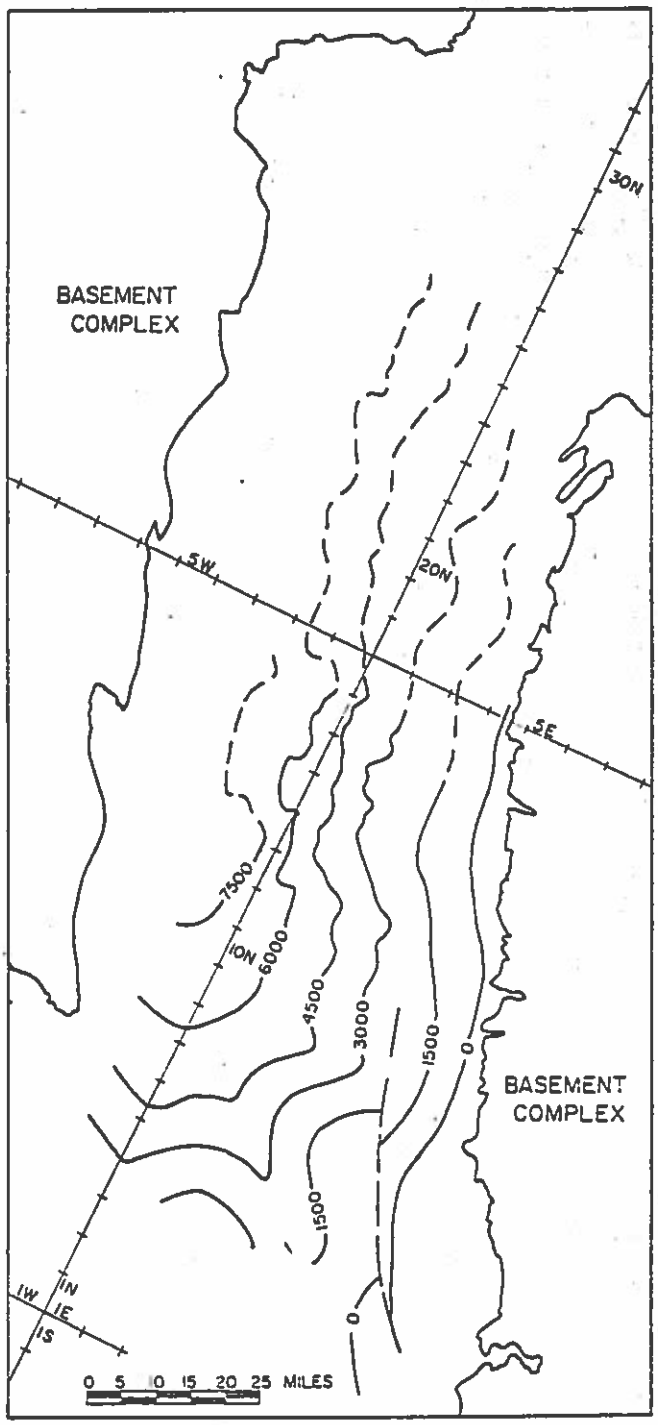

FIG. 2. Isopach of toal F Zone.

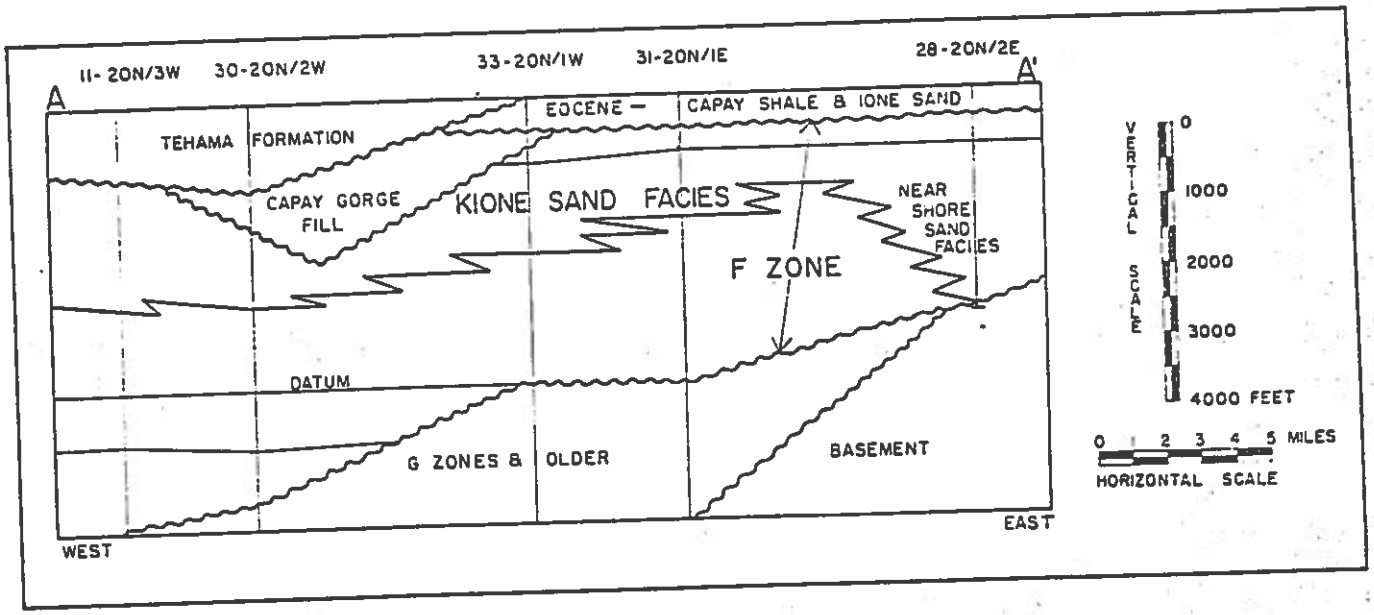

FIG. 3. Correlation Section A-A'

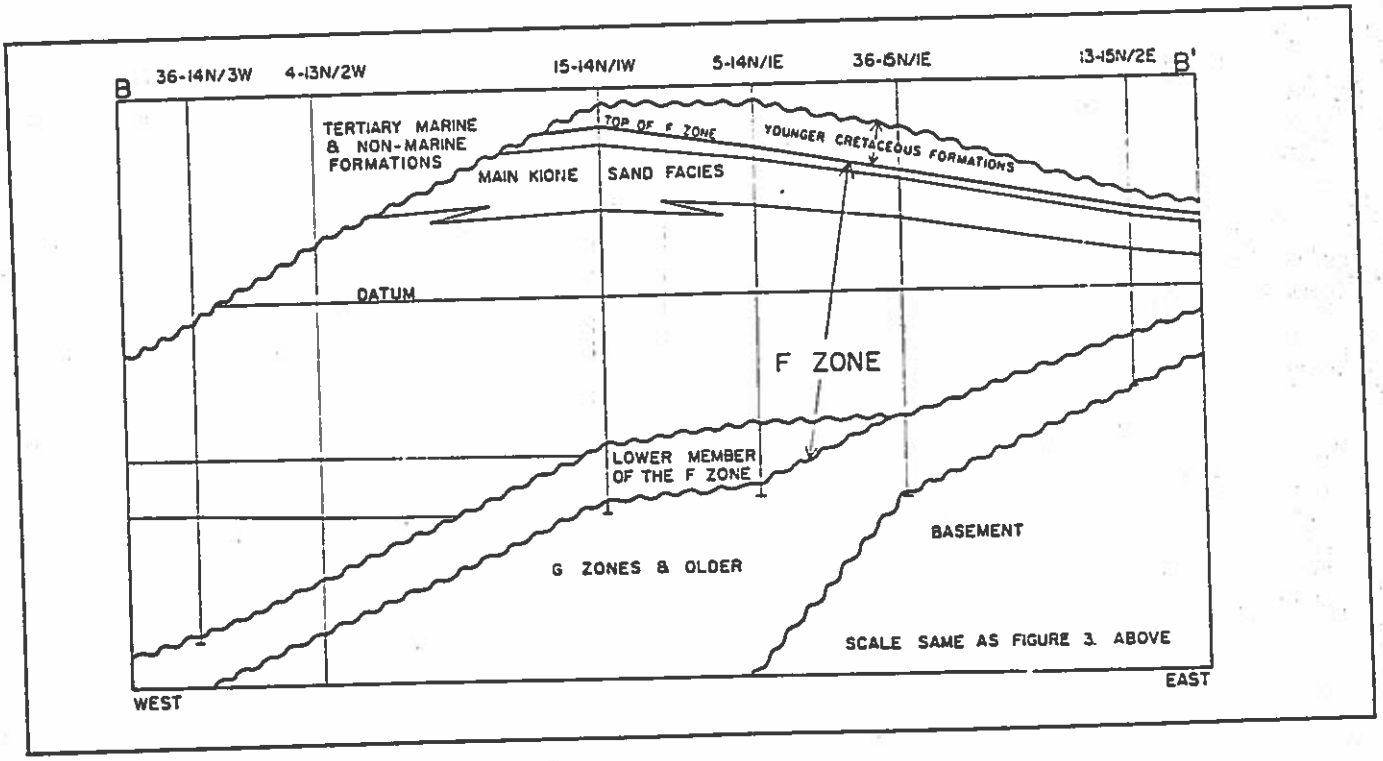

FIG. 4. Correlation Section B-B'

Figure 5 with the left side representing the section in the northern part of the valley and the right side the southern end. These are facies fauna and all three existed simultaneously in environmentally different areas of the basin during the most of F Zone time.

Original desingation of the fauna associated with the Kione Sands as a facies of the E zone was an error. Subsurface control proves it must be a facies of the F zone. The fauna is meager and bears at lea as much similarity to the F zone fauna as to the zone fauna. The faunal differences between F'-1 a F-2 are not too great and it is often difficult for t paleontologist to differentiate the two.

Figure 6 shows correlation section C-C' whose li of section is taken well out into the basin but paral to the eastern margin. The high shown at Potre

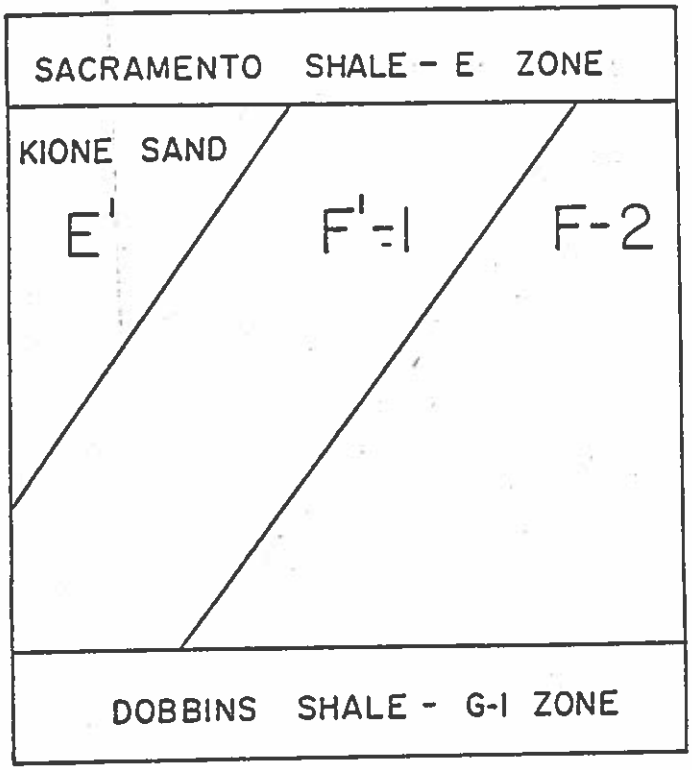

FIG. 5. F Zone Faunal Relationships.

Hills (T 4 N/R 1 W) did not come into existence until F Zone time. This section shows rapid crossing of time lines by faunal contacts with no F-2 fauna at the north and no F'-1 fauna to the south. The first occurrence of F-2 fauna has a vertical stratigraphic range in excess of 6000 feet. The general parallelism of the E' to F'-1 contact and the F'-1 to F-2 contact is most striking. The rate of onlap against the high at Potrero Hills is only 145 feet per mile which makes the initial northward dip of this high no greater than 1½ degrees. Position of faunal contracts and their migration through the section have real significance with respect to depositional environment and basin development.

Kione Sands: The Kione Sands are a shallow water facies of the F Zone. Unlike sands within the Forbes Shale these sands are easily correlated. In places they show characteristics of deltaic deposition but to call the whole Kione development a deltaic deposit would be erroneous. Locally these sands are lignitic suggesting possible lagoonal environment. Significantly the lignitic sections, when present, are at the top of the preserved section. The dominant direction of facies change is from north to south rather than east to west. Detailed examination of the Kione's distribution and thickness reveals probable source areas to the east as well as to the north. Relationship of the Kione to the underlying Forbes Shale is not completely clear though two generalities seem to apply. First, the Kione developes deeper into the section where the contact is a facies change as in the Beehive Bend area. Second, the base of the Kione is higher in the section where much of the thinning occurs within the Kione itself and not by facies change. Locally an unconformity has been noted at the base of the Kione with best development near Grimes.

Basin Development: The break between the Dobbins Shale and the lower member of the F Zone probably represents little more than a regression of the sea, with deposition of the lower member of the F Zone being restricted to what was probably then the deepest portion of the basin. Relatively sudden westward tilting and downwarping beginning far out in the basin brought a close to deposition of the lower member of the F Zone and initiated deposition of the main portion of the F Zone. At least 7000 feet of section were then deposited with gradual eastward onlap onto older formations and finally onto basement. The relatively minor amount of erosion noted beneath this surface of onlap suggests that the sea may have remained over previously deposited formations throughout most of F Zone time. Local unconformities are noted within the F Zone but none other than those mentioned are of any significance.

The author's concept of basin conditions as they existed towards the latter part of F Zone time are shown by Figure 7. Three significant features are shown: (1) There was a gentle southward tilt at less than ½ degree. If this southward tilt were ½ degree the water depth at the southern end would be 2500 feet, a depth greater than that believed to have existed. (2) There was progressive southward regression of the sea with possible emergence of the northern end of the valley above sea level. (3) The faunal zones were controlled by depth of deposition. The E' fauna were deposited above depth A, F'-1 fauna between depths A and B, and F-2 fauna below depth B. This together with the southward regression of the sea produced the crossing of time lines by faunal contacts. Though depth is certainly not the only factor which might control faunal occurrences many other controlling factors are related to depth.

Near the end of F Zone deposition some minor northward tilting took place in the Grimes-Marysville Buttes area. The base of the Afton shale is believed to be the surface along which minor onlap accompanying this tilting occurs. Above this horizon the Kione Sands begin to show some transgressive characteristics and the close of F Zone deposition witnesses a transgression of the sea and a return to conditions so similar to those under which the Dobbins Shale was deposited that some faunal elements of the Dobbins Shale recur in the Sacramento Shale.

Summarizing basin development during F Zone time there were these major changes: (1) A minor regression of the sea followed by deposition of the lower member of the F Zone. (2) Downwarping beginning far out in the basin accompanied by some westward tilting, followed by deposition of the remainder of the F Zone. (3) Gentle southward tilting. (4) Regression of the sea to the south. (5) Transgression of the sea at the close of F Zone time with a deepening of the entire basin.

F Zone Sands: Sands within the F Zone, other than the Kione facies, are somewhat irregular in their distrubtion. These sands normally comprise less than 20 per cent of the section, and the 800 feet of section below the Kione is usually devoid of sand except locally in the Marysville Buttes area. Facies changes are rapid though little change in gross interval thickness accompanies these changes. Two primary cur-

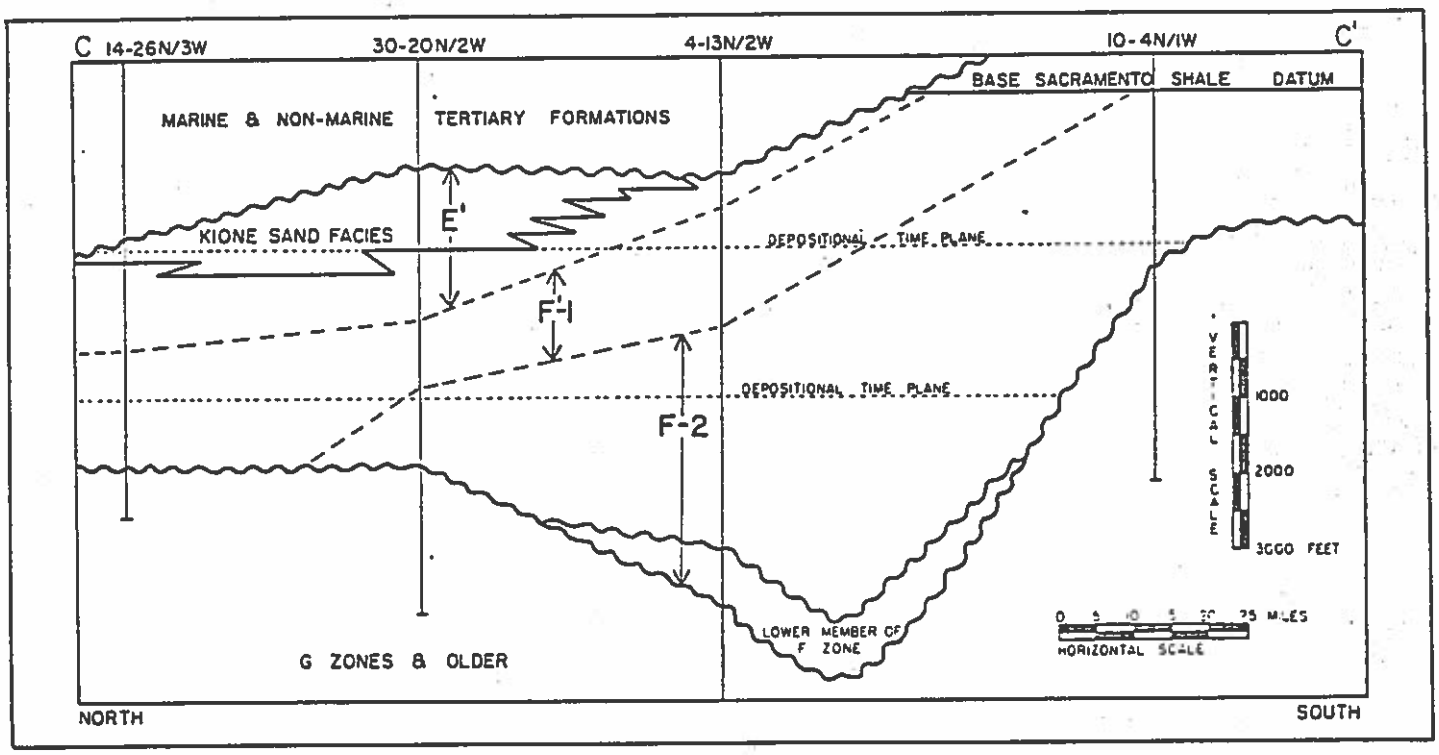

FIG. 6. Correlation Section C-C'.

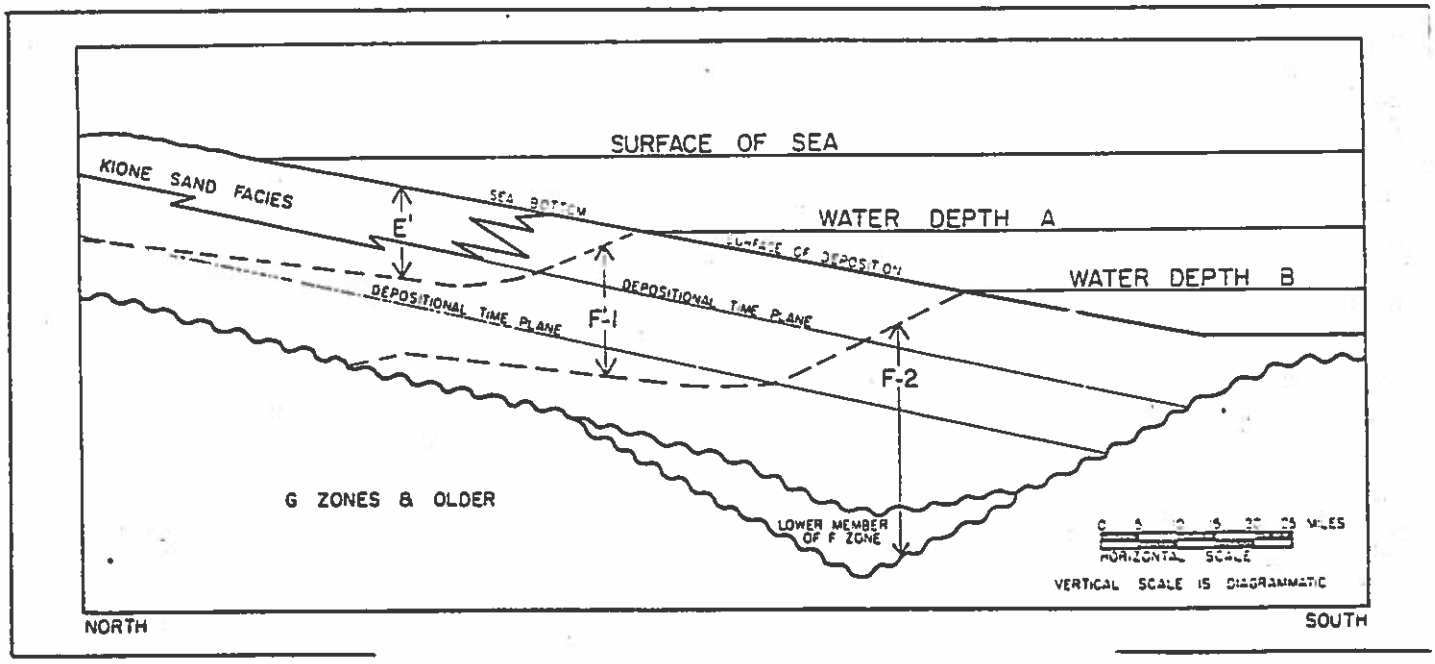

FIG. 7 Diagrammatic section along line of Section C-C' showing depositional conditions during latter part of F zone tim

rent vectors were responsible for sand distribution in the F Zone, one being the southerly along-shore current in the east portion of th basin, the other being westerly currents induced by rivers to the east feeding sediments onto the west sloping basin floor. Velocity changes in these currents were responsible for the pattern of sand distribution and localized the accumulation of sand. Basin floor topography and depth were primary factors affecting velocity changes.

A major sand source was from the north as evidenced by the greater sand percentages and less rapid facies change in the north end of the basin. Typical easterly sand sources are identified by the higher sand percentages at Beehive Bend and eastward, and at Arbuckle eastward through the Colusa Basin. The southerly current component is best exhibited in the distribution of sand from north of Kirkwood to Beehive Bend, to West Butte, to East Grimes. The westerly currents have been found to be most persistent throughout F Zone time.

Turbidite sands have been reported in the F Zone at Putah Creek (T 8 N/R 2 W). It is possible that some of the more westerly sands in the F Zone which had deeper environments of deposition may be at least in part turbidite deposits.

Gas Production: Production from the Kione Sands comes from conventional traps such as anticlinal closure, faulted structures, and well defined stratigraphic traps. Gas reserves of about 350 million MCF have been developed to date from the Kione Sands. Production from the F Zone sands, on the other hand, is due to stratigraphic and fault-stratigraphic entrapment except at Arbuckle and possibly some minor accumulations where the traps are primarily structural. Gas field development during the last three years has shown that structural position is of minor importance towards localizing F Zone stratigraphic accumulations. The best production is found in areas of greater than average sand accumulation and more rapid facies changes. Within any segment of the F Zone the following factors are considered important in localizing sand accumulation and gas production: (1) Distance from zero line of deposition. (2) Depth of deposition. (3) Location of offshore tributary rivers. (4) Basin relief. (5) Initial folding.

Present development of reserves is expanding rapidly and the proved reserves of the F Zone, exclusive of the Kione facies, now exceed 1500 million MCF which makes this the major Upper Cretaceous producing formation in the Sacramento Valley.

Sacramento Shale

The Sacramento Shale, whose limits are shown on Figure 1, is only about 200 to 400 feet thick and it carries the fauna of Goudkoff's E Zone. In the southwestern part of the Sacramento Valley this formation has a horizon which contains recurrent faunal elements of the Dobbins Shale. Disappearance of this recurrent horizon to the north indicates that the basin was deeper to the south. Because the basin was deeper to the south depositional conditions which produced the Sacramento Shale came into being slightly earlier than they did further north and as a result this formation is generally thicker to the south. The top of the Sacramento Shale is typified by an electric log characteristic called "the neck", caused by an increase in resistivity higher in section which is a reflection of siltier deposits resulting from a regression of the sea. This regression affected the entire basin at about the same time.

Winters Formation

The northern, western, and eastern extent of the Winters formation (Fig. 8) is for the most part limited because of truncation by younger formations. The Winters formation extends southward into the northern San Joaquin Valley where it has similar thickness and fauna. In the Sacramento Valley it attains a thickness of more than 2500 feet and, except for the uppermost and lowermost portions, is dominantly sand. This sand goes to shale to the east and north and to a lesser extent to the west. One might assume from Figure 10 that following deposition of the Winters formation there was a major uplift and considerable erosion prior to deposition of the overlying Starkey Sands. There are several serious objections to this assumption and the following sequence of events is offered as a more probable explanation.

Deposition of the Sacramento Shale came to a halt because of a shallowing of the basin and was immediately followed by deposition of the Winters formation with no break in sedimentation. Deposition of the Winters formation was accompanied by a continual regression of the sea and a consequent reduction in the size of the basin. The original limit for any given horizon in the Winters formation may be no more than a few miles beyond the line of truncation by the overlying Starkey Sands. The unconformity near the top of the Winters formation represents a period of non-deposition with only a relatively minor amount of erosion taking place. This regression did not continue to the point of disappearance of the basin and in the central portion of the basin there is no break in sedimentation between the Winters and the Starkey.

The basal Starkey Sand member extends beyond almost all horizons of the Winters formation and begins with a regressive cycle. This forces the conclusion that the Winters closed with a rapid transgression of the sea with deposition extending over a much broader area. An unconformity (Fig. 10) is at the base of the first sediments deposited following this transgression and is estimated to be 50 to 250 feet beneath the base of the Starkey Sands. This lower position of the unconformity (it has been placed by some at the very base of the Starkey Sands) has only locally been recognized on the basis of electric log correlations.

An unusual feature of the Winters formation is the fact that near the eastern limit of the basin the formation is shale with the sand occuring further out in the basin. It is certainly likely that a near shore sandy facies did exist but was removed by erosion following regression of the sea and prior to the transgression that preceded deposition of the Starkey Sands.

In the Rio Vista area (T4N/R3E) and north the sands have sharp contacts with the relatively few shale breaks and some sand bodies are several hundred feet thick with little shale or silty development. South of Rio Vista, in the Lathrop-East Stockton area, these sands become less massive with numerous shale breaks

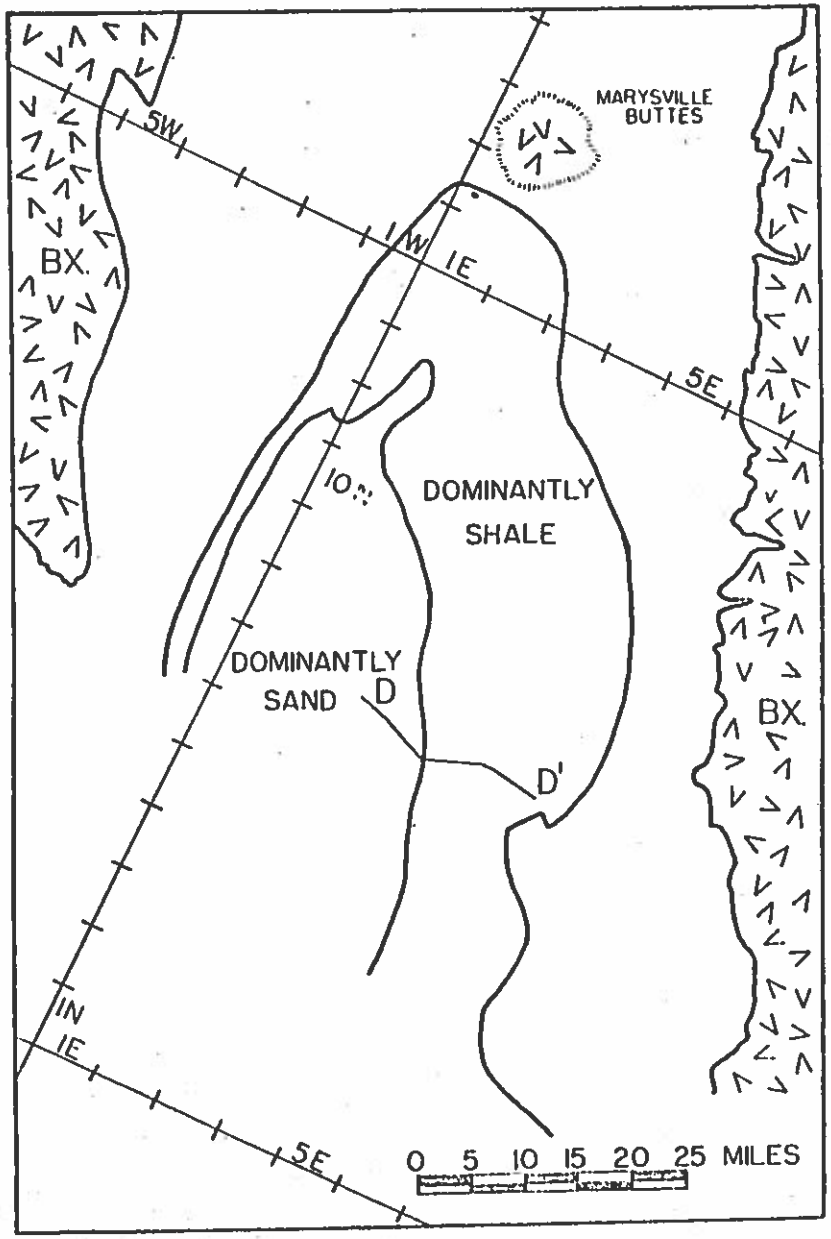

FIG. 8. Present extent of the Winters formation.

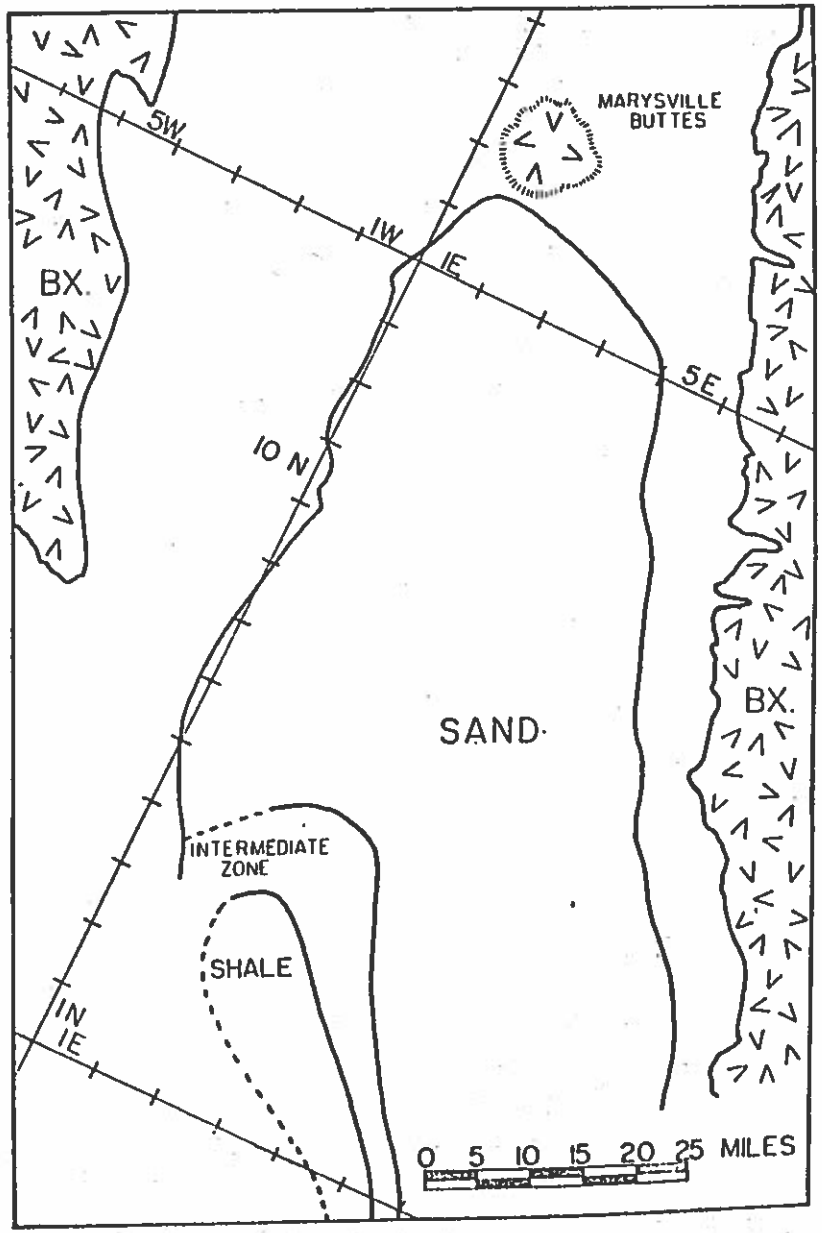

FIG. 9. Present extent of the Starkey Sands.

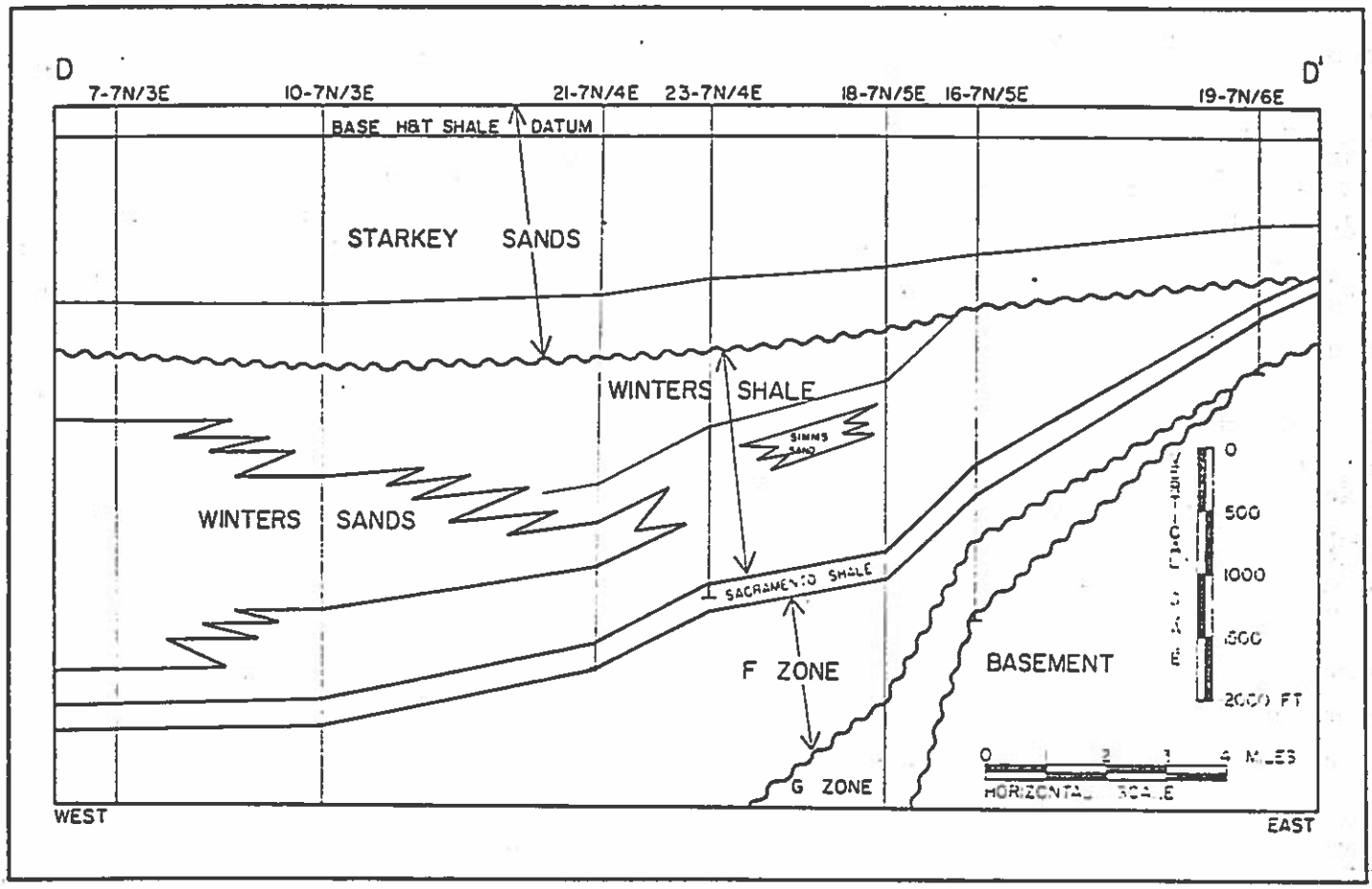

FIG. 10. Correlation Section D-D'

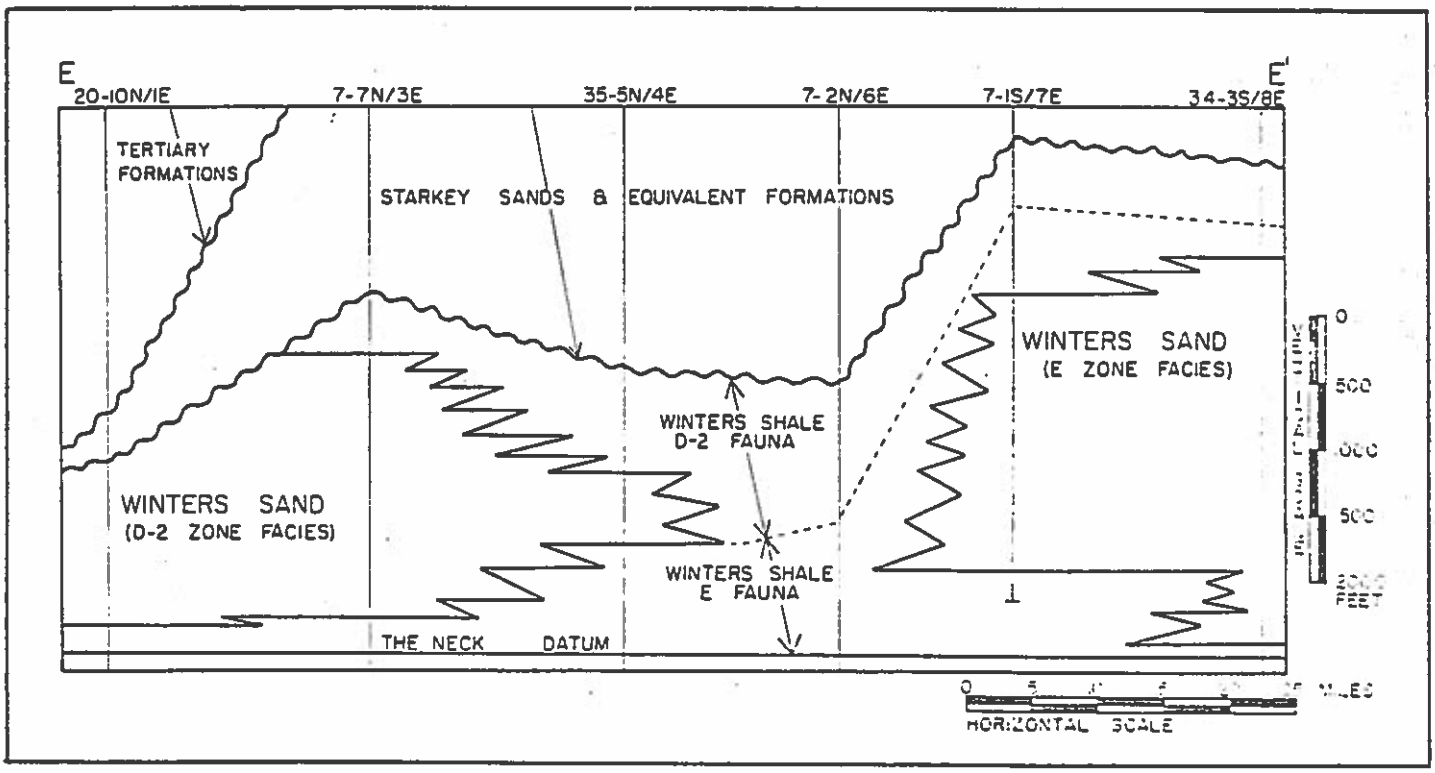

FIG. 11. Correlation section E-E'

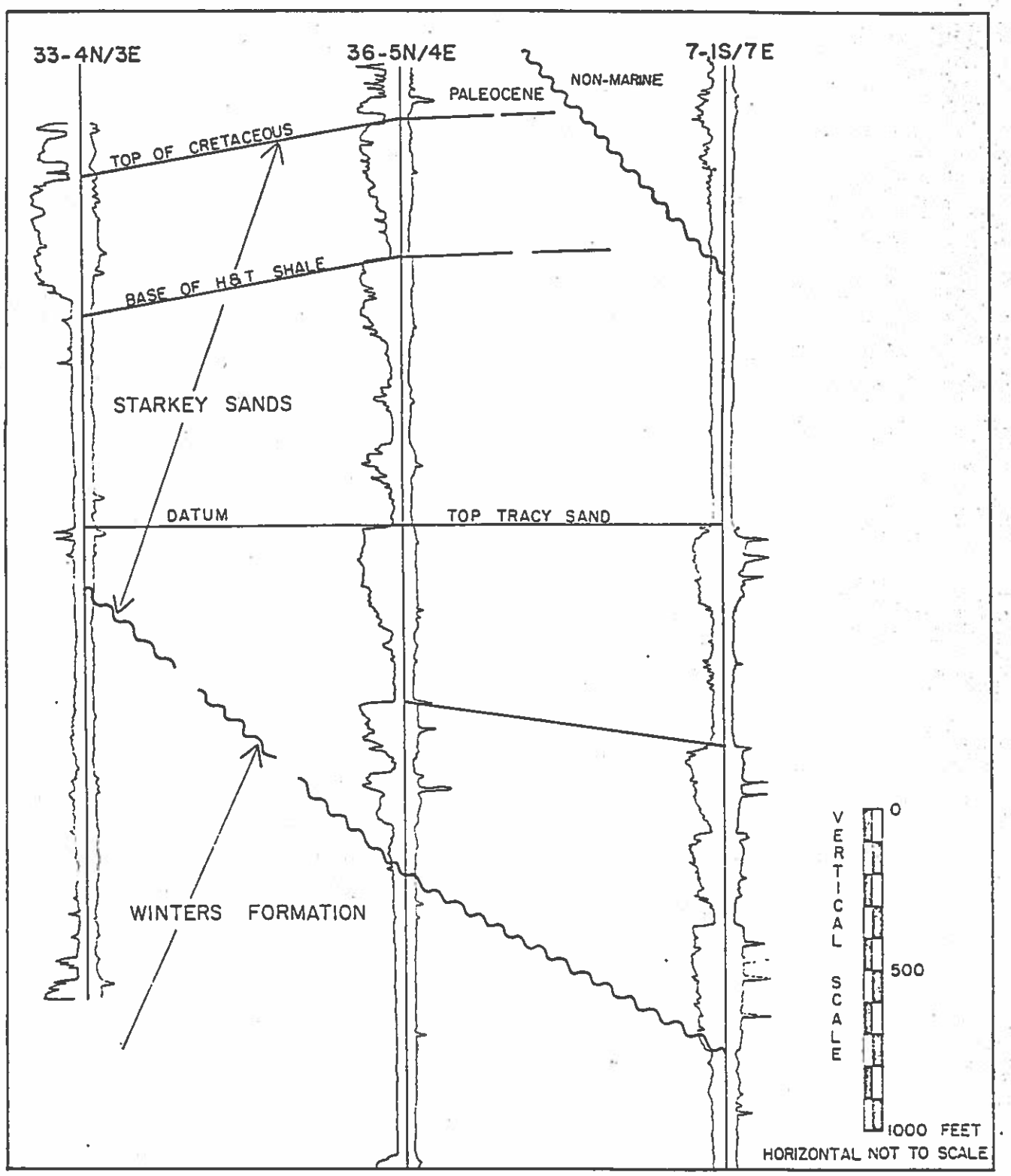

FIG. 12. Correlation Section F-F'

and silty facies and more rapid facies change within the area of sand development. Further south, at Modesto and Vernalis, these sands again become more massive.

Winters Environment: The Winters formation contains the fauna of Goudkoff's D-2 and E zones. In the Sacramento Valley the first E fauna is usually found below the sand development near the base of the formation but in the northern San Joaquin Valley the first E fauna is found above the sand development (Fig. 11) near the top of the formation. These two sand facies and the associated fauna are time equivalents which had different environments of deposition. These two facies merge south of Rio Vista where little data on this formation is available. The shale shown between the two sands on Figure 11 is in large part the result of the line of section used and should not be taken to imply that these two sands are everywhere separated by a shale barrier. A difference in depth of deposition could be an explanation for the different facies though other factors are more likely responsible for the different environments that produced these facies.

Limited data indicates maximum thickness for this formation along a line from Winters (T 8 N/R 1 E) to Lathrop (T 1 S/R 6 E) and this approximates the center of the depositional basin. This basin was certainly bounded by land to the east and northeast and probably to the west and northwest also. Connection to the open sea was either at the southern end of the basin or more likely at some break along the western limits of the basin. It is possible that this connecting channel to the sea may have been southwest of Rio Vista and that the two facies of the Winters sands are a reflection of one being north and the other south of the latitude of this channel.

Winters Production: This formation is productive in five gas fields in the Sacramento Valley with total initial gas reserves of about 160 million MCF. The only oil well of significance in the Sacramento Valley produces from this formation in the Winters field where efforts to extend this production have not yet been successful. During 1961 a major discovery was made at Lathrop from the southern facies of the Winters sand. The trap at Lathrop is structural and individual wells have encountered up to 500 feet of gas sand.

Starkey Sands

The name Starkey Sands as used in this paper includes the Starkey Sands, the H & T Shale and the regressive sand body above the H & T Shale. This is the youngest Upper Cretaceous formation in the Sacramento Valley; its present extent is shown in Figure 9. The occurrence of this formation in the northern San Joaquin Valley is extensive though many stratigraphic, depositional, and environmental changes are encountered that will not be discussed in this paper.

Figure 12 shows correlation of the Starkey Sands. The bottom three regressive sands of the Starkey correlate to the Tracy Sand of the northern San Joaquin Valley, the three regressive sands below the H & T Shale and the H & T Shale occupy that portion of the section occupied by the Blewett and Azevedo Sands and the Moreno Shale; and the regressive sand body above the H & T Shale correlates to the Garzas Sand.

The Starkey Sands contain the fauna of Goudkoff's C, D-1, and D-2 zones though faunal development is usually too poor to allow exact zonation except in the northern San Joaquin Valley where the faunal zones are more clearly defined.

In the Rio Vista area the bottom six of the seven regressive sands are either missing or not developed. The disappearance of these sands is accompanied by a corrsponding loss of total interval suggesting pinch-out rather than shale out, the evidence for which is considerable but not conclusive. More data is needed to completely solve this problem and the conclusion stated above should be considered tentative.

During deposition of the Starkey Sands there were seven rapid transgressions each followed by a more gradual regression. Subsequent erosion has limited our knowledge of the original extent of this unit but in the Sacramento Valley a land mass certainly existed to the east and northeast and probably not too far beyond the limits (Fig. 9) of present occurrence. In the northern San Joaquin Valley the Tracy Sand, which is equivelant to the lower Starkey, shows an eastern source on the eastern side of the valley and a western source for areas to the west. It is assumed that basin limits for the Starkey were similar to those for the Winters with a land mass probably existing to the west except for a possible connecting channel to the open sea.

In the Sacramento Valley four small fields produce from the Starkey Sands with total initial reserves of less than 100 million MCF. In the northern San Joaquin Valley good gas reserves in the equivelant portion of the section have been found in three fields to date.

Close of The Creteceous

Paleontological evidence for the Cretaceous-Paleocene contact is poor, though definite Cretaceous fauna have been found in the H & T Shale. The obvious change in depositional environment noted in the section above the regressive sands of the Starkey argues in favor of placing the contact at the top of the regressive sand body above the H & T Shale. In the central portion of the valley no erosion has been noted at the top of the Cretaceous and the contact appears accordant. At Potrero Hills and elsewhere along the west side the Cretaceous has been eroded with sediments considered to be Paleocene overlying the unconformity.

Basin development after F Zone time to the end of the Cretaceous can be summarized as follows: (1) Deposition of the Sacramento Shale in a relatively deep environment but ending with a regression of the sea. (2) Continued regression throughout deposition of the Winters formation with the basin becoming quite restricted. (3) A rapid transgression, the first of seven cycles of transgression and regression during which the Starkey Sands were deposited.

Following deposition of the Sacramento Shale the basin was bounded by a western land mass with a possible channel to the open sea southwest of Rio Vista. This land mass either came into being during deposition of the Winters formation or it is a more easterly position of a land mass that previously had a more removed position to the west.

GEOLOGY OF THE KIONE FORMATION [1]

John N. Thomson [2]

ABSTRACT

The Kione Formation is an Upper Cretaceous unit with a maximum thickness of 2200′ of alternating sands and shales encountered in the northern two thirds of the Sacramento Valley, California. The formation is trough-shaped in gross form and is truncated by younger formations on its north, west, and east sides. The formation disappears to the south by shaling out at the base into the Forbes Formation. The Kione also shales out at the base to the north and west, and locally to the east.

The sand portion of the formation was derived from the Sierra Nevada to the east and was deposited in a marine environment. The Kione is generally considered to be of shallow water origin, although there is little direct evidence for this conclusion.

Gas is produced from the Kione in numerous fields in the northern portion of the Sacramento Valley. Salinities of formation waters and the heating qualities of the produced gas show a wide range of variation with no set pattern.

Shallow depths and favorable reservoir qualities make the Kione an attractive objective. Future exploration for Kione gas will be stimulated by the increasing amount of data available from the Sacramento Valley.

HISTORY

The Kione Formation in some ways is a difficult unit to work with. This circumstance is reflected in the lack of general material written on the subject. In 1929 Dr. Howell Williams, of the University of California, published a paper on the geology of the Marysville Buttes in which he described some white sandstone outcropping on the south and southwest flanks of the Buttes as Ione Formation, an understandable error considering the state of the stratigraphic knowledge concerning Sacramento Valley at that time.

In 1943, Johnson pointed out that this sandstone was included within the Cretaceous section, and therefore, was older than Ione. Nowhere in the text does Johnson use the term Kione, but in figure 271, which compared the stratigraphic usages of various workes in the Buttes area, Johnson has "Kione" opposite the Ione of Williams and others. The name Kione is reportedly a contraction of K (for Cretaceous) and Ione. The name apparently found quick acceptance, since it was employed in core descriptions written shortly after. Although the naming of the unit would be considered inadequate under the present rules of the Code of Stratigraphic Nomenclature, the name has been widely used and should be retained on that basis.

1. Presented to the San Joaquin Geological Society April 10, 1962.

2. Geologist Partner Pohlmann and Thomson. The author is grateful to Occidental Petroleum for aid in drafting the exhibits.

STRATIGRAPHY

The Kione Formation is an Upper Creataceous u found in the northern two thirds of the Sacramento V ley, generally at the depths from 1500′ to 4500′. thickness ranges from 0′ to approximately 2200′. Fig 1 illustrates portions of two electric logs from w which penetrated the Kione section. The first log, f the Mobil "Llano Seco" 1 in 33-20N/1W, is a more or typical log of the Kione, demonstrating the alterna sand and shale character of the formation. The sec log is from the Honolulu "Honolulu-Humble-Wild Goo No. 1 in 17-17N/1E and shows the appearance of the sa where they contain gas.

A composite description of the sand portion of Kione compiled from numerous core descriptions follo

Sandstone, light to medium gray, generally mas occasionally cross-bedded, soft, locally crumbly, sorted, fine to coarse grained, average medium gr ed, common pebbles to ½″, locally with graded ding, 50% quartz, 25% feldspar, 25% dark gr including common black chert, common mica. mon glauconite, occasional pelecypods, abundant bonaceous material and leaf imprints, occasiona regular clasts of clay shale, locally with calcar shells, permeability and porosity good.

In addition, correlation of electric logs indicates the Kione sands are lenticular on a large scale, and there are occasional minor unconformities within the Some geologists believe that the formation contain least one major unconformity within it, but this has been apparent to the writer.

The interbedded shales may be described as:

Clay shale and siltshale, dark brown to gree gray, moderately hard, locally fissile, fairly sorted, commonly very finely sandy, common bonaceous material including seed pods, occas thin layers and irregular pods of sandstone as cribed above, occasional phosphatic materia

The interbedded shales make satisfactory cap r The Wild Goose field has several different produ zones with individual gas-water interfaces. In add some fields produce from a single sand within the fo tion, the Afton field being a case in point. Becau this, any well to test Kione should penetrate the e section.

Figure 2 is a base map of Sacramento Valley sho the location of Correlation Section A-A′ shown in F 3. The map also served as a base for Figures 4, 5, a

The stratigraphic relationships of the Kione ar tured in the correlation section in Figure 3. The f tion is overlain unconforably by Eocene Capay fro tion 7-17N/1E to the north and overlain conformab Upper Cretaceous Sacramento Shale to the south lower contact of the formation is a facies change, th al portion of the Kione being equivalent to sha

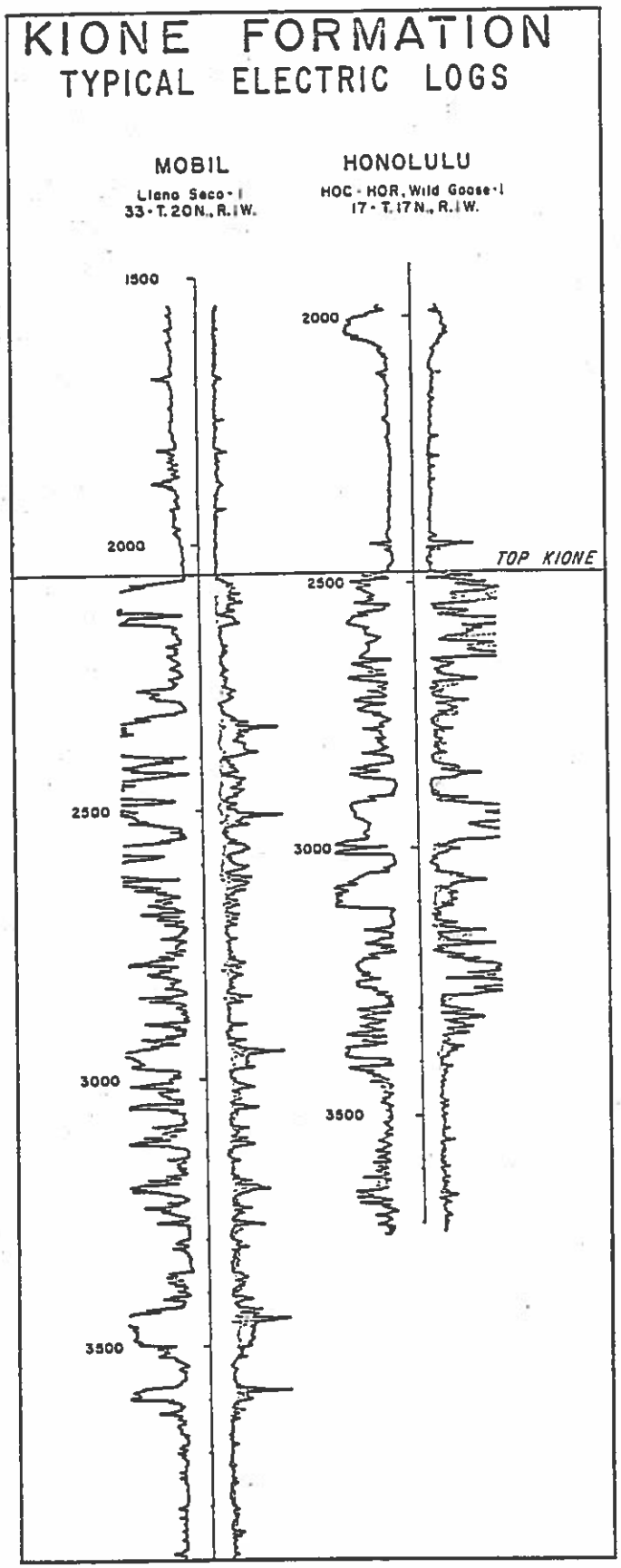

FIG. 1. Typical Electric Log of the Kione Formation.

the Forbes Formation.-The area containing the maximum thickness of Kione extends from Willows to South Corning. Here the upper portion of the Kione is equivalent to the Wild Goose sands producing in the Wild Goose field to the south; the lower portion is equivalent to the Estes, Hill-Elvidge, and Friesen sands in the Willows field. The choice of a point to be picked as the base of Kione is somewhat of a problem in this area. Various publications show the base in various places, but all seem to agree that such sands as the Estes, Hill-Elvidge, and Friesen should be included within the Kione since they are apparently indistinguishable from it.

The Kione is generally considered to be in Goudkoff's "E" zone. Some people consider the Forbes to be "F" zone, some consider it to be "E" and "F" zones. The matter is apparently one of personal preference at the moment, but the Kione is laterally equivalent to the upper part of the Forbes, no matter which age is assigned to it. This fact is best demonstrated in the southern portion of the area occupied by the Kione where it is considered to be overlain conformably by the Sacramento Shale. As Figure 3 illustrates, the Kione disappears to the south and the disappearance must be by shaling out into the Forbes Formation. This shaling out generally occurs at the base of the formation, and the basal sand of the Kione almost always appears to be silty, no matter where the location. As far as the writer knows, at this time no sand similar in appearance to the Kione has been found to occur between the Sacramento Shale and the Forbes or their equivalents in the southern part of Sacramento Valley.

In addition to shaling out to the south, the Kione can be demonstrated, at least locally, to shale out to the west and to the north. The final mode of its disappearance is by truncation by younger beds, but a facies change from sand to shale at the base is a contributing factor. There is also some indication that the Kione shales out to the east in some areas and does not in some other areas. Here again, the final mode of disappearance is by truncation. The writer is not aware of any Kione in out crop, except at Marysville Buttes.

Figure 4 is an isochore map indicating the drilled thicknesses of Kione where it has been encountered. Certain determinations in constructing the map, such as whether a particular sand should be included in the formation, where the basal unit becomes too shaley to be considered Kione, etc., are open to personal interpretation The writer believes, however, that the overall configuration is well within the limits of accuracy necessary to indicate the general shape of the gross body of the Kione. The writer chose to isochore the map because he personally cannot follow any one marker in the Kione far enough to derive from it a regional structural contour map. As stated above, the base is a facies change, and the top is an unconformity over a large part of the area. Neither would be satisfactory to contour. In addition, a structural contour map would probably have little genetic stratigraphic significance.

The thickness of Kione at any one point is determined by 1) original and depositional variations in thickness, and 2) the truncation of the Kione by younger formations. In that area where the Kione is overlain conformably by the Sacramento Shale (see Figure 4) the pattern of thickness is dependent on original variation in deposition. This

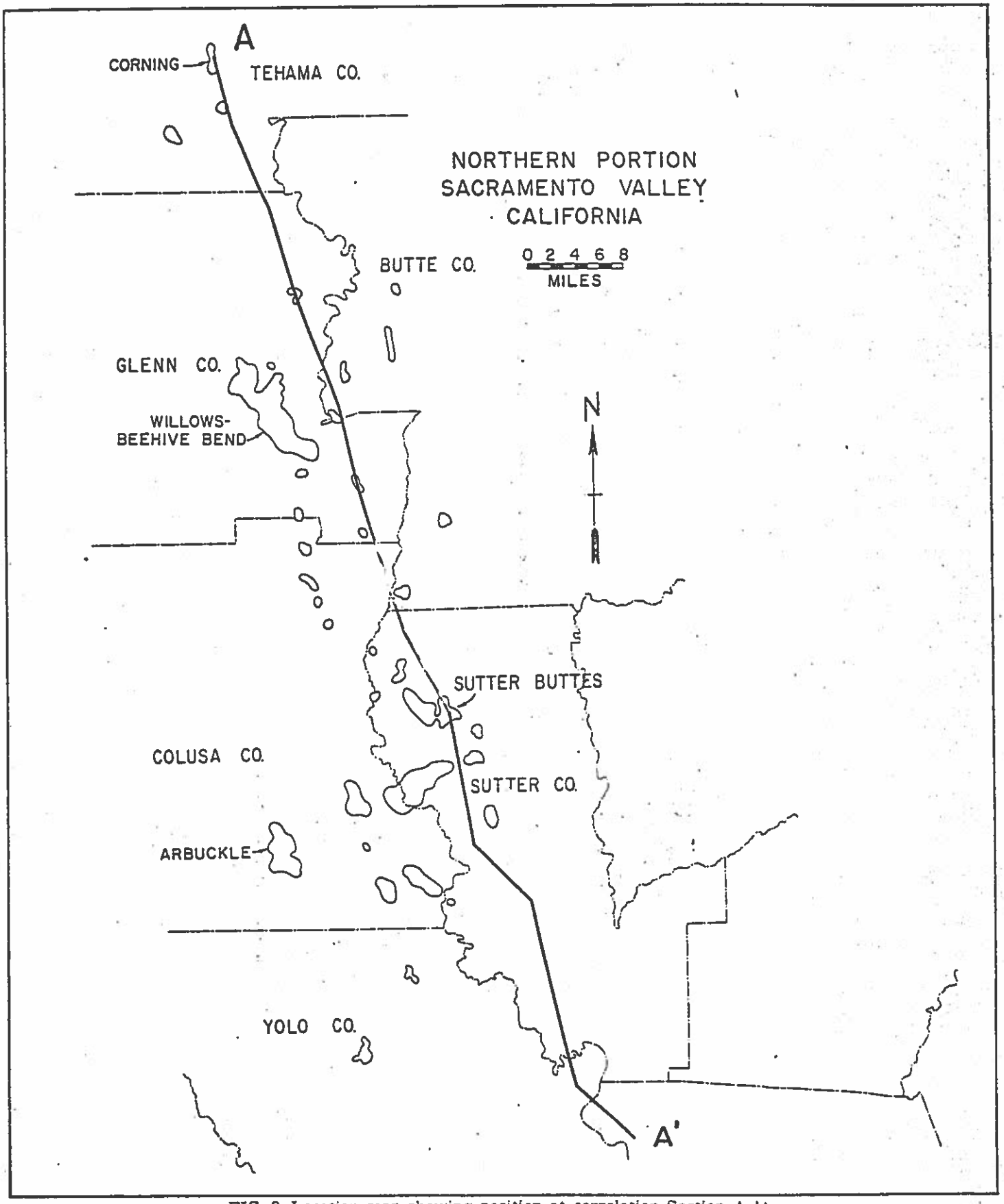

FIG. 2. Location map showing position at correlation Section A-A'

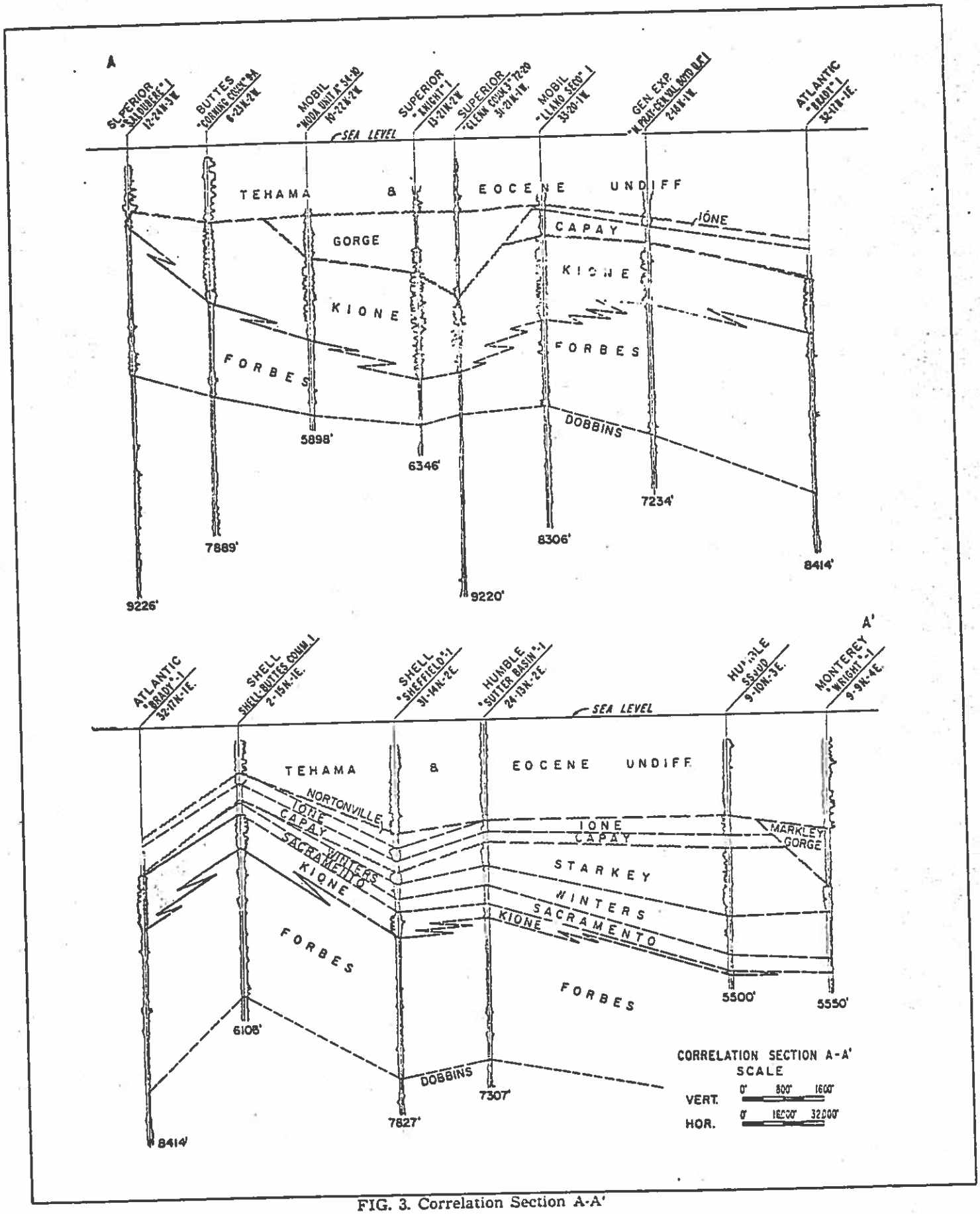

FIG. 3. Correlation Section A-A'

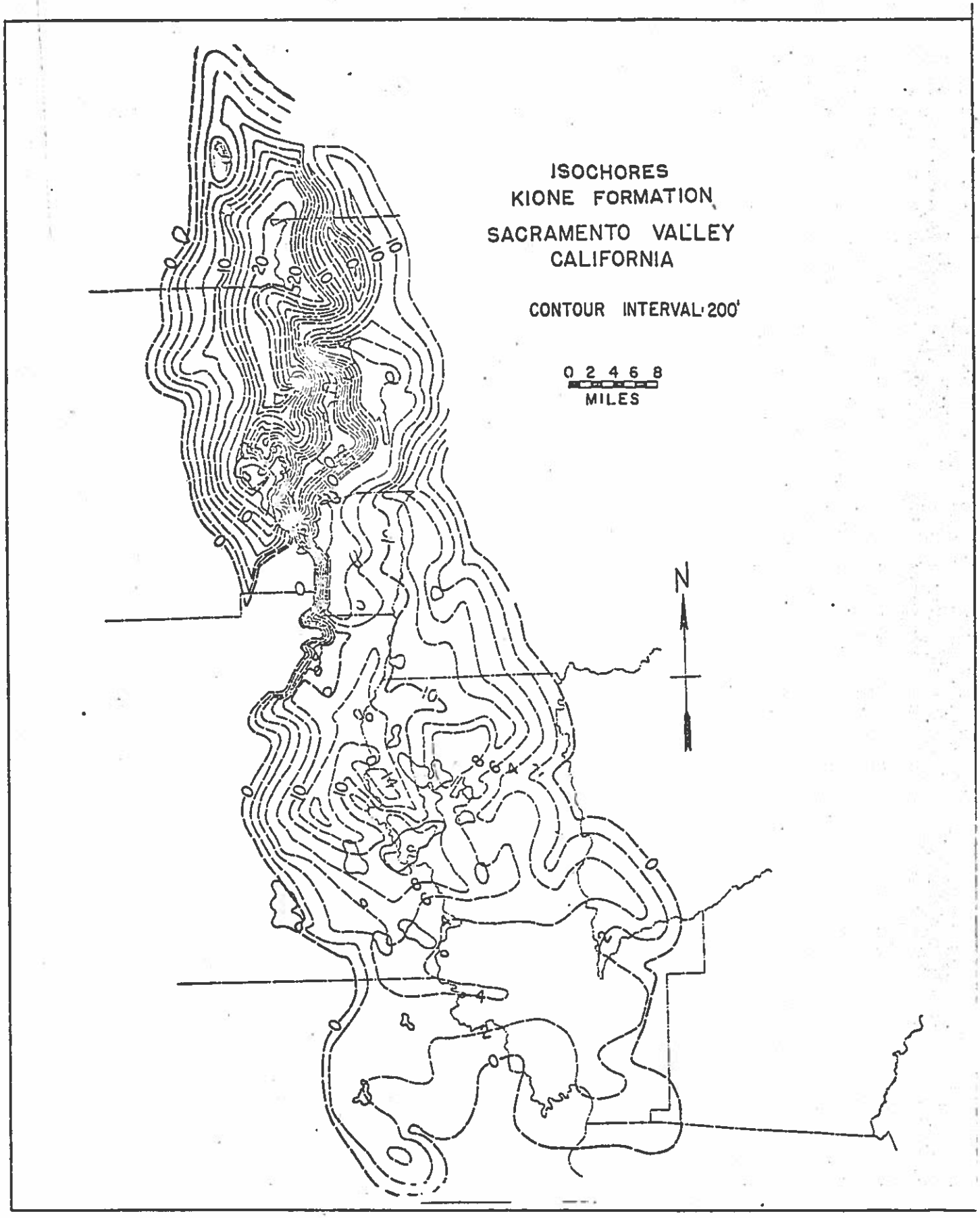

FIG. 4. Isochore map of the Kione Formation.

variation exists in the area where the Kione is overlain unconformably also, but is masked by the greater rate of variation due to truncation.

It is interesting to note that near the Marysville Buttes and the so-called Colusa Buttes, to the west, the Kione thins in a manner inconsistent with the general trough-shaped pattern of the Kione where it has not been eroded.

The thinning of the Kione in this area suggests the presence of an ancestral high area predating the formation of the present day Buttes.

Figure 4 also demonstrates clearly the general course of the "Princeton Gorge." The zero isochore lines along the "Gorge" indicate the boundaries of the area where th Kione was eroded completely away.

Stratigraphic relationships are not clear in the extreme northeastern portion of the isochore map and the question has simply been begged by leaving that area blank.

Figure 5 illustrates the area in which the Kione is overlain by the Sacramento Shale and the various areas in which the Kione is truncated by Capay, "Gorge", and Tehama and Eocene Undifferentiated.

ORIGIN AND SOURCE

The origin of the Kione has been characterized in the past as lacustrine and continental, estuarine, and deltaic. Despite the common carbonaceous matter and seed pods, the lacustrine and continental theory would seem to be ruled out in view of the following:
(1) the underlying and overlying formations were marine, (2) the Kione is laterally equivalent to marine shale, (3) salinities range over 1500 grains per gallon. (4) there is a sparse marine fauna, (5) glauconite is commonly present in the sands.

Estuarine is perhaps partially descriptive of the Kione in the sense that the word is defined as a place where the river meets the sea, but it also carries the implication of a more enclosed area of deposition than seems likely in this case. Because the Kione can be seen to shale out to the west, it is probable that the western edge of the basin, if one existed, was considerably west of the edge of the present day structural basin.

Probably the term deltaic best describes the origin of the Kione. Based on the thicknesses shown on the isochore map and on the assumptions that the Kione is 50% sandstone and that the sandstone has an average porosity of 30%, the volume of sand contained in the Kione is about 115 cubic miles. Considering this volume and the mineralogic content of the sand, it was almost certainly derived from the Sierra Nevada to the east. There is little evidence, however, that the Kione increased in thickness to the east nor that the percentage of sand incrased to the east. Locally the Kione actually seems to shale out at the base to a minor degree in an easterly direction. This suggests the probability that numerous point sources fed sand into the "basin" to form delta-like deposits which coalesced at some distance from shore, followed by some subsequent redistribution of material by current action. It should be also noted that the Kione is approximately 50% shale, and that the depositional processes responsible for the Forbes formation apparently continued during the influx of sand from the east.

The Kione is generally considered to be of shallow water deposition. Although direct evidence of this probably exists in somebody's files, the writer is thus far unaware of it. The "E'" fauna, as listed by Goudkoff, contains only one form not found in "E" zone and two forms not found in "F" zone, both zones being considered deeper water than the "E'". The "E'" fauna is apparently distinct from the "E" and "F" faunas not by what it contains, but by what it does not contain. Whether the missing forms dropped out in "E'" due to shallowing or due to an increased amount of sand in their environment is a question for the paleontologists.

In addition, if the sand in the Kione indicates a shallowing of the area of deposition, it would seem likely that the maximum thickness of Kione should exist on the east border where shallowing would have occurred first. Instead, the Kione appears to be a trough-shaped deposit with the greatest thickness in the center, even in that area where it has not been truncated around the edges.

The writer has no set opinion as to the depth at which the Kione was deposited, but the presence of large amounts of sand in the formation would seem to be more indicative of the conditions in the source area than in the area of deposition.

Whatever the depth involved, deposition of the sand in the Kione must have been relatively rapid. The sand in subsurface samples appears fresh and angular, and the common occurence of wood fragments, seed pods, and leaf impressions suggests rapid transportation and burial.

GAS PRODUCTION

Figure 6 illustrates the fields which produce gas from the Kione, and B.T.U. and salinity values from some of them. Addition of figures published by the California Division of Oil and Gas in "Summary of Operations — California Oil Fields" yields a cummulative production from the Kione as of January 1, 1961 of approximately 91,000,000 M.C.F. and an estimated reserves total as of that date of approximately 109,000,000 M.C.F. The D.O.G. figures for fields producing from more than one objective are not broken down, and the Kione portion of production from such fields as Willows was approximated by the writer. Reserve figures on various fields computed by engineers of the companies involved may differ somewhat from the D.O.G. figures.

The reservoir characteristics of the Kione are generally conducive to gas exploration. Porosities are commonly 25% to 30%, and permeabilities range from 300 md. to 5000 md. Pressures are normal for the depths involved, while drawdowns are relatively small. The Kione sands are under partial water drive, and recovery factors are good in most cases.

Kione gas is produced from both structural and structural-stratigraphic traps. Those areas in which the Kione has been exposed to erosion cannot be discounted in exploration. The Schohr Ranch field produces from sand directly below the Capay Shale which unconformably overlies the Kione. Compton Landing and Princeton Fields produce from Kione sands which are truncated updip by sediments filling the "Princeton Gorge."

Generally, Kione gas is 800 B.T.U. or better. The B.T.U. values shown on Figure 6 seem to follow no set pattern. They certainly do not support the idea that the methane content of Sacramento Valley gas is inversely proportional to the proximity to basement.

Salinities of formation waters are also erratic. None are as high as normal present-day sea water, although those of the Afton and Wild Goose fields approach it. It

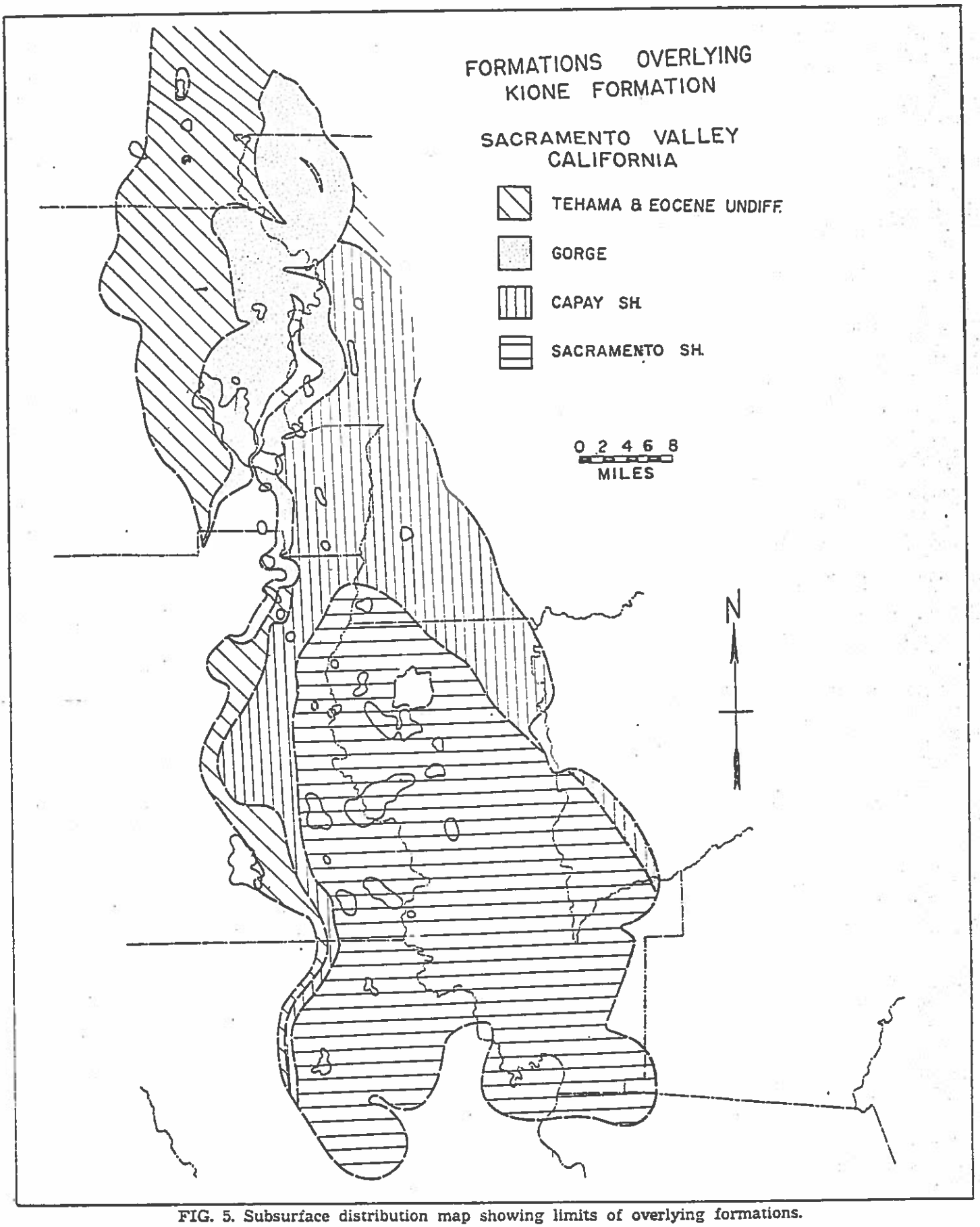

FIG. 5. Subsurface distribution map showing limits of overlying formations.

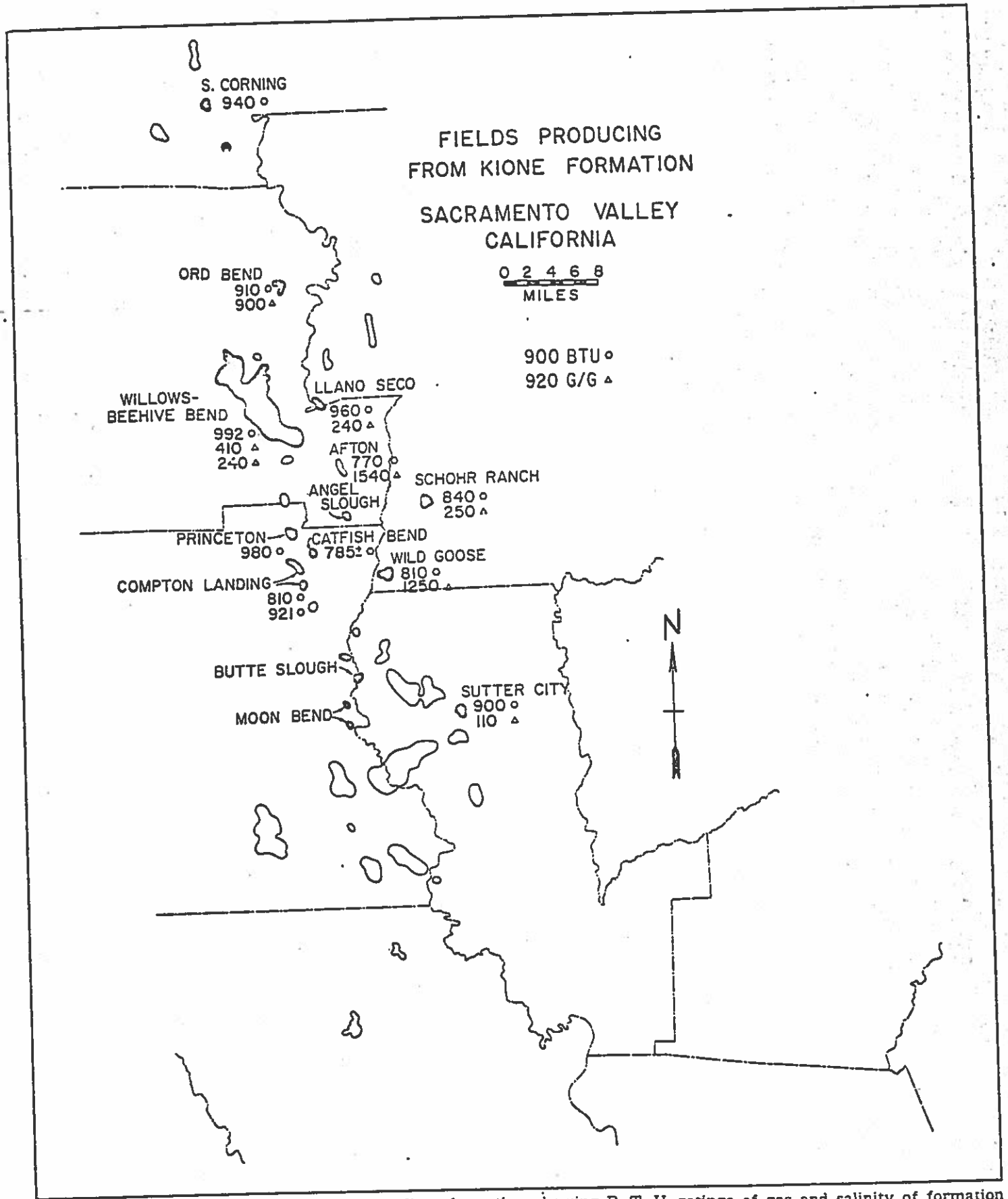

FIG. 6. Map of gas fields producing from the Kione formation showing B. T. U. ratings of gas and salinity of formation waters.

is of interest to note that salinities in the Kione near the "Princeton Gorge" are low, suggesting contamination from the "Gorge" sediments and giving rise to some interesting speculation regarding the origin of the gas encountered against the "Gorge."

FUTURE KIONE EXPLORATION

Shallow depths, rapid drilling, and inexpensive completions make the Kione an attractive objective. Although most of the obvious structural closures have been explored for Kione gas, the increasing amount of data becoming available in the Sacramento Valley will undoubtedly indicate prospects for other types of accumulations. Exploration along the edges of the "Princeton Gorge" has not been extensive, because no trustworthy method of locating the "Gorge" has been developed short of drilling through it. In those areas where drilling has been extensive in the northern portion of Sacramento Valley, faults are found to be the rule rather than the exception. Increased drilling should delineate these faults to the point where they can be extrapolated into areas of less dense drilling. In addition, there are some possibilities where the Kione is truncated around the borders of the basin, and further possibilities of accumulations beneath the Capay Shale in the central portion of the basin.

Although the major portion of the northern Sacramento Valley is under lease at the present time with accent on Forbes exploration, increasing amounts of information and attractive economics will encourage future drilling in the Kione.

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GRIMES GAS FIELD [1]

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Abstract

The Grimes gas field is an example of a complex stratigraphic and fault stratigraphic accumulation that is now in balance with a fluid-pressure environment that is also an important parameter in the trap. The gas occurs in sand lenses that are elongate bodies oriented parallel to depositional strike. These sand bodies occur in the Cretaceous F-zone section and were probably deposited by turbidity currents. The gas occurs in 20 separate lenses that vary in depth from 5500 to 8500 feet.

Structurally the field is on a southwest dipping homocline adjacent to the main structural syncline of the valley. A conjugate system of faults trending northesterly and northwesterly form part of the trap for many of the gas filled lenses.

The time of accumulation is not known, but if it were early it must have been locally redistributed at least twice, once during an early Eocene period of folding, faulting, and uplift, and again in a Pliocene period of orogeny.

INTRODUCTION

The Grimes gas field is one of the most significant F-zone discoveries in recent years in the northern Sacramento Valley. The field was discovered by the Cameron Oil Company on a farmout from Franco Western Oil Company. The discovery well was the Cameron-Franco Western No. 1 Armstrong, now called the Unit 7-2 well. At this stage of development and with only a short productive history, it is impossible to make a reasonable estimate of ultimate recoverable reserves, but it is evident that Grimes will be a major gas field. At this time there have been 44 wells drilled in the field, four of which are dry holes. The production limits of the field have not yet been defined.

LOCATION

The Grimes gas field is located in the northern Sacramento Valley, 40 miles northwest of the city of Sacramento, California. The field lies partly on the west side of the Sacramento River in Colusa County. (Fig. 1) and partly on the east side of the river in Sutter County. Geologically the field lies on the east flank of the Sacramento Valley gas basin, immediately adjacent to the major syncline that divided the basin into an eastern and western flank.

PRODUCTION

The field has been on production since January 1, 1962, and since that date has produced at a maximum rate of 4000 MCF/D per well. Calculated volumetric reserves per well varies from 3.5 million MCF to 18 million MCF. The gas produced at Grimes is dry gas with an average methane content of 98 per cent, an average specific gravity of .56 and a heating value range 970-1015 BTU.

STRUCTURE

The Grimes field lies on the east flank of the Sacramento Valley gas basin adjacent to the main north-south syncline that forms the axis of the present structural basin. The contour map (Fig. 2) on the unconformity at the base of the Eocene Capay formation, shows the structure of the Grimes field at this horizon as well as the regional structural setting of the field. Grimes is on a southwest dipping homocline, that has been somewhat modified by the intusive caused Marysville Buttes and Colusa highs to the northeast and northwest. The strutural pattern shown on the Capay map was created by late Miocene or early Pliocene folding. Very little faulting accompanied these tectonic episodes in this part of the basin.

Figure 3 shows the structure of the Grimes field on an electric log marker within the producing part of the F-zone section. The general structural configuration is similar to that shown on the base Capay map, but the dip is steeper and a fault pattern is present that is absent at the base of the Capay. A profound valley wide period of uplift, folding, and erosion occurred in late Paleocene or early Eocene time before the deposition of the Eocene Capay formation. The structural pattern shown on the Z-marker map is the sum of the effects of that early Tertiary orogeny, the late Tertiary folding described in the paragraph above, and to minor tectonic adjustments that occured during Cretaceous time.

The faults in the Grimes field probably originated during F-zone time; most of the displacement, however, occurred during the early Tertiary orogeny. The four faults shown and numbered on Figure 3 and also on the cross section, (Fig. 4), are production and pressure barriers.

Fault 1 is the westernmost fault shown on the map. It is left lateral in displacement and divides a high pressure block on the west from a lower pressure block on the east.

Fault 2 that trends northwest-southeast is apparently a down to the east fault. This fault, together with the left lateral Fault 1, creates a wedge of production that is included between the two faults. The reservoirs that produce from within this wedge are at a slightly different pressure than the reservoirs east of the wedge. Fault 3 is also a northwest-south-

1. Presented to the San Joaquin Geological Society May 8, 1962.
2. Division geologist, Franco Western Oil Company.

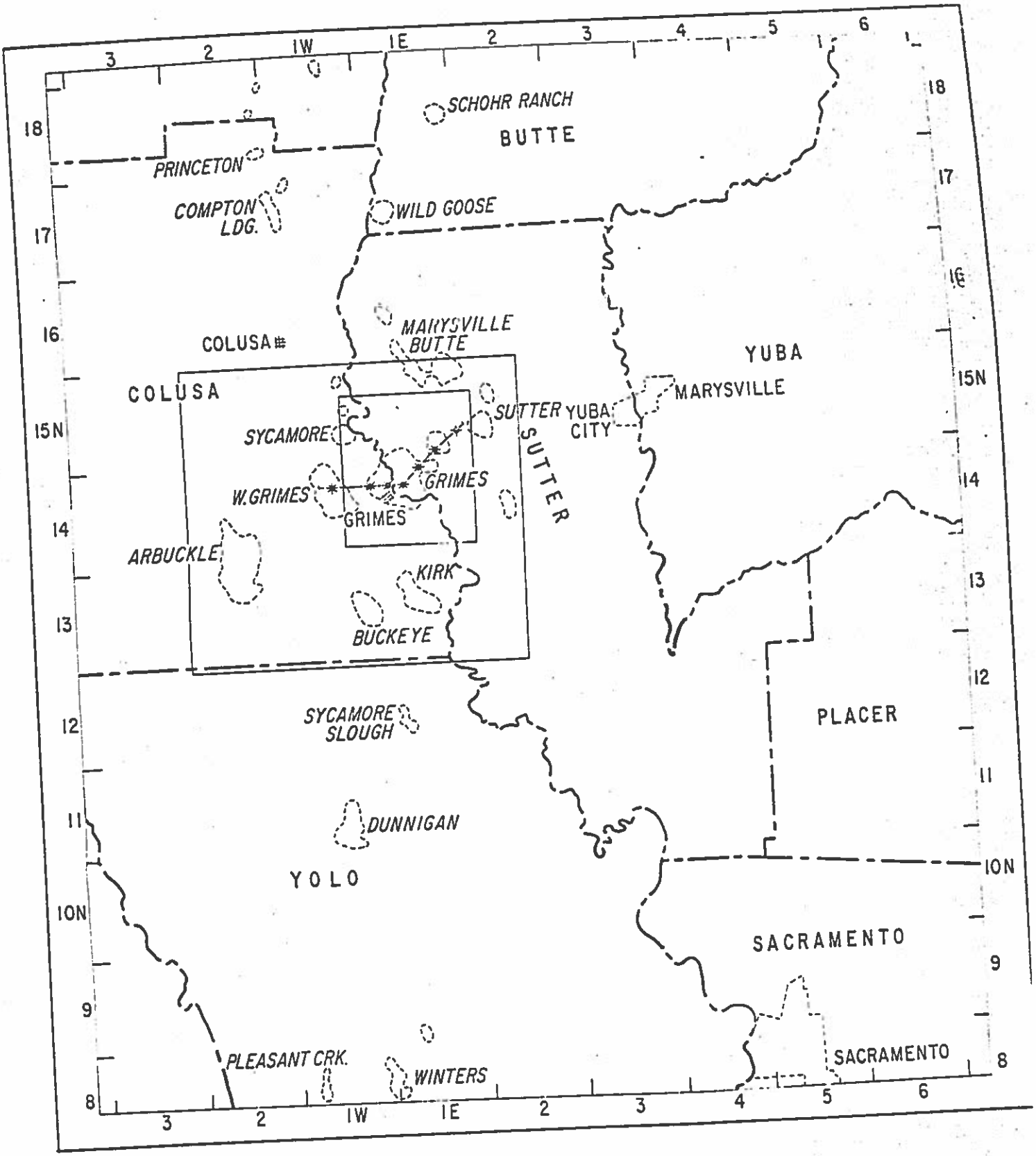

FIG. 1. Location map of Grimes Gas Field.

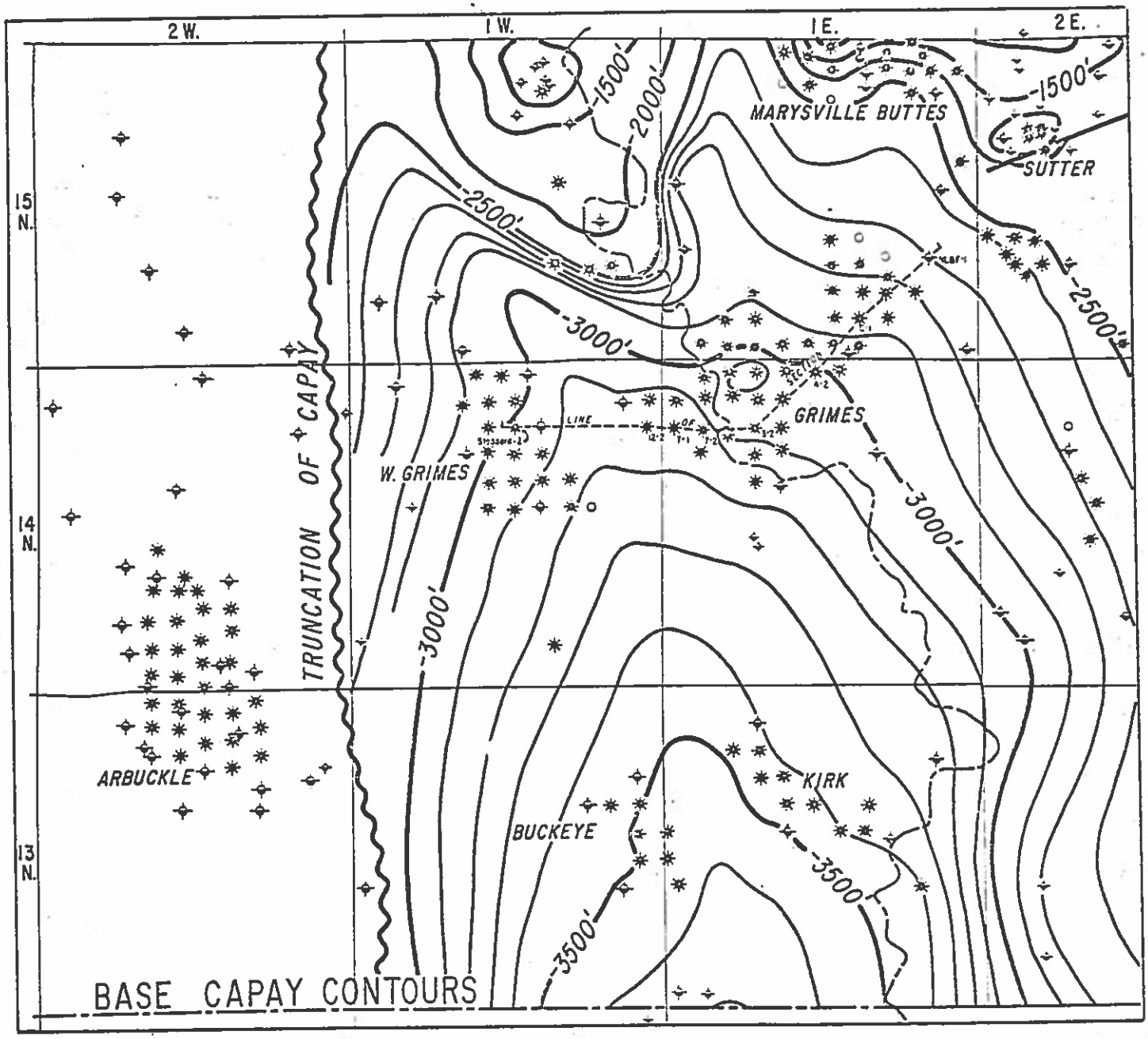

FIG. 2. Structure map drawn on Base Capay Level.

east trending fault, down to the west. It may be either a right lateral fault or a down to the west normal fault. This fault separates a lower pressure area on the east from a higher pressure area on the west. These three faults create a fault block system that consists of four different producing blocks in the Grimes area. Producing blocks successively decrease in pressure for equivalent zones at equivalent depths in an easterly direction. The highest pressure block is west of the Fault 1, the lowest pressure block is east of Fault 3.

Fault 4 cuts two wells, the 32-33-3 and the 32-33-4 This fault has a northwest-southeast orientation and is apparently a normal fault, down to the east. It is not a pressure or production barrier except for the Sanborn zone in the 32-33-3 well; the intersection of this fault with Fault1 creates a small triangular fault block pool around the 32-33-3 well.

Summary of the Geologic History

We can use the unconformities, fauna, and lithogic information in the Grimes area to make the following summary of the geologic history.

1. In G-zone time there was an easterly transgression of the G-zone seas with a development of a basal transgressive sand. This transgression was followed by the deposition of G-zone shales in a moderately deep water environment. The faunal assemblage that includes abundant radiolaria in-

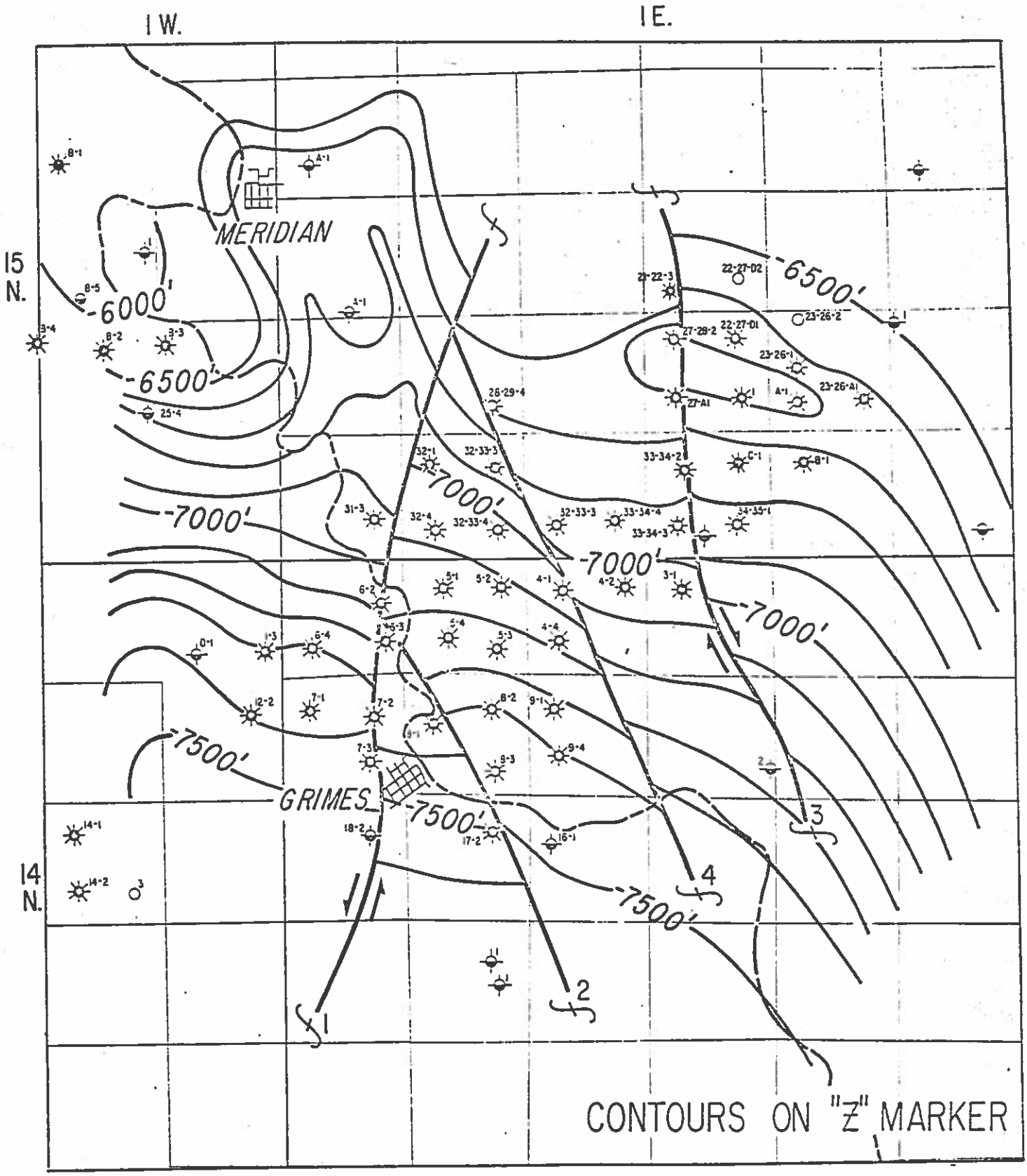

FIG. 3. Structure contours drawn on 'Z" Marker.

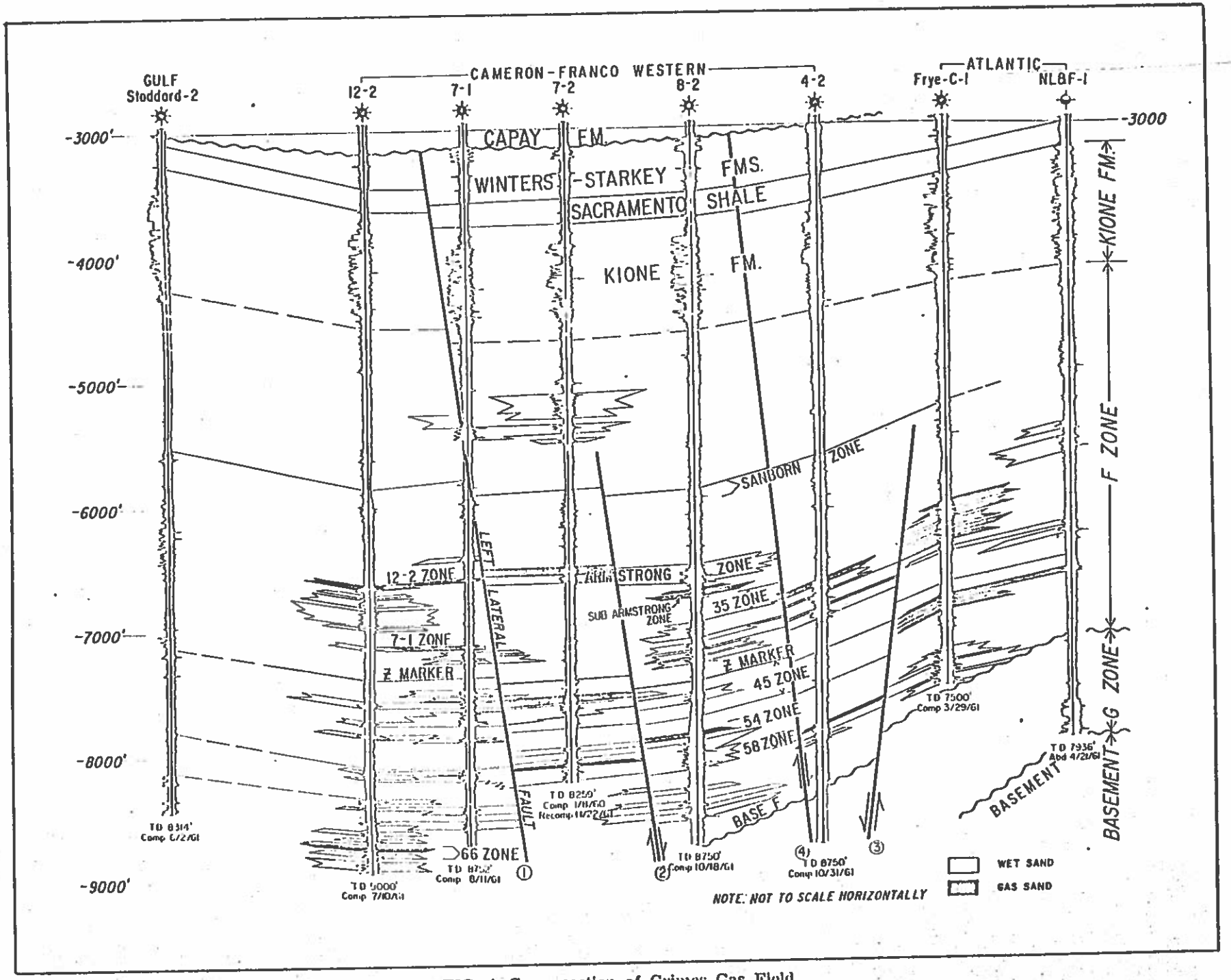

FIG. 4. Cross section of Grimes Gas Field.

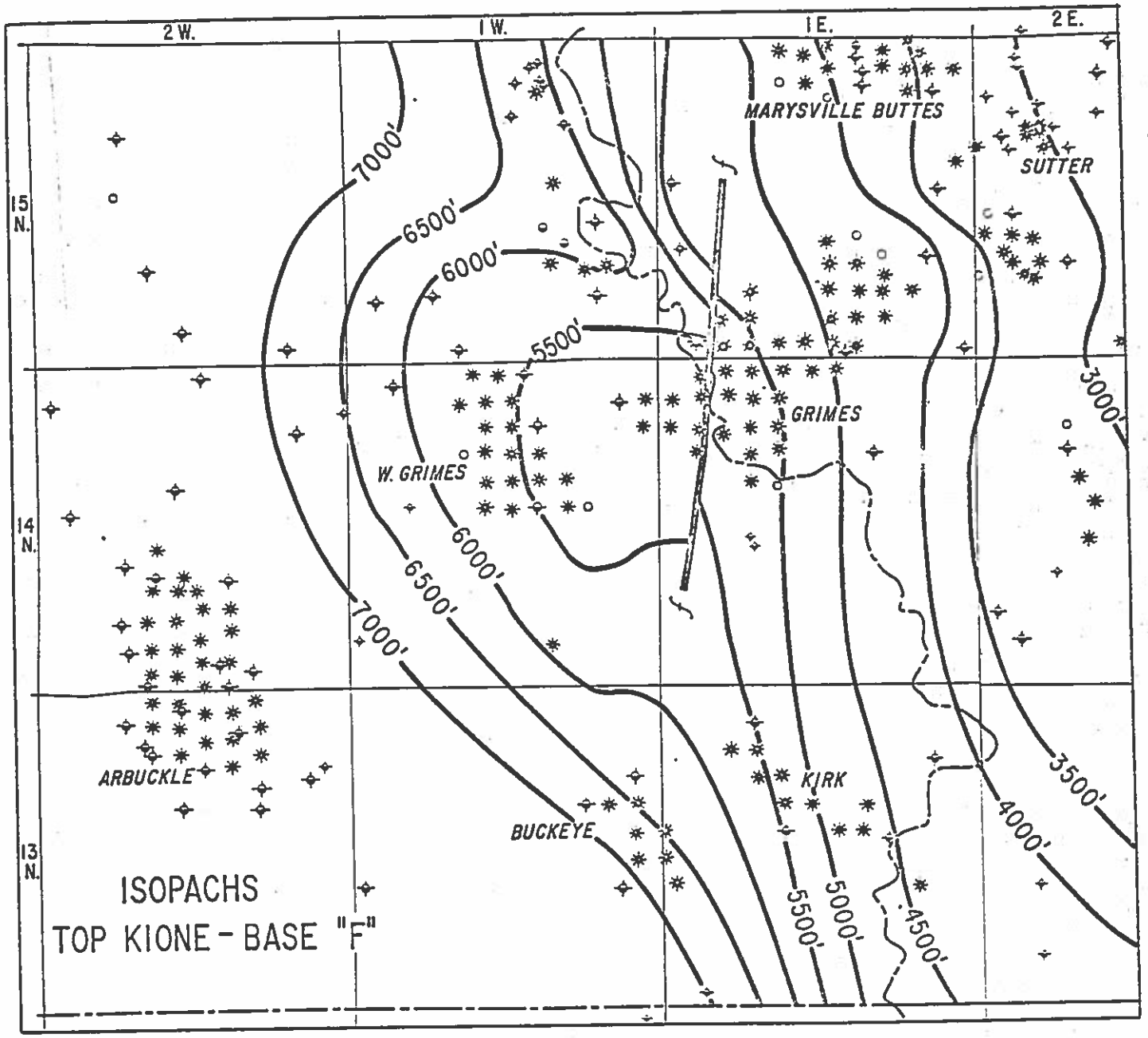

FIG. 5. Isopach map of interval between top of Kione to base of "F" Zone.

dicates there was probable free access to open ocean waters. Following deposition of the G-zone shales there was uplift and westerly tilt of the basin and withdrawal of the seas from the eastern part of the basin.

2. In F-zone time there was transgression of the F-zone seas, the sediments being deposited by progressive onlap on the G-zone shale. East of the Grimes area the G-zone is finally fully overlapped by the F-zone, and the F-zone sediments rest directly upon basement rocks. The angular discordance that is present between the G-zone and the F-zone is the result of the tilting of the basin in G-zone time, is profound enough to indicate that a regression and transgression must have occurred between the time of deposition of the G- and time of deposition of the F. Most of the thickness change that occurs across the Grimes area in an east-west direction is actually due to onlap rather than to true stratigraphic thinning. From the ecology of the forminifera in the F-zone we can say that F-zone sediments were deposited in a broader and shallower basin than the G sediments and that the rate of sedimentation was slightly greater than the rate of subsidence so that the basin gradually shallowed during F-zone time. A discussion of the F-zone sand development will be included under a section "Stratigraphy of the F-zone".

3. The Kione formation represents the shallowing of the F-zone basin which resulted in the development of a shallow near-shore environment and the

deposition of the near-shore Kione sands. The Kione sands were probably deposited in a series of deltas that lay at the mouth of the major drainages coming off of the Sierran land areas to the east. These deltaic sands were further distributed along the east side of the valley by action of along-shore currents and by normal shore-line processes.

4. Basinal shallowing was accompanied by uplift along the basin margin with the regression of the sea to a position southwest of Grimes. The basin then subsided very rapidly and the Sacramento shale sea transgressed the area. Sacramento shales were deposited in an environment very similar to that of G-zone, as shown by faunal similarity in the two intervals. This basin must have been a moderately deep water basin similar to that of the G-zone.
5. The Winters shales were deposited under gradually shallowing conditions.
6. The Starkey represents a very shallow sea environment with deposition of a series of regressive-transgressive beach or near-beach sands. Only the lowermost regressive-transgressive cycle is present in the Grimes area.
7. Cretaceous sediments younger than those described in the Grimes area were removed in the erosional episode that preceded Capay deposition.
8. Following deposition of the Upper Cretaceous sediments, probably in late Paleocene time, judging from relationship in other parts of the valley, the basin was uplifted, tilted southerly, and folded into a broad syncline with a north-south trending axis. The area was peneplaned and then subsided to allow Eocene transgression and deposition of the Capay, Domengine, and younger Eocene sediments. These sediments were deposited in a series of transgressions and regressions in a broad and relatively shallow Eocene sea.
9. The area was again uplifted, folded, beveled, and non-marine sands and shales of the Tehama formation were deposited unconformably upon the Eocene sediments. This tectonic episode occurred in early Pliocene time. At about the same time the intrusive plugs at Marysville and Colusa were implaced.
10. In Pleistocene time the northern Sacramento Valley was affected by a moderate tectonic episode This period of folding had little or no effect upon the Grimes area structure.

F-ZONE STRATIGRAPHY

The F-zone sediments in the Grimes area were deposited in a moderately deep water environment too far from the shore to be affected by shore line winnowing processes, at least throughout most of F-zone time. These sediments consist of interbedded dark grey claystones and siltstones, and grey, fine grained friable lenticular sands. The relative percentages of sand and shale, as well as the range in thickness of the sands can be seen in the cross section, (Fig. 4). The F-zone basin did become progressively shallower with time and the E-zone Kione sands as well as some of the uppermost F-zone sands, are the near shore sands associated with that shallowing.

The total isopach map of the F-zone, (Fig. 5) shows the general configuration of the F-zone basin in the Grimes area. As the Kione formation is genetically, closely related to the F-zone, the isopach map includes both formations. Continuous westerly thickening of some 1500 feet occurs across the Grimes field. Most of this thickening, (Fig. 4) is due to easterly onlap of the F-zone sediments on the G-zone shales, rather than to stratigraphic thinning, although both occur. One fault that apparently was growing during F-zone time is shown on the isopach map. West of this fault is a pronounced thin in the West Grimes area, however, the thinning shown involves only the lowermost part of the F-zone section. Isopach maps of portions of the F-zone section (not included with this paper) show somewhat different configurations than the isopach map of the total F-zone section. This is due to the onlapping nature of the F-zone on the G-zone and to the presence of two local unconformities in the section, one near the base of the F-zone, and one near the top of the F-zone.

The F-zone sands were deposited in a moderately deep water environment, too far offshore to be affected by shore line winnowing processes, and are the result of offshore basinal currents of some sort, probably turbidity currents. Widely differing interpretations of gross sand distributional patterns exist at the present time. Perhaps some light can be shed on this problem by considering the geometry of some of the producing sand bodies in the Grimes area. In general, the individual sand bodies that can be correlated have an elongate elliptical shape (Fig. 6) with the long axis of the sand body parallel (Fig. 7) to depositional strike. The size of individual sand lenses varies from 2 to 3 miles wide and 8 or more miles long to lenses that are present in only one or two wells. It seems probable that the majority of gross sand buildups have the same orientation as individual lenses, that is, parallel or sub-parallel to depositional strike.

PRODUCING ZONES

So many producing zones are present in the Grimes field it is impractical in a paper of this nature to show them all. A total of 20 zones in all fault blocks are recognized at present and they vary in depth from 5500 to 8500 feet. Ditch and sidewall samples show all sands to be fine grained and to vary in shaliness from very dirty to well sorted and clean. Sidewall sample analyses give porosities ranging from 25 to 30 percent and permeabilities ranging from 15 to 70 millidarcies. Thickness of individual producing reservoirs varies from a minimum of 8 feet to a maximum of 60 feet.

The accompanying sand distribution map, (Fig. 6) shows the configuration of some of the producing sands of the Grimes field. Figure 7 shows net sand isopachs gas-water interfaces, and superposition of the isopachs of the Armstrong zone on 500 foot Z-marker contours. In the sand bodies shown in Figure 6, accumulation is wholly controlled by stratigraphic variation, that is the gas is within a sand lense that shales out in all directions. In the Armstrong zone, however, Fault 1, in conjunction with sand shaleout creates the trap. The Armstrong zone is wet west of Fault 1 at elevations that are productive east of Fault 1. In addition, the

STRATIGRAPHY

The stratigraphy of the Grimes area is covered by a table of rock units, a summary of the geologic history, and a discussion of the F-zone stratigraphy.

Rock Units Present in the Grimes Area

The following table summarizes the lithology of the rock units present in the Grimes area:

GEOLOGIC AGE	FORMATION	THICKNESS	LITHOLOGY
Pliocene to Recent	Tehama	1800-2000′	Interbedded sequence of continental sands, conglomerates and shales. Sands comprise about 80% of section.
	Unconformity		
Eocene	Undifferentiated but includes Domengine equivalent.	1000′	Conglomeratic, poorly sorted sands, and thin interbedded grey shales.
Eocene	Capay	250′	Light grey, glauconitic shale with a glauconitic gritstone at the base.
	Unconformity		
Upper Cretaceous D-1 Zone	Starkey	0-200′	Fine to medium grained sand.
Upper Cretaceous D-2 Zone	Winters	250-300′	Grey siltstones and silty shales.
Upper Cretaceous E-Zone	Sacramento Shale	200′	Dark grey siltstone and shale.
Upper Cretaceous E′-Zone	Kione	900-1000′	Grey, fine to medium grained sands, interbedded with grey siltstones.
Upper Cretaceous F-Zone (F-1 and F-2 Zones)	Forbes	3000-5500′	Dark grey siltstones and claystones with interbedded fine grained, friable, lenticular sands.
	Unconformity		
Upper Cretaceous G-Zone	Dobbins and Guinda		Grey soft shales and siltstones and a basal sand and conglomerate.
	Basement		Granite and other more basic igenous rockes.

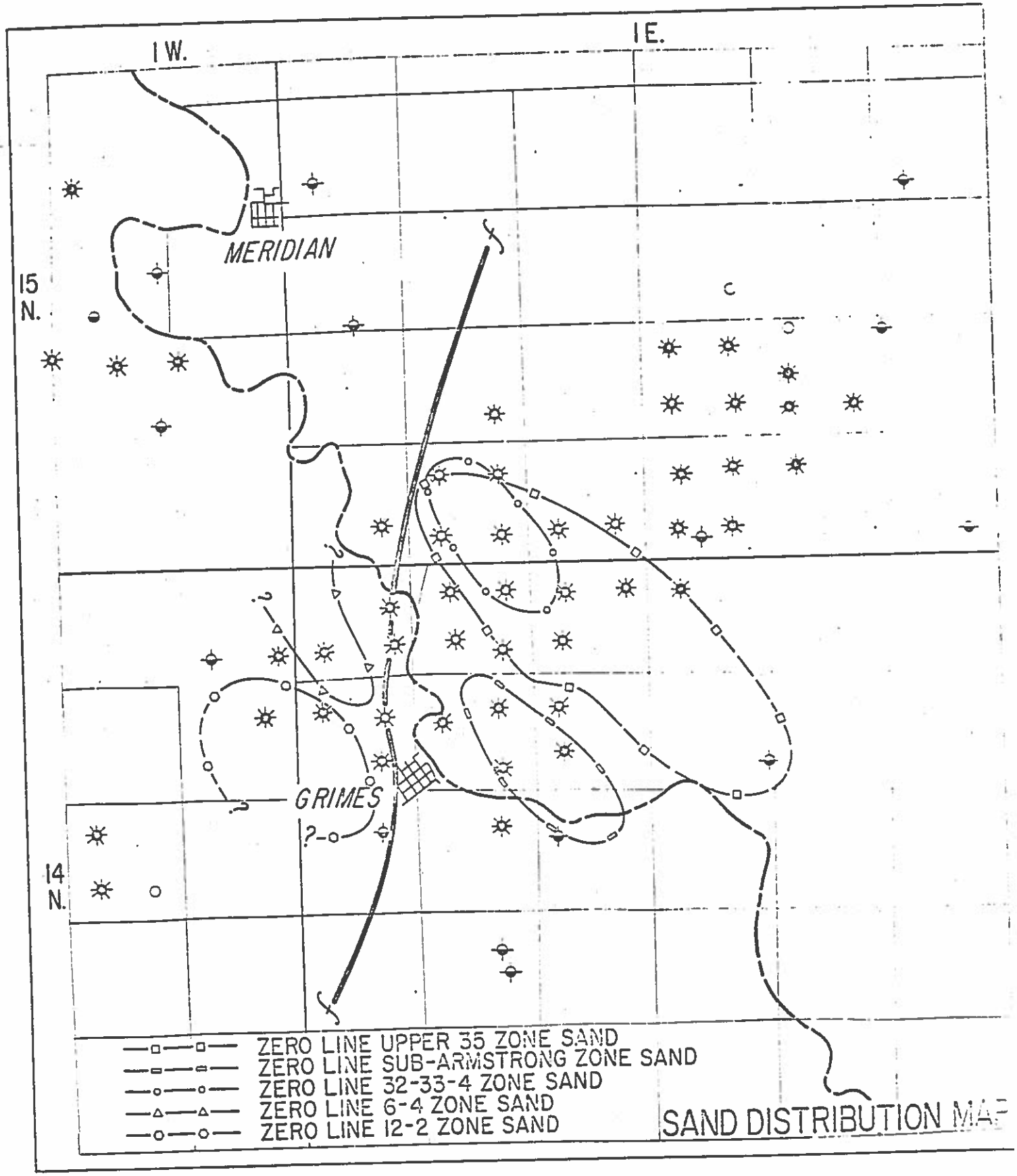

FIG. 6. Sand distribution map showing elongate shape of sands.

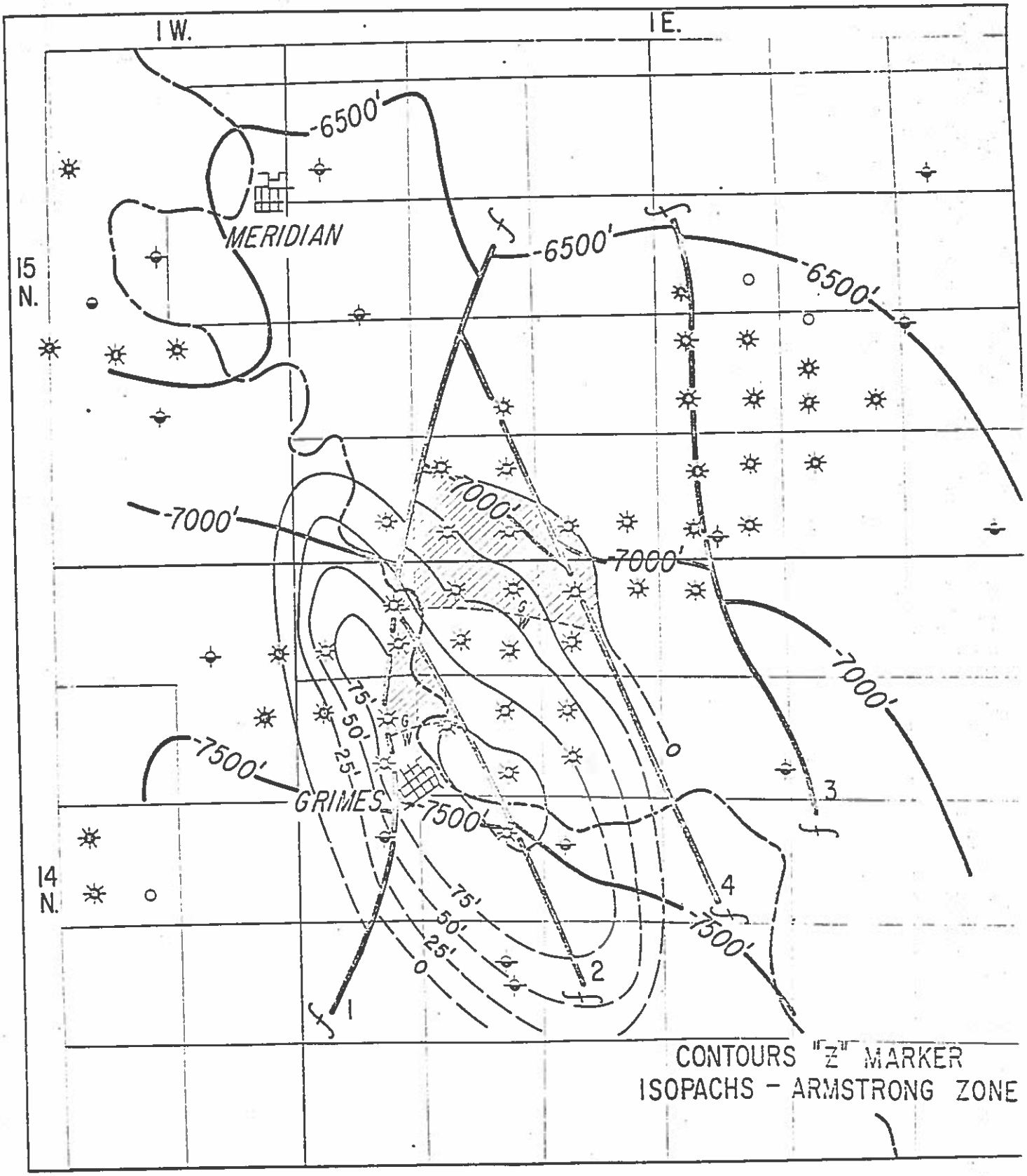

FIG. 7. Contour map drawn on "Z" marker with Armstrong Zone Isopachs.

intersection of Fault 1 and Fault 2 provides a small trap around the 7-2 well.

The trapping mechanism illustrated by Figures 6 and 7 is responsible for the accumulation in all other producing zones of the Grimes field. Grimes is an example of a primary stratigraphic trap modified by faulting. In many of the reservoirs the faults shown form an important part of the trap, in other reservoirs individual sand geometry forms the complete trap.

FLUID-PRESSURE RELATIONSHIPS

In an indirect way the faults may be more important to the total accumulation that an analysis of individual sands would indicate. The faults shown in the Grimes field divide the area into separate pressure and producing blocks. As mentioned above under "Structure", the producing blocks successively decrease in pressure in an easterly direction. Within each block pressures increase rapidly above normal hydrostatic starting at a depth of about 5500 feet. The presure gradient increases in a series of jumps across shale intervals, rather than as smooth curve. The presure variation is from 2500 pounds at 5500 feet in the central fault block, to 6600 pounds at 8500 feet in the westernmost fault block.

Pressure studies show that within each fault block, gas phase continuity in some reservoirs exists over a considerable vertical height of 500 feet or more, and that in certain reservoirs gas phase continuity may exist between lenses that are separated by a 100 feet or more of shale. Gas column heights of 500 feet create entry pressures higher that F-zone shales and siltstones can hold under hydrostatic conditions.

The anomalous pressure relationships and the high gas columns suggest that the fluid pressure environment of the Grimes area is also an important factor in the accumulation.

TIME OF ACCUMULATION

The primary stratigraphic nature of many of the Grimes field reservoirs suggests that accumulation in those reservoirs occurred very early, probably in F-zone time. However, the intimate relationship of some of the reservoirs to the fault pattern which was not fully developed until Paleocene or early Eocene time, indicates that the accumulation in those reservoirs either occurred post faulting or readjusted to the faulting. Finally, the intimate relationship of production to the present fault-pressure pattern of the area, with gas column heights that seem to exceed hydrostatic fluid environment capabilities, indicates the accumulation is controlled and is in balance with the present fluid-pressure environment. This fluid-pressure environment probably originated with the Pliocene folding and creation of an outcrop pattern that is essentially what it is today. Therefore although accumulation may have begun in F-zone time, the accumulation as it now exists went through at least two profound periods of adjustment and reaccumulation. It is possible, of course, that the field is entirely a late phase accumlation or reaccumulation connected with the present fluid-pressure environment.

CONCLUSIONS

1. The Grimes field is a complex of stratigraphic, and fault-stratigraphic lenticular traps on a southwesterly dipping homocline.
2. The accumulation may have started in F-zone time, but it has gone through at least two major periods of adjustment and reaccumulation. At present the fluid-pressure environment is one of the important trapping parameters.
3. The productive limits of the field have not yet been established. From the number of F-zone fields in the Grimes vicinity and from the relative small number of dry holes it seems likely that the Grimes field and some of the other nearby fields will merge into one large continuously productive area.

DISTRIBUTION OF UPPER MIOCENE SANDS AND THEIR RELATION TO PRODUCTION IN THE NORTH MIDWAY AREA, MIDWAY SUNSET FIELD, CALIFORNIA [1]

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Bakersfield, California

ABSTRACT

Upper Miocene sands in the North Midway area are members of the Reef Ridge (Delmontian) and Antelope (Mohnian) formations. Paleontological control is hampered in the Reef Ridge by a complete lack of a diagnostic faunal assemblage. The Antelope has diagnostic faunas but extreme sandiness in the upper part of the formation has resulted in poor definition of the top of the Antelope.

The excellent electric log correlations in the area aid in defining the many sands within the Antelope.

The Williams and Republic Sand members of the Lower Antelope are deltaic deposits. The next younger Antelope member is the Spellacy Sand, a "dump" type deposit. A group of channel sands, the "555", Orloff, Sub-Lakeview, and Lakeview members, are found in the Upper Antelope.

Reef Ridge members include the Potter channel sand and the "33-B" and "42-9" bar sand deposits.

In every case, assuming the rapid formation and migration of oil, production is related to structural high areas developed shortly after the deposition of the various sands. Structural closure, truncation, pinchout, and tar seal and/or surface cementation are the trap types found.

Introduction

On the southwest edge of the San Joaquin Valley of California, snuggled against the Temblors and surrounding the towns of Taft, Maricopa and Fellows, is one of the largest oil fields in the state. The Midway Sunset Field, discovered in 1901, has produced over 853 million barrels of oil. Of this, close to 75% is from Upper Miocene sediments, to date the oldest producing sediments in the field. The total production for this field is almost one seventh of the entire production of the San Joaquin Valley.

Stratigraphy

The youngest sediments beneath the Recent alluvium are Pleistocene Tulare sands, silts, clays, and conglomerates of continental origin which lie unconformably on all formations from Pleistocene age (Fig. 1) to Upper Miocene age. Beneath this unconformity are the Pleistocene-Pliocene San Joaquin formation and Pliocene Etchegoin formation consisting of marine clays and sands. An unconformity exists between the Etchegoin and Pliocene-Miocene Reef Ridge formation.

The Reef Ridge — was first defined by Barbat and Johnson in 1934 and later modified by Seigfus in 1939. Today, in the type area, the Reef Ridge is restricted to the gray and greenish gray, soft, silty claystone and crumbly shale whose age at the top is Pliocene, and at the bottom grades into the McLure brown shale of Upper Miocene age. The type Reef Ridge has a good diagnostic faunal assemblage, but in the Midway Sunset area it contains only nondiagnostic radiolaria and sponge spicules. R. S. Beck believes the type Reef Ridge to be a time equivalent but different facies than that in the Midway Sunset field.

The Reef Ridge shale is impossible to differentiate from the Upper Miocene Antelope formation on the basis of lithology. Both shales are brown, both are locally diatomaceous. With no fauna to aid in identifying the Reef Ridge, the contact is more or less guessed at.

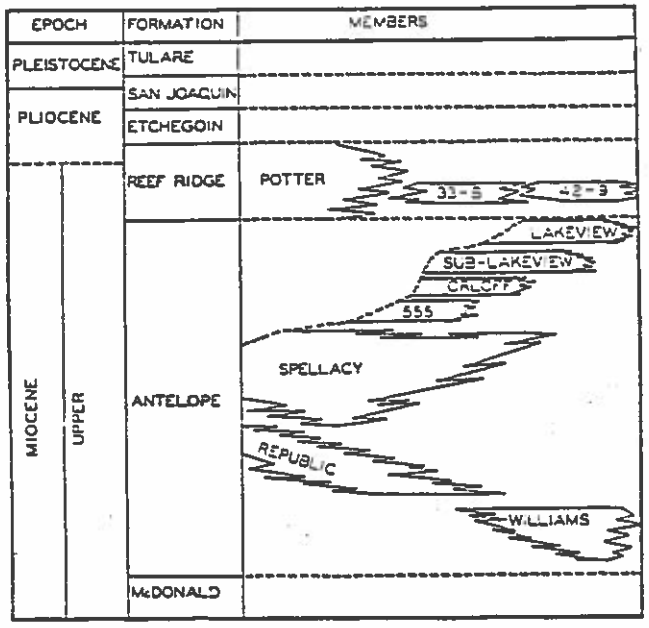

FIG. 1. Stratigraphic column of north Midway Sunset Field

1. Presented to the San Joaquin Geological Society, May 18, 1959.
2. Geologist Great Basin Petroleum Company.

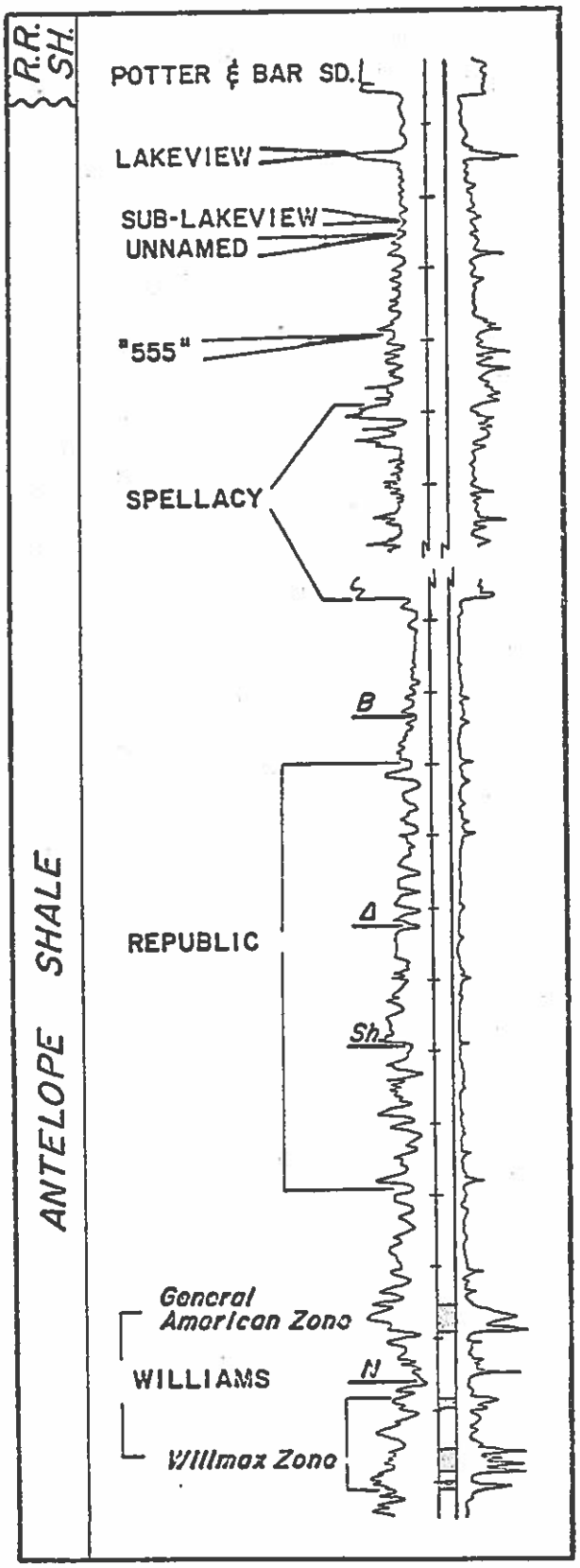

FIG. 2. Type Electric log show stratigraphic occurence of Upper Miocene Sands.

The top of the Antelope formation is usually determined by the first occurrence of *Bolivina vaughani* Natland, but where the top of the Antelope is quite sandy and not an environment to which forams were well adapted, their first occurrence has been as much as 4000 feet low to the true top. In the Midway Syncline area, a lithologic break can be identified from electric logs. This break is approximately 100 feet above the highest occurrence of *Bolivina vaughani*. Electrically the shale above the break reacts on the S. P. curve with a flat response typical of shales. Below the break the S. P. curve exhibits kicks of cyclic nature of from 10 to 30 millivolts. I have picked this break (Fig. 2) as the Reef Ridge—Antelope contact. In the Reef Ridge the resistivity curve can be utilized for correlation, while in the Antelope the S. P. kicks are very easy to correlate. From these correlations it is evident, especially on the United Anticline, that thre is an unconformity at the base of the Reef Ridge. The Antelope here has quite an angular discordance with the Reef Ridge.

Within the Reef Ridge are three sand members, the Potter, the "33-B", and the "42-9" sands. The Potter is considered to be Pliocene-Miocene in age, while th "33-B" and "42-9" sands are Upper Miocene only.

The Antelope Formation is referred to as being a brown shale, but is in reality a siltstone for the most part, sometimes sandy, sometimes diatomaceous, sometimes siliceous. The maximum thickness of the Antelope formation is greater than 7500 feet. As mentioned before the Antelope has, in its siltstone section, a pseudo-porosity which registers on the S. P. curve of E-logs. These kicks are very regular and easily correlatable throughout the area. They reflect minutely different, depositionally controlled, lithologic charactics. Correlation lines between these kicks are in essence time lines. This is substantiated by their paralleling a bentonite bed in the lower Antelope (Fig. 2) referred to herein as the "N" marker. The S. P. correlations in the Upper Antelope aid in easy identification and differentiation of the closely related sands found there. These sands lie between marker silt beds and do not replace the siltstone to any great degree. This is probably due to the rapid deposition of the sands as compared to the slower deposition of the silts which are found to drape over the sands.

The Lakeview, Sublakeview, and Orloff sands are members of the Antelope which are found to occur only in the subsurface east of the area of this paper As noted on Figure No. 1 they are in the upper portion of the Antelope but are overlain by Pliocene sediments because of their high structural position. From east to west these sands are respectively older. The most westerly sand of this group is the "555" sand which because of its low structural position is overlain by Reef Ridge.

The Spellacy sand is locally known as Marvic and Monarch in part. An attempt to correlate anything but the top and the base of the Spellacy sand meets with considerable frustation. The silty intervals within the sand do not adapt as well to correlation as they do above and below.

The lowermost Antelope sand members are the

Republic and Williams sands. The Republic sand is time transgressive while the Williams sand is stable with relation to time.

Structure and Lithology

Figure 3 is a geologic—geographic index. For the unfamilar a review of names may be in order. The main features are the Midway Sunset and Buena Vista Hills Oil Fields.

The Midway Monocline, a structural feature expressed in the Pleistocene and Pliocene sediments, extends from the Midway Syncline to the Republic Anticlinal trend. This trend can be broken into the Republic Anticline, the Willmax Anticline and the General American Anticline. South of this trend another line of folding contains the Bee, Westates and the Williams Anticlines. To the north lie the Globe, Old Belgian and United Anticlines.

Figure 4 is a structure map of the Lower Antelope. The contours are on the "delta" marker. All of the Antelope structures are reflected in the younger sediments except two which are to the north of the Republic anticlinal trend, quite deep in comparison, and have only Williams sand for an objective.

Generally Lower Antelope structures are quite assymetrical with the steep flank on the north. In the "G" Pool area of the Republic Anticline the fold is overturned and is almost directly above the Willmax Anticline.

Faulting is not too common in the area. One and possibly two faults cut the Bee Anticline, three faults cut the Republic Anticline and three cut the Westates Anticline. All the faults are vertical normals and are roughly perpendicular to structural axis. One small reverse fault of 40 feet magnitude has been found between the Oceanic Oil Company "CWOD" No. 2-6, and its redrill in Section 6, T. 32 S., R. 23 E, on the north flank of the Republic Anticline. It is suspected that this fault increases in magnitude with depth and parallels the axis of the anticline. Some faulting is found on the Globe and Old Belgian Anticlines, but the faults are more evident in the younger beds.

The Williams Sand outcrops in Sections 28, 33, 34 and 35, T. 32 S., R. 23 E., as a locally confined body of lensing sand beds. The areal distribution (Fig. 5) of this sand shows a fan shape which streams off to the northwest. In the outcrop area the Williams is quartzose, fine grained to pebbly conglomeratic, but mainly fine to coarse with local occasional beds of subrounded quartz and shale pebbles. Siltstone streaks are rare. As the distance from the outcrop increases the grain size decreases. Well cores in the area of the Midway Syncline find the sand to be silty to fine grained with occasional medium grains. Silt streaks are abundant. Further from the outcrop the sand silts out completely.

The Republic Sand outcrops in Sections 12 and 13, T. 32 S., R. 22 E., and Section 18, T. 32 S., R. 23 E. Although slightly younger than the Williams Sand it is an exact duplicate lithologically. Isopachs and areal distribution (Fig. 5) show a picture very similar to that of the Williams sand. Both sands are deltaic deposits but with one main difference which is a result of the history of their development. The Williams sand was deposited in the Miocene sea as a deltaic deposit. Offshore currents redistributed the deeper sand along the beach to the west and to the east. At this time uplift to the southeast offset the river mouth to the west where Republic sands were then deposited. A slightly different condition set in. While the Republic sands were being deposited uplift to the southeast continued, but even though this uplift continued, the river mouth remained in the same place and the sands became displaced more and more to the west until at last the river mouth was again shifted. In effect the instigation of the rapid uplifting of the granitic mass to the southeast and the rate of its continued growth caused the Williams Sand to be deposited as time static and the Republic Sand to be deposited as time transgressive. Figure 6, a diagrammatic longitudinal section from the west end of the Republic Anticline to the east end of the General American Anticline indicates the time static nature of the Williams sand and clearly shows the Republic sand becomming younger to the west in relation to time equivalent electric log markers. These E-log markers are S. P. "kicks" which can be identified in almost all the wells that penetrate the Antelope in this area. In fact these markers can be identified in a long narrow belt from the McDonald Anticline to the San Emigdio Nose, some 55 miles. Along a line from the north end of the Bee Anticline, down the axis to the southeast, approximately one and one half miles, the Republic Sand drops in stratigraphic interval 325 feet. On the axis of the Republic Anticline the sand gains 325 feet of stratigraphic advantage in just two miles from southeast to northwest. Because of the rapid climb in time of the Republic Sand it is possible in some cases to locate downstructure to gain a higher sand position for a well.

The Spellacy is a series of lensing, lenticular, and discontinuous (Fig. 7) bodies of sand. Lithologically the Spellacy ranges from fine grained to boulder conglomeratic. It is arkosic, kaolinitic, biotitic and has beds of angular to round quartz, feldspar, chert grits and pebbles. Massive granitic boulders are common and silt beds are rare near the outcrop. Further from the outcrop this relation reverses, the boulders becoming rare and siltiness increasing.

The Spellacy is equivalent to Simonson and Kreuger's Santa Margarita of the Crocker Landslide Area. The source of the sand is from an uplifted granitic high area immediately southwest of the San Andreas Fault. Isopachs (Fig. 8) indicate the Spellacy to be confined to the southwest of the Buena Vista Hills, the pinchout of the sand probably occurring low on the flank of Buena Vista. The areal distribution and lithologic character of the Spellacy suggests a "dump" type of deposit filling the low area between the San Andreas granitic high and the growing submarine high of Buena Vista Hills.

"555" Sand— The "555" sand lies in the saddle between Globe, Old Belgian, and United Anticlines and is found only in the subsurface. A tongue of this sand extends up the Midway Monocline and is found in only one well there, the C.W.O.D. No. 39, in Section 25, T. 31 S., R. 22 E. The "555" sand pinches out to the west, south, and east, (Fig. 9) and is also truncated by the Reef Ridge.

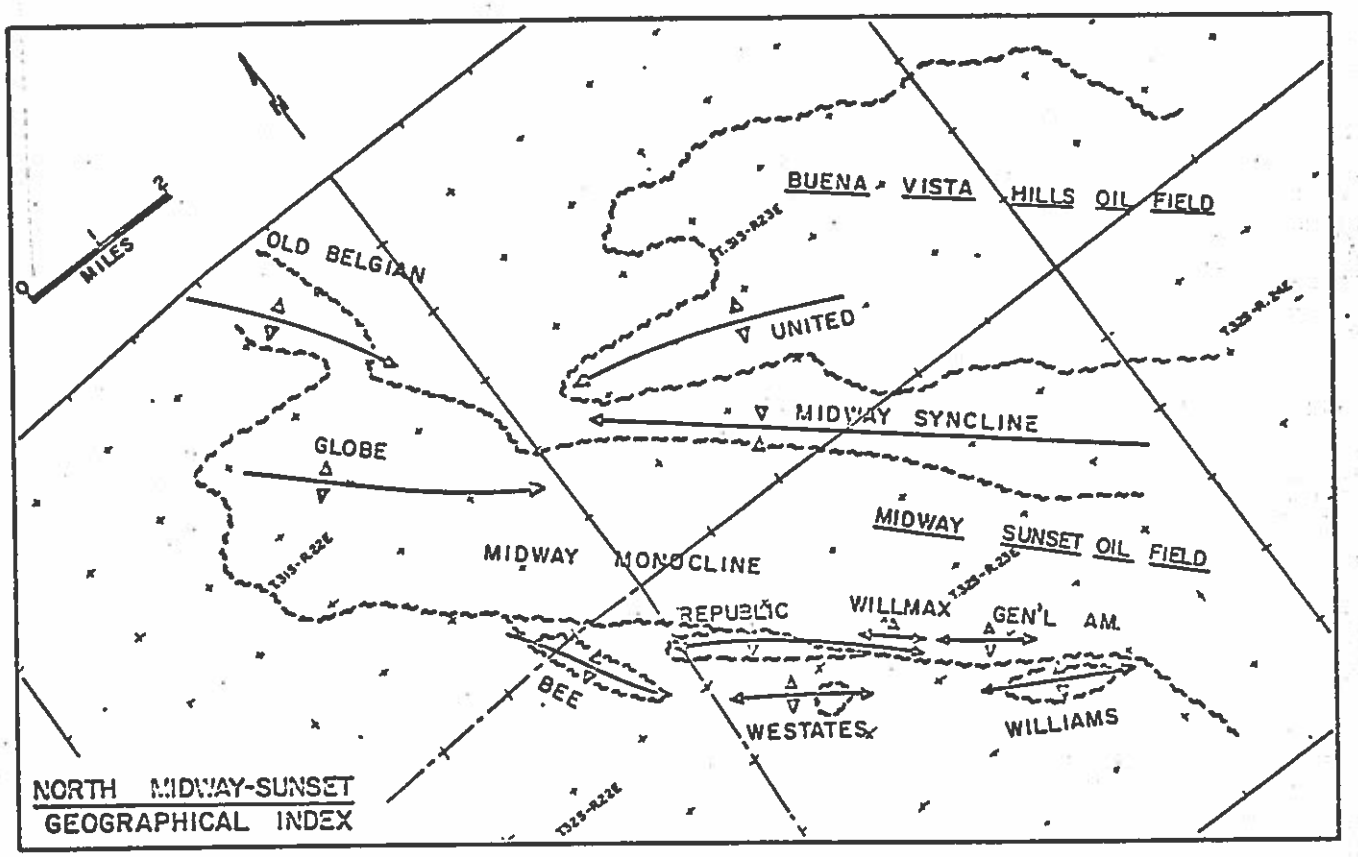

FIG. 3. Index map of geologic and geographic features.

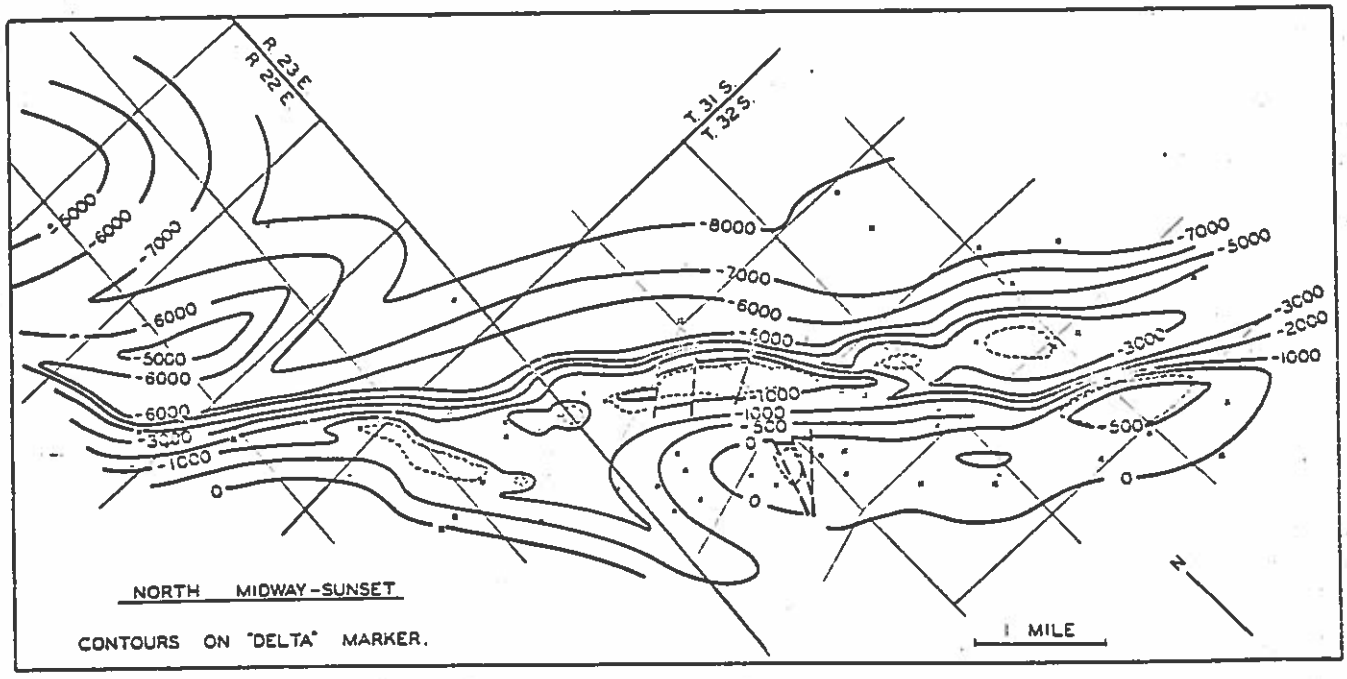

FIG. 4. Structure map drawn "Delta" marker.

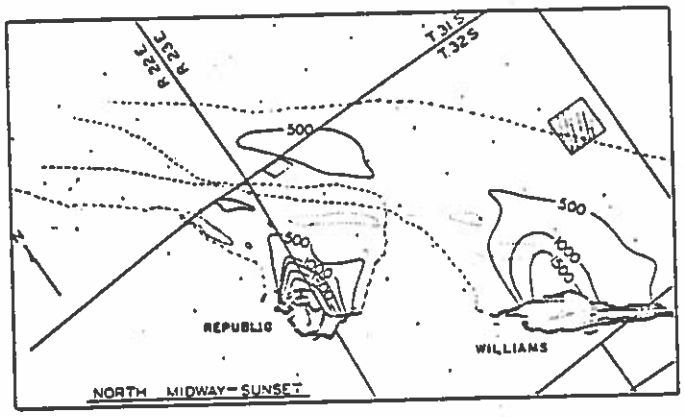

FIG. 5. Aerial distribution and Isopachs of Republic and Williams Sands.

on the nose of the United Anticline. Lithologically the sand is fine to very coarse grained, pebbly, cobbly, kaolinitic, and ill sorted. This lithology is typical of the associated sands to the east, as the Lakeview, etc., In light of areal distribution and lithology the classification of channel sand is suggested. The source material for these channel sands is probably from Spellacy to the southwest.

"33-B" and "42-9" Sands are two closely related Reef Ridge sands. The "33-B", the most westerly sand, forms a single lobe which pinches out on the flank of the Midway Monocline. A maximum of 30 feet of sand has been penetrated. Interfingering with the "33-B" is the "42-9" Sand which also pinches out on the flank of the Midway Monocline but has a double lobed characteristic caused by a small erosional gully in the northwest corner of Section 15, T. 32 S., R 23 E. The updip pinchout of the easterly lobe has not been defined as yet. The maximum thickness of this sand is 100 feet. Lithologically these two sands are both fine to medium grained and well sorted. The areal distribution and lithology of both sands suggests them to be bar sand deposits.

The Potter Sand, the youngest of the Reef Ridge Sands, outcrops (Fig. 7) high on the Midway Monocline. The outcrop thins to southeast and is covered by alluvium to the north. In the subsurface to the north and east the sand pinches out, except on Old Belgian Anticline where erosion has removed it from the crest of the structure. At the outcrop the Potter lies unconformably upon the Spellacy Sand, every where else it lies on Antelope Shale. Overlying the Potter are sediments of Pliocene and Pleistocene age The contours in Figure 10, on the top of the Potter sand, are in reality contours on the unconformity between the Potter and the Etchegoin and do not represent a true picture of Potter structure. Near the updip pinchout of the Potter, on the Midway Monocline, the true dip approaches 45 degrees. Off structure in the Midway Syncline, the dips are more gentle and approximate those shown by the contours. Isopachs show (Fig. 10) that the thickest portion of the sand runs north-south along the east edge of R. 22 E. Before erosion the thickest part of the Potter was probably much further west. Thinning of the Potter to the east is due to shaling out while thinning to the west is the result of erosion. Lithologically the Potter in the outcrop area is a conglomeratic sand; a silt to very coarse-grained matrix with grits and pebbles of shale, quartz, and granite, and granitic boulders. To the north the Potter rapidly becomes less coarse as the distance from the outcrop increases. The areal distribution and lithologic characteristics of this sand suggest it to be a channel sand.

History of Structural Development

During Antelope time the Miocene sea covered the entire valley area. A strong high existed immediately south of the San Andreas Fault which parallels the Midway-Sunset to the southwest. The Williams river (Fig. 11) ran off this high and deposited the Williams deltaic sediments into the sea until uplift to the south east diverted the mouth of the river to the west to the Republic area. Deltaic deposition was then resumed while uplift continued causing the Republic Sand

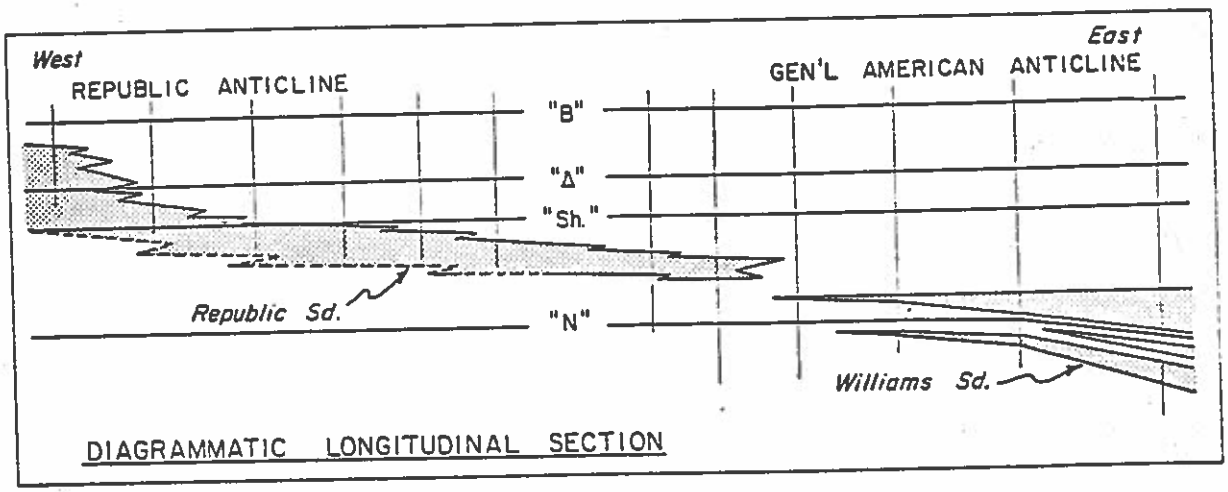

FIG. 6. Diagrammatic section shows relation of Republic to the Williams Sand.

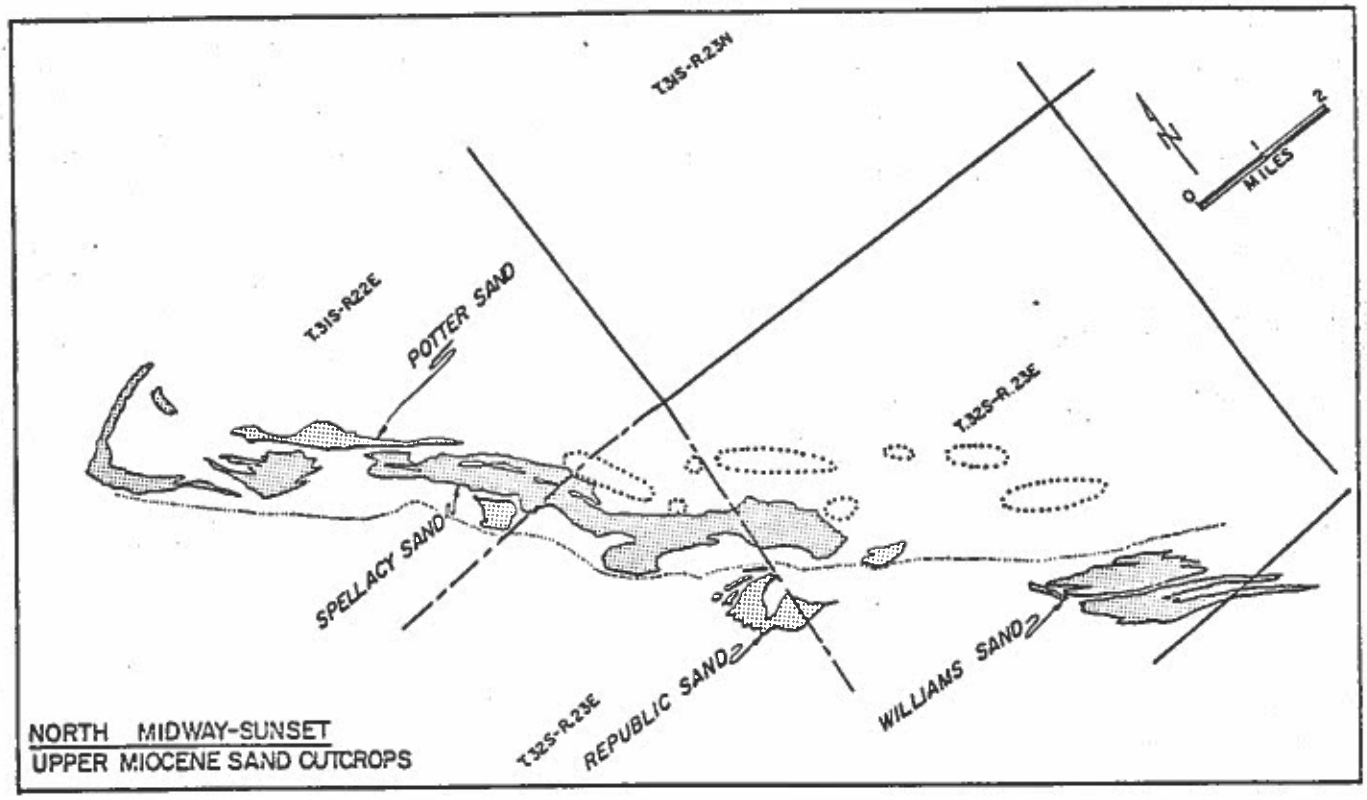

FIG. 7. Outcrop pattern of Upper Miocene Sands

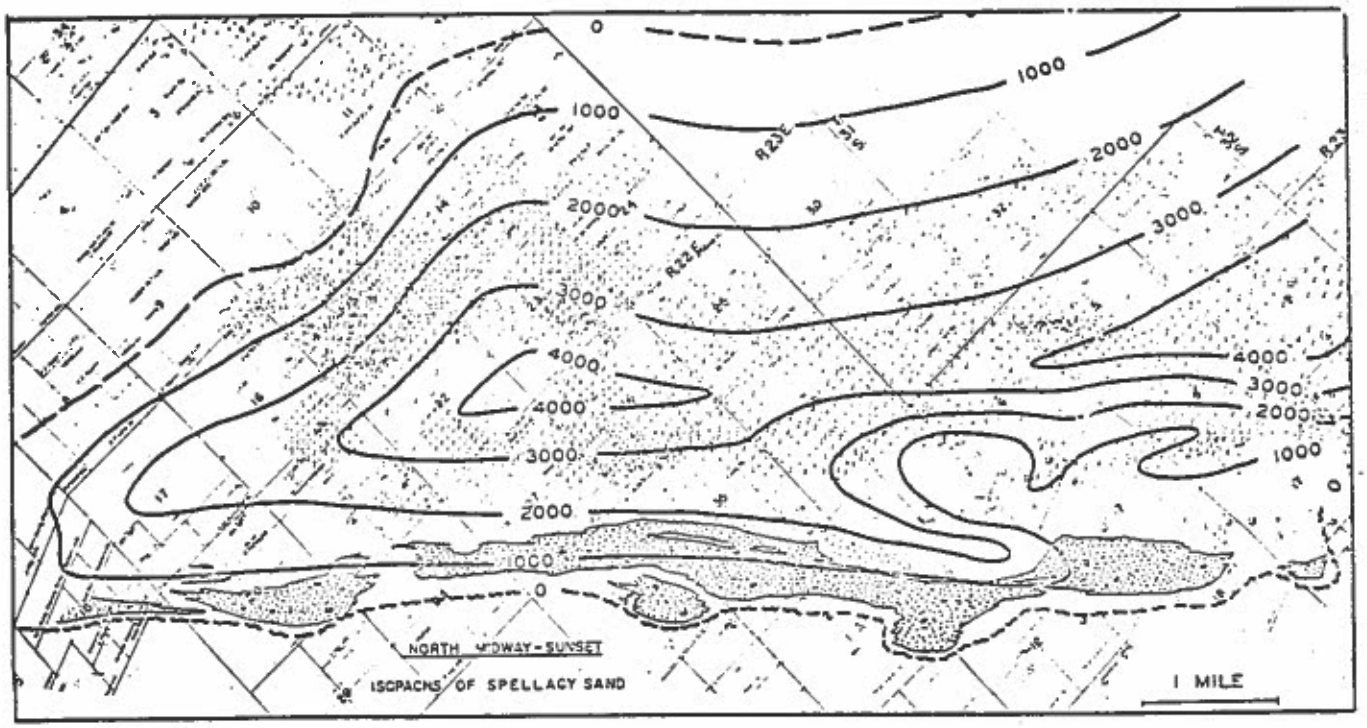

FIG. 8. Isopachs of Spellacy Sand

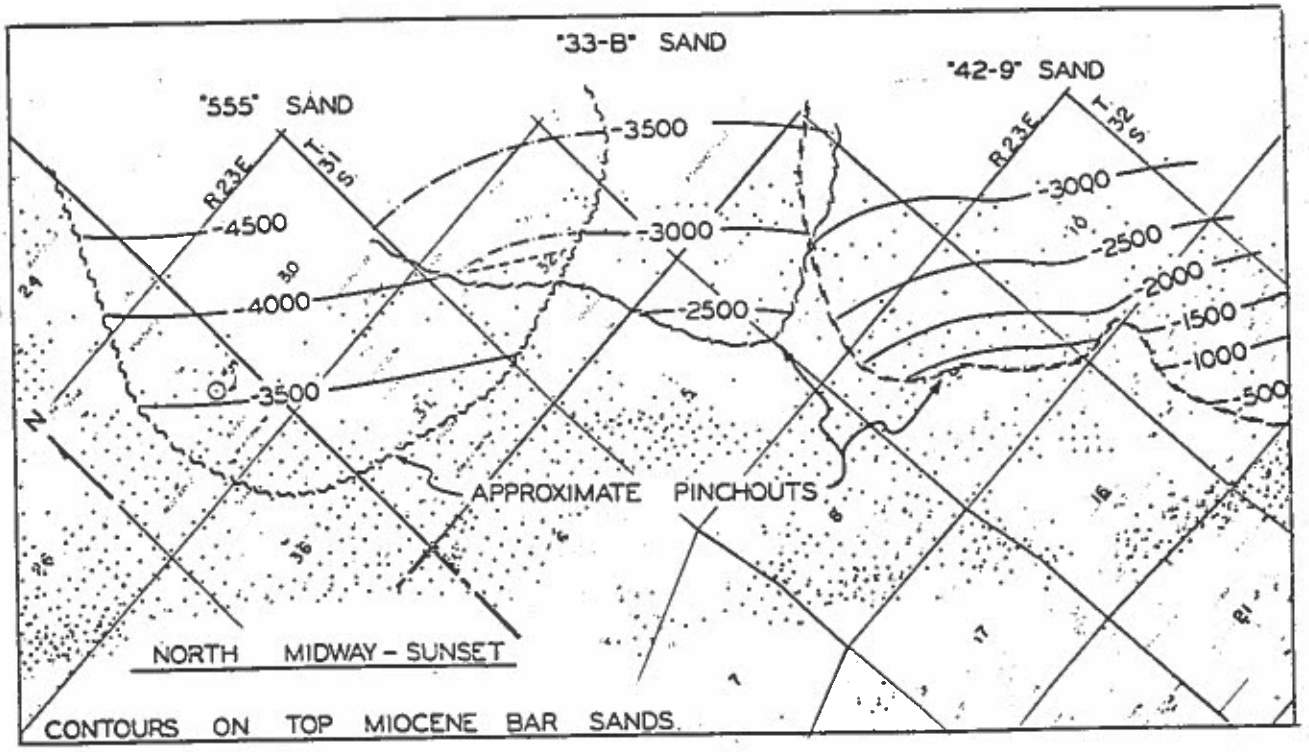

FIG. 9. Structure contours on Miocene Bar Sands.

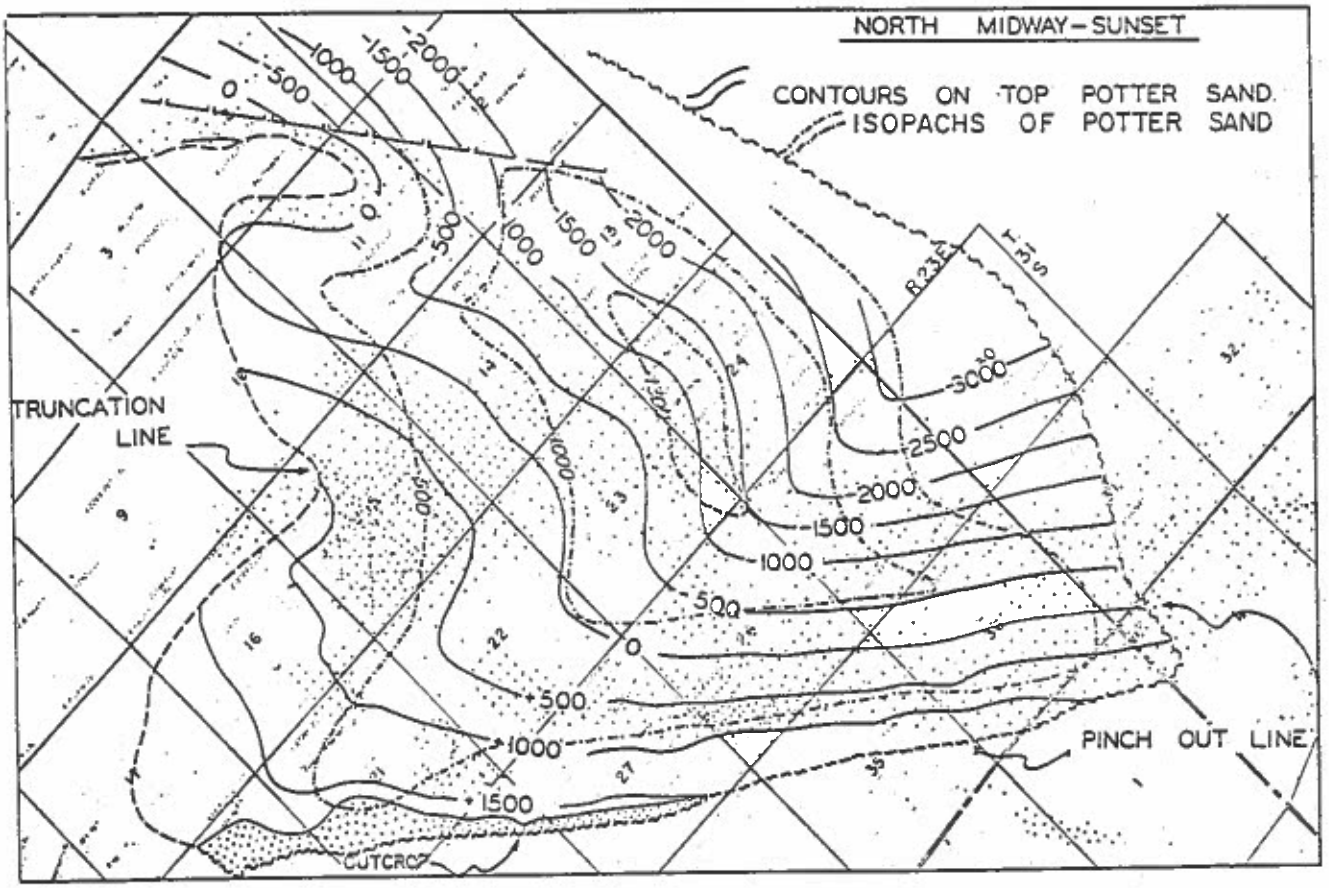

FIG. 10. Potter Sand structure and Isopachs.

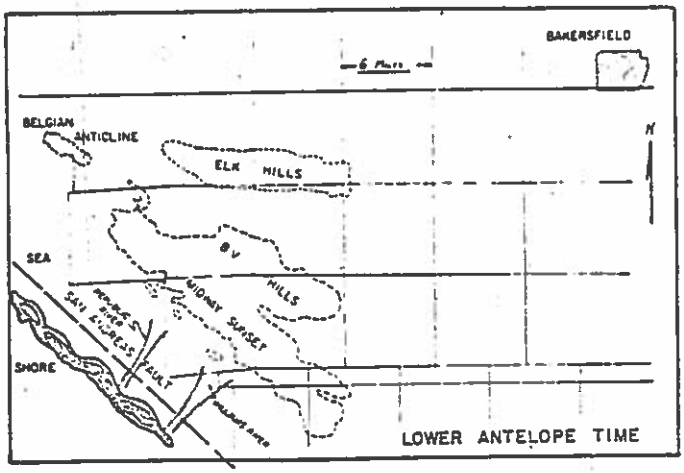

FIG.11. Paleogeographic map of Lower Antelope Time.

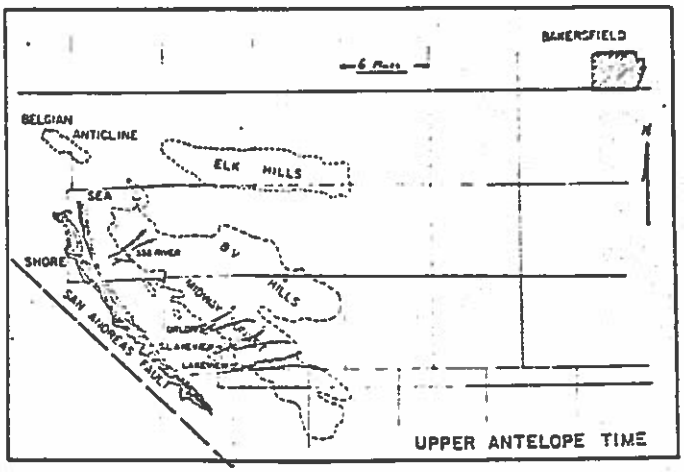

FIG. 12. Paleographic map of Upper Antelope Time.

position to migrate more and more to the west, in effect transgressing time to the west, until the river channel was again diverted to the west and out of this area. At this time Buena Vista Hills began to grow due to compression from the north and south; the gentle submarine growth at Elk Hills and increased uplift south of the San Andreas area.

The granitic mass south of San Andreas was rapidly eroded and the Spellacy sediments were dumped into the hole between Buena Vista Hills and the San Andreas high. Continued compression from the north and south caused a buckling of the sediments in the Temblor-Republic area and increased the growth of Buena Vista Hills. At this point the Temblors emerg-

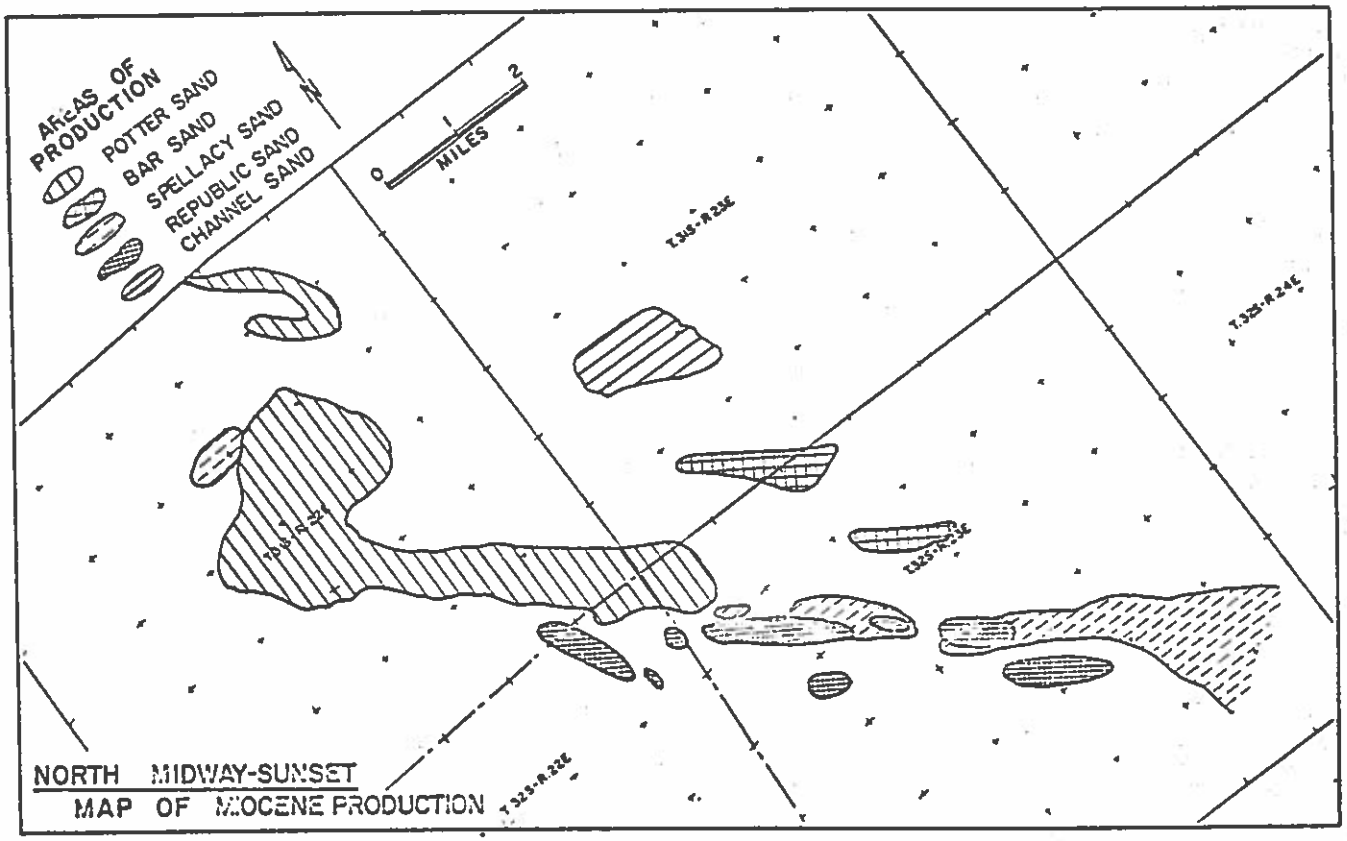

FIG. 13 Aerial distribution of Miocene Productive Sands.

ed from the sea and streams eroded the Spellacy sediments and redeposited them as channel sands (Fig. 12) between the Antelope underwater highs ("555", "Lakeview, etc.") Uplift increased at a rapid rate to the west behind Belgian Anticline causing the Spellacy to again contribute to a large stream which poured into the low area between the Republic trend and around the nose of Buena Vista where the sediments were redeposited as the Potter Sand.

As uplift continued the Potter soon became subject to erosion. After Potter deposition the Buena Vista Hills began to subside allowing Pliocene and Pleistocene sediments to cover them completely to a thickness almost as great as found there today. Compression then recommenced from the north and south reraised Buena Vista, tightening the Republic folds and creating between them a new structure, the Globe Anticline. Nonmarine Tulare sediments were deposited last of all completing the sequence.

Production

Potter Sand: The area of Potter Sand production (Fig. 13) forms a horseshoe around Old Belgian Anticline. Erosion has removed the sand from the crest of the structure, and the sand pinches out to the west. Both truncation and pinchout trap 16.5° oil on this fold. On Globe Anticline and the Midway Monocline three factors: truncation, pinchout, and tar seal and/or cementation by surface waters (in the area of the outcrop) create the traps for production. The gravities range from 11.5° to 16°.

"555" Sand: On the nose of the United Anticline truncation and pinchout trap production in the "555" Sand. This pool has a sizeable gas cap and the oil gravities range from 25° to 30°.

Bar Sands: Pinchouts are the trapping mechanisms for these two sands. The northwesterly pool is the area of "33-B" Sand production. This sand is subcommercial due to the extreme thin and tight nature of the sand. To the southeast the "42-9" Sand produces 20° gravity oil.

Spellacy Sand: On the west edge of the production on Globe Anticline pinchout traps 13° oil in the Marvic Pool. Pinchout is also the trapping agent for the two small pools immediately north of the axis of the Republic Anticline. Various combinations of truncation, pinchout and structural closure result in the trapping of 10° to 16° oil on the rest of the Republic and General American Anticlinal trend.

Republic and Williams Sands: For these sands the majority of the traps are structural closure with a minor contribution due to pinchout. Faulting probably has a negligible influence on the trapping of oil. Oil gravities range from 16° to 24°. Some gas is produced with the oil and the water tables all have some tilt. The Westates Anticline has a very steeply tilted water table in the area of production and oil has been completely flushed from a closure on the easterly end of the Westates fold.

Structure vs. Production: Assuming the rapid formation and migration of oil we find that the early development of the Republic Anticlinal trend resulted in the localization of oil from the early Upper Miocene horizons i. e. Republic, Williams and Spellacy sands. Folding of the Globe Anticline was evidently too late to catch any of this oil except for a very small amount as found in the Marvic Pool, even though a large Spellacy trap was available. Globe was not formed too late for the Potter Sand traps to be filled to a great degree yet late enough so that some Potter oil reached the Midway Monocline.

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