Petroleum Systems and Geologic Assessment of Oil and Gas in the San Joaquin Basin Province, California

Chapter 6

# Middle Tertiary Stratigraphic Sequences of the San Joaquin Basin, California

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## Contents



## Abstract

An integrated database of outcrop studies, borehole logs, and seismic-reflection profiles is used to divide Eocene through Miocene strata of the central and southern San Joaquin Basin, California, into a framework of nine stratigraphic sequences. These third- and higher-order sequences (<3 m.y. duration) comprise the principal intervals for petroleum assessment for the basin, including key reservoir and source rock intervals. Important characteristics of each sequence are discussed, including distribution and stratigraphic relationships, sedimentary facies, regional correlation, and age relations. This higher-order stratigraphic packaging represents relatively short-term fluctuations in various forcing factors including climatic effects, changes in sediment supply, local and regional tectonism, and fluctuations in global eustatic sea level. These stratigraphic packages occur within the context of second-order stratigraphic megasequences, which mainly reflect long-term tectonic basin evolution. Despite more than a century of petroleum exploration in the San Joaquin Basin, many uncertainties remain regarding the age, correlation, and origin of the third- and higher-order sequences. Nevertheless, a sequence stratigraphic approach allows definition of key intervals based on genetic affinity rather than purely lithostratigraphic relationships, and thus is useful for reconstructing the multiphase history of this basin, as well as understanding its petroleum systems.

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## Introduction

A growing recognition over the past quarter century that the distribution of petroleum source and reservoir rocks is best understood in a sequence-stratigraphic context motivated analysis of San Joaquin Basin fill as an underpinning element of a regional San Joaquin Basin petroleum-resource assessment conducted by the U.S. Geological Survey (USGS). Accordingly, we present a sequence-stratigraphic framework for the San Joaquin Basin in which Eocene through Miocene third- and fourth-order (<3 m.y.) sequences, the focus of this paper, are set against a backdrop of long-term, second-order (approximately 3 to 50 m.y.) stratigraphic megasequences. These short-term, higher-frequency, middle Tertiary sequences form many of the intervals for petroleum assessment that are the main emphasis of the regional project. In addition to helping define large-scale stratigraphic architecture of the San Joaquin Basin, this sequence-stratigraphic framework integrates outcrop relations with subsurface mapping controlled by seismic and borehole data and thus provides control points for geochemical and stratigraphic basin modeling reported in other chapters in this volume.

## Database

The area analyzed in this paper includes the east-west width of the San Joaquin Basin from the San Andreas Fault to the Sierra Nevada and extends from the Bakersfield Arch to just north of Coalinga (~ Range 15 East through Range 26 East, Township 18 South through Township 29 South; fig. 6.1). Data used in this study include more than 500 line-miles (> 800 km) of publicly released and proprietary two-dimensional seismic-reflection data, and standard well-log suites (mainly spontaneous-potential and resistivity curves) from more than 200 exploration and production boreholes. These data are integrated with literature summarizing outcrop and subsurface relations, including more than 20 unpublished or partially published M.S. theses and Ph.D. dissertations produced as part of the San Joaquin Basin Consortium at Stanford University during 1981-1999.

## Methods

Stratigraphic fill in marine basins records changes in accommodation space and sediment supply, which are controlled

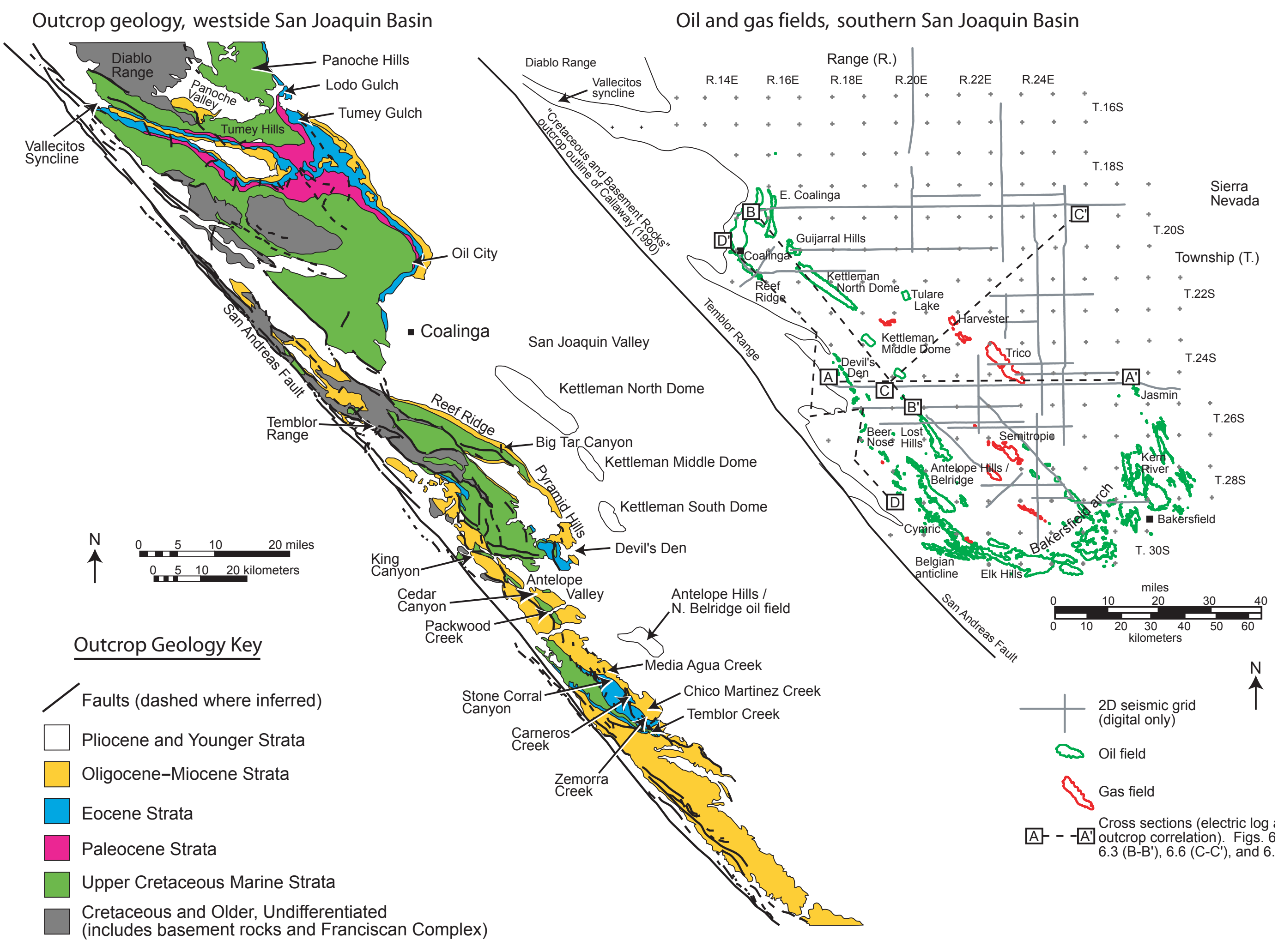


**Fig. 6.1.** Location map of study area, showing (right side) oil and gas fields of the southern San Joaquin Basin, part of the grid of two-dimensional seismic data used in this study (figure shows only those surveys available in digital format), and cross section lines for well correlations presented in figures 6.2, 6.3, and 6.6. Not shown are more than 200 key well locations for other boreholes used in this study. Left-side shows Upper Cretaceous through Miocene outcrop geology of the western San Joaquin Basin. Geologic relations are simplified from California Division of Mines and Geology

by a complex interplay of factors including global eustatic sea-level changes, local tectonic subsidence and uplift, and climate change (Emery and Myers, 1996; Posamentier and Allen, 1999; Coe, 2003). Isolating the signatures and relative importance of each of these individual factors is both challenging and controversial. The San Joaquin Basin records a long history (> 100 m.y.) of marine and marginal-marine deposition, and therefore, might seem to be a prime candidate for correlation of basin stratigraphy to global coastal onlap curves (for example, Haq and others 1988; Hardenbol and others, 1998). However, the Cenozoic history of the San Joaquin Basin also includes its evolution from a one-sided forearc basin to an initially embayed and finally ponded transform-margin basin (Graham, 1987; Bartow, 1991). Thus, impacts of tectonism on sedimentation and stratigraphy have been dominant. Additional controlling factors such as climate change and rates of sediment input (particularly along the eastern margin of the basin, coordinate with the evolution of Sierran volcanic provinces; for example, Bent, 1985) seem likely to have influenced sequence-stratigraphic development in the San Joaquin Basin. To date, these factors have been incompletely incorporated in regional syntheses of basin stratigraphy.

Sequence-stratigraphic concepts and methods were slow to be applied to the San Joaquin Basin following publication of American Association of Petroleum Geologists Memoir 26 (Payton, 1977), the seminal volume on sequence stratigraphy, although important concepts of stratigraphic packaging were anticipated by Foss (1972a,b). Published interpretations of the sequence stratigraphy of the San Joaquin Basin began to appear in the last half of the 1980’s and early 1990’s, including Bloch (1991a,b), Callaway (1990), Callaway and Rennie (1991), Hewlett and Jordan (1993), and Tye and others (1993). These studies produced generally compatible stratigraphic frameworks, although they differed slightly on sequence definition and more significantly on interpretation of controls. These major advances, nonetheless, were limited by temporal and/or geographic scope or by a paucity of corroborating data. Fifteen years later, they remain the principal published regional sequence-stratigraphic studies of the San Joaquin Basin, although subsequent largely unpublished proprietary studies exist (summarized by Nilsen and others, 2004; Reid and others, 2004).

Following Van Wagoner and others (1990), Emery and Myers (1996), and Posamentier and Allen (1999), we recognize a hierarchical arrangement of stratigraphic cycles or sequences in the fill of the San Joaquin Basin, based on the distribution of regional unconformities and patterns of sediment accumulation. These range from large, long-duration (approximately 3 to 50 m.y.; Emery and Myers, 1996) megasequences (equivalent to second-order sequences; Hubbard, 1988; Graham and Johnson, 2004) recognizable on reflection-seismic data, to relatively short-duration third-order (approximately 0.5 to 3 m.y.), fourth-order (approximately 0.1 to 0.5 m.y.), and higher-resolution sequences (also referred to as parasequences; Van Wagoner and others, 1990; Emery and Myers, 1996) recognizable in borehole logs and in outcrop. We suggest that the existence of stratigraphic megasequences reflects long-term tectonic controls on basin evolution (table 6.1) Graham, 1987; Johnson and Graham, 2004); these megasequences provide a context for the third-order sequences usually emphasized in petroleum-related studies. However, in this paper, we focus not on the megasequences, but on the third-order and fourth-order sequences of the Eocene through middle Miocene stratigraphic section that are principal concerns of the USGS San Joaquin Basin petroleum-resource assessment. These sequences also comprise the smallest, relatively easily correlated, stratigraphic subdivisions of the basin fill, and correspond to most mapped formation and member units, as well as petroleum source and reservoir rocks.

In keeping with the original definitions proposed by Mitchum and others (1977), the depositional sequences described in this study are stratigraphic packages bounded by unconformities or their correlative conformities. Unconformities are recognized in subsurface data as surfaces that overlie erosionally truncated units, and/or surfaces that progressively lap onto older units. Although significant angular unconformities exist in the San Joaquin Basin, particularly along its western margin, depositional unconformities not directly formed by significant tectonic folding and beveling of units commonly demonstrate only minor evidence of erosion. In these cases, onlapping reflectors indicating a major landward shift in marine deposition (transgressive surfaces) are commonly the best evidence of a genetic sequence boundary (Galloway, 1989).

Because of the relatively low resolution of many seismic data sets, and in particular, portions of our San Joaquin seismic data set, our sequence-stratigraphic framework is based to a significant extent on borehole data, including wireline logs, micropaleontologic age determinations, and core descriptions. As noted by Galloway (1989), borehole data often provide the best sequence-stratigraphic information, such as documentation of flooding surfaces, where cycles are too thin to be resolved by the reflection-seismic method, or where sequence boundaries lack significant angularity.

The departure point for our analysis was the work of Bloch (1991a,b), who pioneered integrated sequence-stratigraphic analysis of biostratigraphy, lithofacies, core description and seismic and wireline log responses in the San Joaquin Basin. The following description of Eocene through middle Miocene units of the San Joaquin Basin generally follows the framework erected by Bloch (1991a,b), with a few modifications. For each sequence, we briefly discuss distribution, existing knowledge of age control, and sedimentary characteristics. In this summary, we do not discuss details of stratigraphic subdivisions, nor do we interpret controls on the stratigraphy. Rather, we emphasize observations that relate to sequence-stratigraphic relations and hydrocarbon potential.

Understanding San Joaquin Basin stratigraphy involves unraveling a complex and confusing nomenclature (Callaway and Rennie, 1991). We generally follow usages and correlations outlined by Foss and Blaisdell (1968), Foss (1972a,b), the Correlation of Stratigraphic Units of North America (COSUNA) Project (Bishop and Davis, 1984), and the geologic names lexicon website (http://ngmdb.usgs.gov/Geo-

**Table 6.1.** Overview of 3rd through 4th order stratigraphic sequences of the central and southern San Joaquin Basin.

[Approximate ages of sequence boundaries are shown, along with environmental and systems tracts assignments, where possible. Formation names in italics are informal; see references listed below. Abbreviations are as follows: SB = Sequence boundary, LS/HS/RS/TS = Lowstand/Highstand/Regressive/ Transgressive systems tracts, FS = Flooding surface, Olig. = Oligocene, Eo. = Eocene]

| | | Sequence | Landward-onlapping deposits (TS) | Shelf and slope deposits (LS + HS) | Slope & basin floor turbidite fan systems | Basinal shale deposits |
|---|---|---|---|---|---|---|
| | | **~15 Ma SB** | | | | |
| "Olcese/Monterey Megasequence" (continues to ~6.5 Ma) | lower Miocene | "Olcese/upper Temblor equivalent" | Devilwater Sh. Mbr., Buttonbed Ss. Mbr. | upper Temblor Formation | | Gould Shale Member, *600 ft shale* |
| | | | **~16.5--17.5 Ma SB / TS** | | | |
| | | | | upper Olcese Sand (HS) | | Media Shale Member, *800' shale* |
| | | | **FS (800' shale)** | | | |
| | | | middle Olcese Sand (TS) | lower-middle Olcese Sd. (LS?) | Carneros Sandstone Member (LS) | |
| | | | **~21Ma SB** | | | |
| | | | | lower Olcese Sand/ *lower variegated sh.; Rio Bravo sand* | | Freeman Silt (FS), upper Santos Shale Mbr. |
| | | **~23 Ma SB** | | | | |
| "Vedder/Temblor Megasequence" | upper Olig. | "upper Vedder/ Vaqueros/ lower Temblor equivalent" | *Felix slts.? 5th sand, Rio Bravo sand./* Pyramid Hills Sand Mbr. | lower Temblor Fm., upper Vedder Sd. / *Burbank sd.* (LS); Agua Sandstone Bed (HS?) | *Belridge 64 sand / Bloemer sand (LS?)* | lower-mddle Santos Shale Member |
| | | **~28-29 Ma SB** | | | | |
| | lower Oligocene | "lower Vedder/ Vaqueros equivalent" | | *Allison sand /* upper Vaqueros Formation (HS) | | *Whepley sh.* / upper Vaqueros Fm. / lower Vedder Sd. / lower Santos Sh. Mbr. |
| | | | **FS (Upper Cymric Shale)** | | | |
| | | | upper Vaqueros Fm. (?) | Vaqueros Fm. / lower Vedder Sd. (LS?); lower Temblor Fm. (Wygal Ss. Mbr.) | lower Vaqueros Formation (LS?) | lower Vaqueros Fm. / lower Santos Shale Mbr. / lower Cymric Shale Mbr. |
| | | **~36 Ma SB** | | | | |
| "Kreyenhagen Megasequence" | upper Eo. | "Tumey/ Wagonwheel" | Wagonwheel Formation | Wagonwheel Fm. (LS?), *Leda sand* (RS?) | | *Tumey formation* |
| | | **38-40.5 Ma SB** | | | | |
| | middle Eocene | "Kreyenhagen" | Domengine Formation | *Famoso sand* (HS - eastern San Joaquin Basin | Point of Rocks Sandstone Member | Kreyenhagen Formation |
| | | **~49-50 Ma SB** | | | | |
| "Moreno/Lodo Megasequence" | lower Eocene | " Lodo" | | *Gatchell sand*, Yokut Ss. / *Loescher sds.* (HS?), *upper McAdams ss.* (LS) | Cantua Sandstone Member (LS?) | upper Arroyo Hondo Shale Member |
| | | | **~ 52 Ma SB** | | | |
| | | | | *sub-Gatchell sand; lower McAdams ss. (HS/LS)* | | lower Arroyo Hondo Shale Member |
| | | **~54-55 Ma SB** | | | | |
| | Paleo-cene | "Martinez/ Lower Lodo" | Martinez Formation (glauconitic silt) | Martinez Formation (HS) | *San Carlos sand* | Cerros Shale Member |
| | | **~ 60 Ma SB** | | | | |

References for informal geologic formation names:
5th sand of Kuespert (1985); 600 ft shale of Dodd and Kaplow (1933); 800 ft shale of Dodd and Kaplow (1933); Allison sand of Sullivan (1963); Belridge 64 sand of Foss and Blaisdell (1968); Bloemer sand of Williams (1938); Burbank sand of Sullivan (1966); Famoso sand of Edwards (1943); Felix siltstone of Dodd and Kaplow (1933); Gatchell sand of Goudkoff (1943); Leda sand of Sullivan (1963); Loescher sands of Callaway (1990); McAdams sandstone of Sullivan (1963); Rio Bravo sand of Noble (1940); San Carlos sand of Wilkinson (1960); Tumey formation of Atwill (1935); variegated shale of Dodd and Kaplow (1933); Whepley shale of Dodd and Kaplow (1933).

lex/geolex_home.html) of the USGS, unless otherwise noted. Our chronostratigraphy follows Bloch (1991b), with some modifications. Interpretations of sedimentary facies and paleoenvironment are also key to accurate sequence-stratigraphic interpretations. Such interpretations are most commonly and easily evaluated for outcropping strata along the western margin of the basin, and the eastern margin of the basin around Bakersfield. Well-substantiated environmental interpretations for the majority of basin fill in the subsurface are limited, and significant facies changes from the outcrop belts to the subsurface basin center render paleoenvironmental extrapolations quite difficult. In this discussion, we have attempted to use as many sources of information as possible to constrain our sequence-stratigraphic correlations and paleoenvironmental determinations into the center of the basin, but we acknowledge significant uncertainty in some interpretations.

# Eocene Through Lower Miocene Sequence Stratigraphy of the Central San Joaquin Basin

The sequences defined here highlight Eocene through Miocene strata containing important hydrocarbon source or reservoir intervals, or units of particular sequence-stratigraphic significance. Depositional sequences highlighted in this paper include all or parts of the “Moreno/Lodo,” “Kreyenhagen,” “Vedder/Temblor,” and “Olcese/Monterey” megasequences of Graham and Johnson (2004). These megasequences are major stratigraphic divisions of sedimentary fill, representing time intervals of about 8 to 14 m.y. We summarize these in table 6.1 and illustrate areal relations of the third-order sequences contained within the megasequences by means of two intersecting stratigraphic sections shown in figures 6.1 through 6.3. These roughly orthogonal sections were chosen to sample stratigraphy along a transverse (depositional dip) direction (fig. 6.2), as well as longitudinally from north to south along the early and middle Cenozoic basin axis, now uplifted along the crest of the frontal folds of the basin’s western fold-thrust belt (fig. 6.3). A chronostratigraphic section (fig. 6.4) generally coincident with the longitudinal section (fig. 6.2) helps clarify stratigraphic relations. The dip section is placed to illustrate relations in the vicinity of the deep hydrocarbon play of the last few years along the eastern flank of Lost Hills anticline, as well as to be approximately coincident with control provided by a published seismic line (Bloch, 1991b).

The two stratigraphic sections are ornamented with four basic lithofacies (table 6.1): (1) basin-floor fan and other bathyal sand-rich deposits (orange), (2) mudstone/shale (blue) known or presumed to be bathyal in origin (for example, Bandy and Arnal, 1969), (3) transgressive sandy deposits onlapping significant unconformities (green), and (4) sand-rich progradational highstand deposits (yellow). In this paper, lowstand prograding complexes are undifferentiated from highstand progradational deposits. The bathyal mudstone certainly includes highstand depositional-systems tracts, as predicted by sequence-stratigraphic models (Emery and Myers, 1996), but also includes deep-water mud deposited during all other relative sea-level states, because the central portions of the basin remained at bathyal depths for nearly all of Eocene through Miocene time (Bandy and Arnal, 1969). All types of sandy units produce oil and (or) gas in some locality in the basin, whereas nearly all of the mudstone sequences contain source-rock intervals, as documented in other chapters of this volume (for example, Lillis and Magoon, this volume, chapter 9). The datum for the east-west section (fig. 6.2) is the easily correlated Round Mountain Silt flooding interval, whereas the datum for the north-south section (fig. 6.3) is the “N Point chert” flooding unit (Graham and Williams, 1985) within the upper Monterey Formation, because it is more readily recognized along the northwestern basin margin. The sections share two common wells at their right-angle intersection on Lost Hills anticline.

## Upper Paleocene Through Lower Eocene Martinez Formation and Lodo Formation

Upper Paleocene through lower Eocene strata of the San Joaquin Basin are poorly known compared to the rest of the Paleogene section. Various studies have assigned the Martinez Formation to either the upper part of the Moreno Formation (Dos Palos Shale Member and Cima Sandstone Lentil; discussion in McGuire, 1988a,b) or to the lower member of the Paleocene through Eocene Lodo Formation (Goudkoff, 1945; Mallory, 1959). Several lines of evidence support the presence of an unconformity-bounded sequence assigned to the upper Paleocene Martinez Formation in the subsurface. Almgren and others (1988) described an unconformity-bounded, upper Paleocene section at Oil City, Lodo Gulch, and Media Agua Creek, which is implied to form the lower part of the Lodo Formation. According to Bloch (1991a), the upper Paleocene sequence is transgressive at its base, and regressive upward, based on well-log character, which also implies the existence of a separate unit. Thus, it is likely that the Martinez Formation constitutes a depositional sequence distinct from the Lodo Formation. Given the lack of published data on Martinez Formation stratigraphy, we emphasize the overlying Paleocene through Eocene Lodo Formation in this discussion.

### Distribution and Stratigraphic Relations

Paleocene through Eocene strata of the Lodo Formation extend from the northern San Joaquin Valley to Media Agua Creek on the west side of the San Joaquin Valley (fig. 6.4). The best exposures of Eocene strata occur in the Vallecitos Syncline on the western edge of the northern San Joaquin Basin, where Paleocene-lower Oligocene strata form up to 2,300 m of cumulative section (Anderson, 1998). The Lodo Formation is dominantly shaley, but includes sand-rich turbidite members in the western basin region (for example, San Carlos sand of Wilkinson, 1960, hereafter referred to as San Carlos sand, and Cantua Sandstone Member) (Anderson, 1998) and equivalent sand-rich shelfal facies to the east (for example, Gatchell sand of Goudkoff, 1943, hereafter referred to as Gatchell sand) (Graham and Berry, 1979). Members of the Lodo Formation are mapped extensively in the subsurface throughout the San Joaquin Basin, although significant westward tilting and erosion beneath the overlying Domengine Formation unconformity limit its preserved thickness in some areas (Schulein, 1993). The Lodo Formation unconformably overlies the Moreno Formation in the Panoche Hills and Vallecitos Syncline, where the unconformity with the basal San Carlos sandstone likely represents less than a 3 m.y. hiatus (McGuire, 1988a,b). The uppermost Arroyo Hondo Shale Member exposed in the Vallecitos area north of Panoche Hills is the deep-water equivalent to the shallow-marine Gatchell sand (equivalent to the lower McAdams sandstone of Sullivan, 1963) described by Harun (1984) in the subsurface south and east of the Coalinga anticline. The Gatchell sand also appears to be at least partially time-equivalent with deposition of the Cantua Sandstone Member (Graham and Berry, 1979).

### Age

Anderson (1998) reviewed and improved age control for the Lodo Formation. According to him, the turbiditic basal San Carlos sand overlies shale with CP4 nannofossils (as old as 60 Ma).

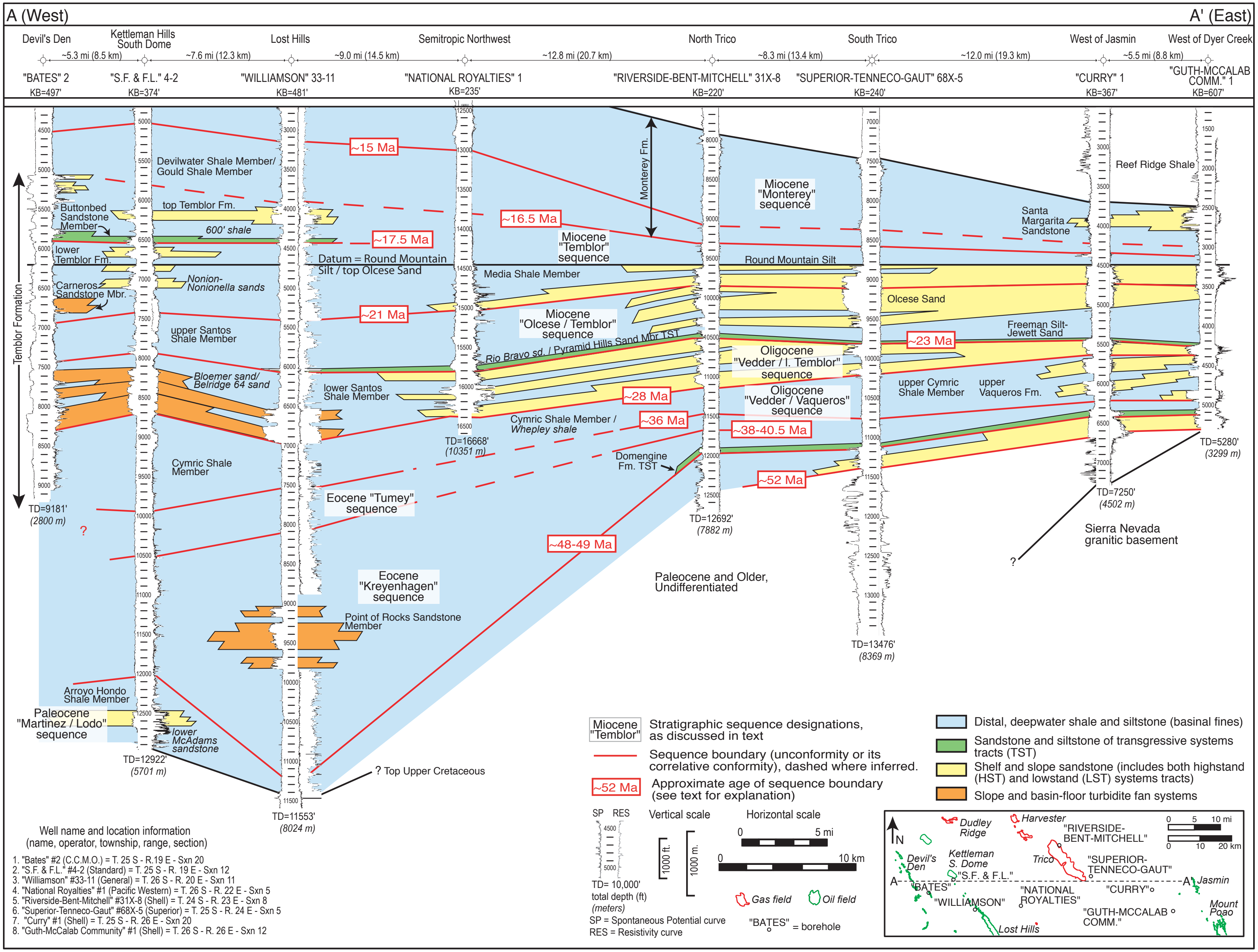


**Fig. 6.2.** East-west (depositional dip) stratigraphic cross section, central San Joaquin Basin. Location of key wells shown in inset. Interpretation of stratigraphic sequences, sequence boundaries including approximate age assignments, and systems tract assignments follows text and table 6.1. Formation names in italics are informal; references for these appear in text and table 6.1.

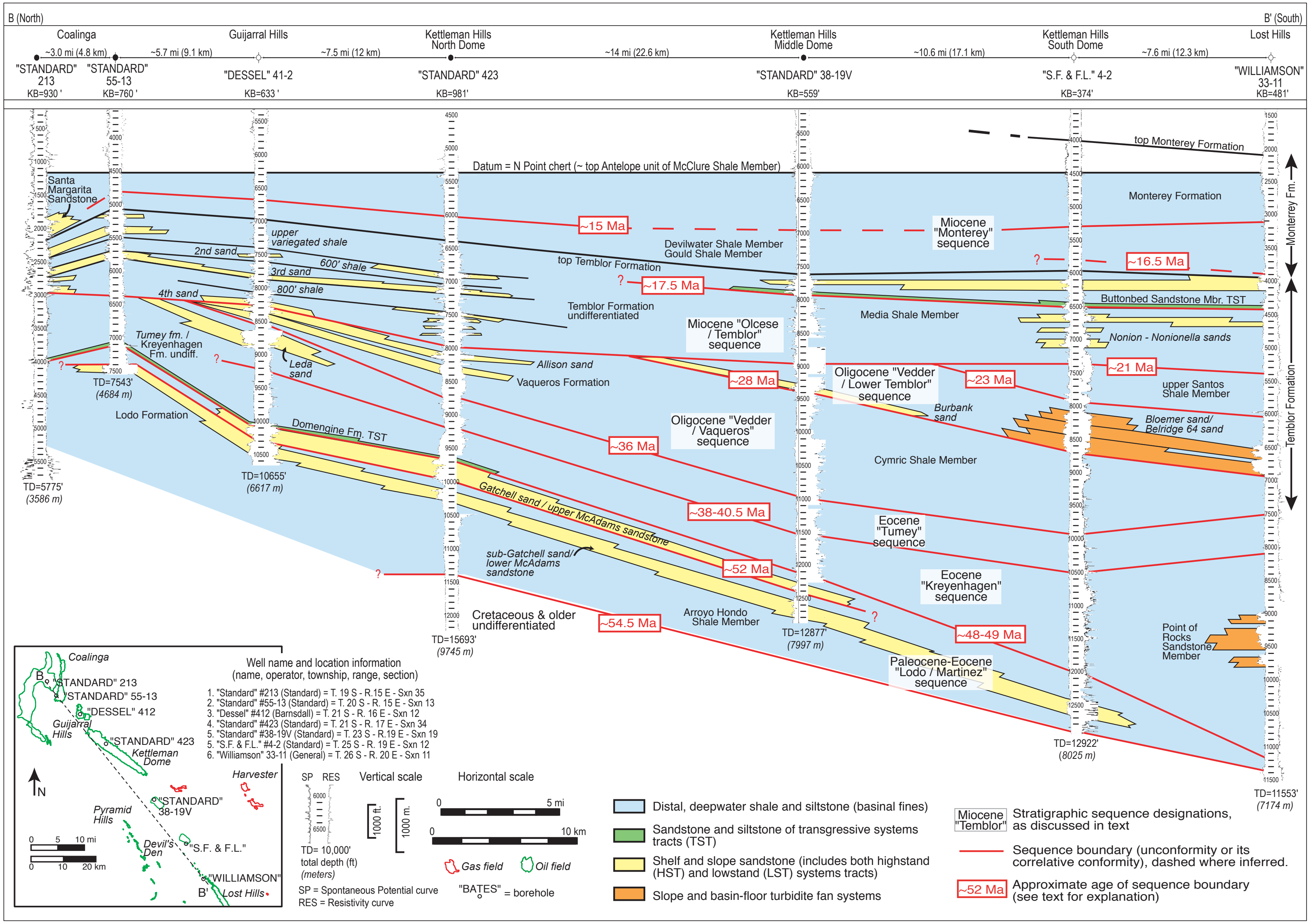


**Fig. 6.3.** North-south (parallel to basin axis) stratigraphic cross section, west-side San Joaquin Basin. Locations of key wells are shown in inset. Interpretation of stratigraphic sequences, sequence boundaries including approximate age assignments, and systems tract assignments follows text and table 6.1. Formation names in italics are informal; references for these appear in text and table 6.1. Other informal names not previously defined are the second, third, and fourth sand, all of Kuespert (1985).

The overlying Cerros Shale Member contains CP8b to CP9b nannofossils. The turbiditic Cantua Sandstone Member is assigned to zone CP10, and underlies the bathyal Arroyo Hondo Shale Member, which also contains CP10 to CP12a nannofossils. These data constrain the age of the entire Lodo Formation to about 60 to 48 Ma (and most likely 57.1 to 49.5 Ma) (Anderson, 1998).

## Middle Eocene Domengine Formation and Middle Eocene Kreyenhagen Formation

### Distribution and Stratigraphic Relations

A major middle Eocene transgression affected the entire central California margin and submerged a broad area spanning hundreds of kilometers from the southern Temblor Range to the San Francisco Bay area (fig. 6.4) (Milam, 1984, 1985; Bartow, 1991; Bloch, 1991a,b) and eastward in the subsurface nearly across the entire basin. The Kreyenhagen Formation represents the second of three major highstand sequences of latest Cretaceous to Recent age (including deposits of the Moreno and Monterey Formations). Bathyal facies of the Kreyenhagen Formation are proven oil sources (Lillis and Magoon, this volume, chapter 9; Peters, Magoon, Valin, and Lillis, this volume, chapter 11). Members of the Kreyenhagen Formation are exposed along the entire western outcrop belt from the Temblor Range to the northern Diablo Range.

The Kreyenhagen Formation is dominantly shaley, but it encloses turbiditic sandstone members and has transgressive shallow-marine sandstone units at its base (Domengine Formation; fig. 6.2) and as eastern equivalents (Harun, 1984).

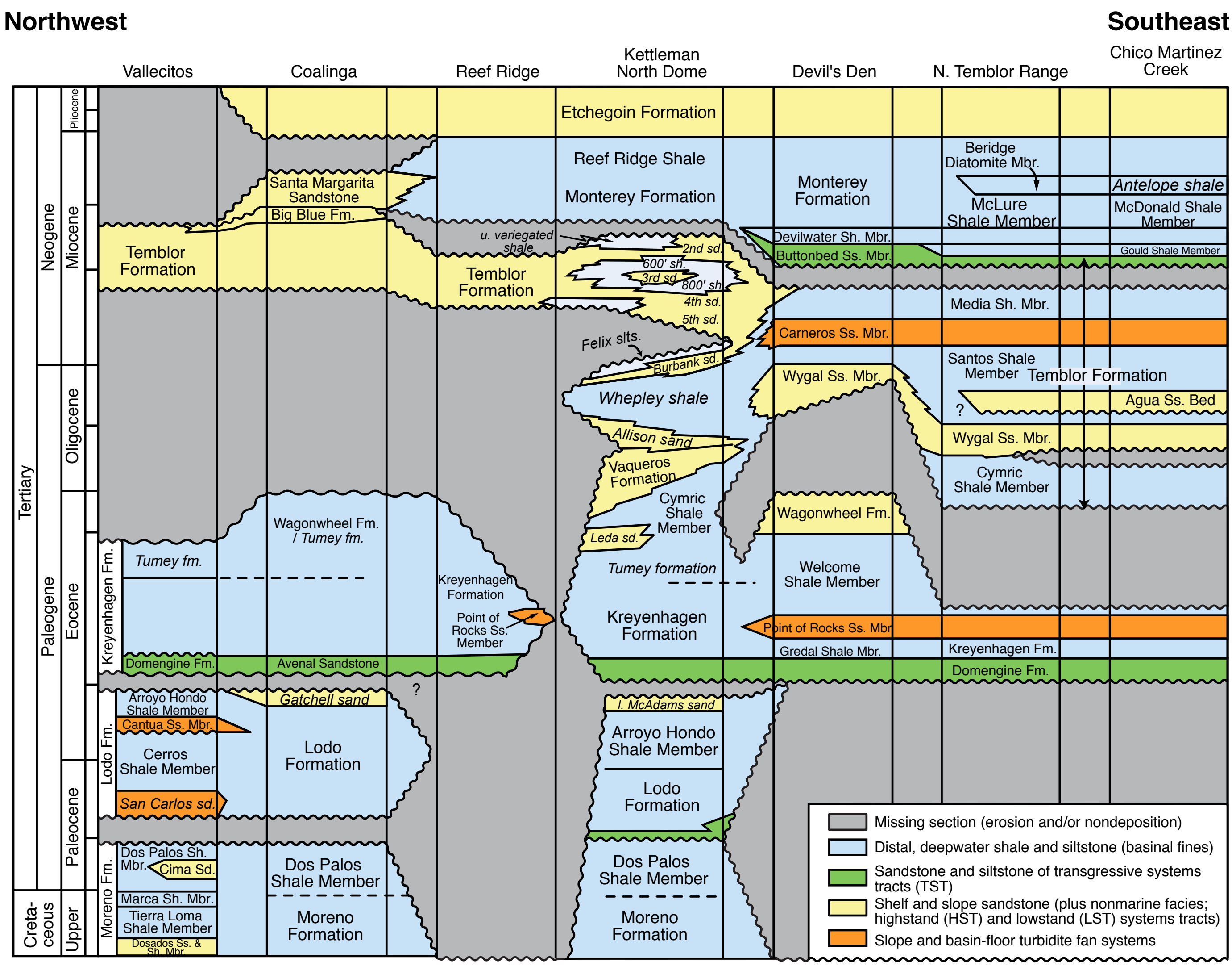


**Fig. 6.4.** North-south chronostratigraphic correlation chart, west-side San Joaquin Basin. Sections from Reef Ridge to Devil's Den (see locations, fig. 6.1) are greatly modified from Kuespert (1985); other sections are from this study and references herein. Formation names in italics are informal; references for these appear in text and table 6.1. One informal name not previously defined is the Antelope shale of Graham and Williams (1985) (also referred to by the USGS as the Antelope shale unit of McLure Shale Member of Monterey Formation).

The Domengine Formation lies unconformably on the Lodo Formation in the Vallecitos Syncline area, and represents the basal transgressive sand underlying the Kreyenhagen Formation (fig. 6.4). Erosion prior to deposition of the Domengine Formation truncated Cretaceous through lower Eocene strata in the San Joaquin and Sacramento basins, and represents a major period of basin reorganization (Harun, 1984; Schulein, 1993). Along the northwestern limb of the Vallecitos Syncline, deposition of bathyal shale of the Kreyenhagen Formation represents 1,500 to 2,000 m of flooding across the Domengine-Kreyenhagen Formations boundary (Schulein, 1993). The Domengine-Kreyenhagen Formations boundary may also represent an unconformity, although probably a minor one: Milam (1984, 1985) suggested a depositional hiatus of less than 1 m.y. on the basis of late-early Eocene calcareous nannoplankton and planktonic foraminifera in the Domengine Formation compared to early middle Eocene fauna in the lower Kreyenhagen Formation. The Domengine Formation is equivalent to the Avenal Sandstone along Reef Ridge (Harun, 1984).

Bathyal shale of the Kreyenhagen Formation includes fine-grained siliceous and calcareous biogenic facies deposited, at least in part, under low-oxygen conditions (Milam, 1985). The fine-grained units thicken westward (fig. 6.2) (Bloch, 1991b) and range up to about 300 m thick, except where they encase the thick turbiditic Point of Rocks Sandstone Member. In the eastern San Joaquin Basin, basinal facies of the Kreyenhagen Formation transition to thin shallow-marine and nonmarine equivalents (the Famoso sand of Edwards, 1943, and the Walker Formation, respectively) (Callaway, 1990; Bloch, 1991b). The Point of Rocks Sandstone Member (fig. 6.2) is interpreted as a base-of-slope turbidite fan (Clarke, 1973) exceeding 1 to 1.5 km thickness in outcrop (at Devil's Den) and in the subsurface south and west of the Lost Hills anticline.

### Age

The Domengine Formation underlying the Kreyenhagen Formation on the west side of the San Joaquin Basin is generally thought (for example, Bloch, 1991a) to correlate to the transgressive systems tract overlying the ~49.5 Ma type 1 sequence boundary of Haq and others (1988) and Hardenbol and others (1998). This correlation is supported by biostratigraphic age control in the Vallecitos Syncline, where Schulein (1993) established an absolute age of 49.5 to 49.8 Ma, as well as at Oil City (Almgren and others, 1988). Similarly, Prothero (2001a) correlated the Domengine Formation north of the city of Coalinga to 47.9 to 49 Ma based on linked biostratigraphic and paleomagnetic studies. However, regional biostratigraphic studies indicate that the Domengine Formation is a time-transgressive deposit, becoming younger toward the north, and it may be as old as 55 Ma south of Coalinga (Berggren and Aubert, 1983; Schulein, 1993). Given the apparent age correlation, in at least part of the study area, between the basal Domengine Formation and a global relative sea level fall, it is tempting to assign this sequence to a eustatic driver. However, one cannot ignore the significant erosion and angular truncation of units underlying the Domengine Formation unconformity (for example, Schulein, 1993), which indicate that coeval tectonism substantially amplified the effects of falling sea level at the onset of deposition of this sequence.

The upper boundary of the Kreyenhagen Formation (not including the Tumey formation of Atwill, 1935, discussed below, hereafter referred to as the Tumey formation) is somewhere within the Refugian stage (NP17 to NP19; Armentrout, 1981), and is most likely within CP14b (~ 41 to 37 Ma; Okada and Bukry, 1980; Almgren and others, 1988). The Point of Rocks Member also spans the Narizian-Ulatisian benthic-foraminiferal stages of Mallory (1959), which range from ~50.5 to 46 Ma based on paleomagnetic data (Prothero, 2001b).

## Upper Eocene Tumey Formation

Stratigraphic relations and depositional environments of the Tumey formation (equivalent to the Wagonwheel Formation; Foss and Blaisdell, 1968) are problematic because of limited and poor outcrops, and sparse documentation in the subsurface. Because of uncertainties in genetic affinity, workers have variously ascribed the Tumey formation to both the underlying Kreyenhagen Formation and the overlying Vaqueros Formation-Vedder Sand (lowermost Temblor Formation-equivalent) sequences. Bloch (1991a) chose to include the Tumey formation as part of the overlying Oligocene strata, but reported that the Wagonwheel Formation is conformable with underlying strata of the Kreyenhagen Formation at Devil's Den based on mapping by Dibblee (1973). We consider the Tumey formation to be a separate sequence from strata of both the Kreyenhagen and Temblor Formations because it is reportedly bounded by both upper and lower unconformities in some areas (Foss and Blaisdell, 1968; Milam, 1985; Bloch, 1991a,b).

The Tumey formation is best exposed at its type section southeast of Tumey Gulch. At this locality, it conformably overlies fine-grained strata of the Kreyenhagen Formation and has a basal, massive sandstone member over 200 m thick. Milam (1985) inferred this basal member to be a turbidite sandstone body, based on the lack of shallow-marine sedimentary structures or in-place megafossils, and its enclosure in bathyal shale bodies. The overlying shale of the Tumey formation is within the Refugian benthic-foraminiferal stage, in part including the upper Eocene, although the age of this stage is not well known (Prothero and Thompson, 2001). Prothero and Sutton (2001) reported the age of the Wagonwheel Formation south of Devil's Den as 35.3 to 34 Ma, slightly older than the unconformably overlying basal units of the Temblor Formation.

The Tumey formation at its type area ranges up to 400 m thick (including the basal sandstone member), and contains mollusk and benthic-foraminiferal assemblages indicative of bathyal to outer-shelf environments (Bloch, 1991a). However, an interbedded sandstone unit also contains oyster coquinas indicating shallow (<3 m) water. The Wagonwheel Formation exposed in the Devil's Den area also contains shallow-marine biofacies, and is apparently age-equivalent to the upper part of the Tumey formation at the type area. The shallow-marine facies may indicate an internal unconformity and rapid sea-level fall during the late Eocene or early Oligocene. Alternatively, Milam (1985) speculated that the shallow-marine deposits may reflect transport into deep water by slope failure, perhaps without a significant change in relative sea level.

## Oligocene-Miocene Temblor Formation and Equivalent Strata

### Temblor Formation of the Western San Joaquin Basin

Confusion over absolute age, facies relations, and competing stratigraphic nomenclature has greatly complicated understanding of the Oligocene through lower Miocene section of the San Joaquin Basin, since the name "Temblor Formation" was first applied to outcropping strata of the Temblor Range by Anderson (1905). As described by Graham (1985), the term "Temblor" has been used as both a lithostratigraphic identifier referring to Oligocene through Miocene strata lying east of the San Andreas Fault in the Temblor Range, and a biostratigraphic term referring to a provincial middle Miocene marine-megafaunal stage (summarized by Dibblee, 1973). Nomenclatural confusion is also associated with the Vaqueros Formation, a term derived from a formal type section in the Salinas Basin west of the San Andreas Fault (Thorup, 1943; Graham, 1978) and inappropriately applied to Zemorrian-age strata of the north-central San Joaquin Basin subsurface around Tulare Lake oil field. Zemorrian-age strata within the San Joaquin Basin are thus correlative to the lower part of the type Temblor Formation. However, the term "Vaqueros" also refers to an upper Oligocene through middle Miocene provincial molluscan stage predating the "Temblor" molluscan stage (Addicott, 1970, 1973). Thus, only the uppermost sandstone member (the Buttonbed Sandstone Member) of the lithostratigraphic type Temblor Formation is of biostratigraphic "Temblor" age (Graham, 1985).

Documentation of the type Temblor Formation in the Zemorra Creek/Carneros Creek area of the Temblor Range (fig. 6.1) and correlation studies spanning about 100 km along the Temblor Range (Carter, 1985; Cooley, 1982; Pence, 1985; Bate, 1985) helped clarify stratigraphic relationships within the Temblor Formation (fig. 6.5) (Graham, 1985). However, these studies also served to highlight complexities within the unit, which must be considered in any study or sequence-stratigraphic interpretation. The Temblor Formation at its type area spans nearly 20 m.y. of deposition from Oligocene through early Miocene. It encompasses multiple unconformities, and represents diverse depositional environments from shoreline to bathyal to base-of-slope turbidite fan (fig. 6.5) (Graham, 1985). Unfortunately, however, the type Temblor Formation is less complete than subsurface sections to the east, as at Cymric and Lost Hills oil fields, complicating outcrop-to-subsurface correlations. Reconstructions of the Oligocene through early Miocene landscape, and hence stratigraphic correlations, are also complicated by 315 to 320 km of post-early Miocene slip on the San Andreas Fault (Graham and others, 1989), as sediment source terranes and formerly contiguous strata are now offset by the fault. In sum, the Temblor Formation is an amalgam of distinct depositional sequences recording a complex middle Tertiary tectonic history that is obscured by treating the Temblor Formation as one genetic unit.

#### Distribution

The type section for the Temblor Formation is located between Carneros and Zemorra Creeks in the central Temblor Range (fig. 6.1) (Carter, 1985). The Temblor Formation crops out along the entire length of the Temblor Range from the Vallecitos Syncline to the type area in the southern Temblor Range (figs. 6.4 and 6.5) (Dibblee, 1973). The base of the Temblor Formation lies on strata ranging from the upper Eocene Tumey formation, to the middle Eocene Point of Rocks Sandstone Member of the Kreyenhagen Formation, to Cretaceous strata (Dibblee, 1973). The Temblor Formation is correlated eastward into the subsurface of the San Joaquin Basin as far as Kettleman North Dome, Tulare Lake, Lost Hills and Elk Hills oil fields, although separate local subsurface nomenclature has been applied to subcrop stratigraphy (for example, Kuespert, 1985). Farther east near the basin axis, Temblor Formation nomenclature transitions into eastern-basin nomenclature (for example, Freeman Silt, Jewett Sand, Olcese Sand, and Vedder Sand; see Bartow and McDougall, 1984, for discussion). Although some east-west correlations have been established, parts of the Oligocene-Miocene section of the western-basin likely form a unique lithostratigraphic succession not correlated to the east, because by the middle Tertiary, sediment was supplied to the basin from both eastern and western sources (Bent, 1985; Bartow, 1991; Bloch, 1991b).

#### Age

At the type area, the Temblor Formation spans lower Oligocene through lower Miocene strata (fig. 6.4), and contains three unconformities (fig. 6.5). Published correlations of California benthic faunal zones to planktic zonations aid in absolute age constraints (for example, Bartow and McDougall, 1984; Barron and Isaacs, 2001; McDougall, this volume, chapter 4), although different correlation schemes exist and it is difficult to constrain some boundaries to within a few million years in absolute time. Using well-log and seismic data, Bloch (1991a,b) correlated Temblor Formation-equivalent units of the subsurface near Kettleman Hills to sequences within the Vedder Sand and Olcese Sand in the eastern San Joaquin Basin (fig. 6.6). Bloch's (1991a,b) age-equivalent se-

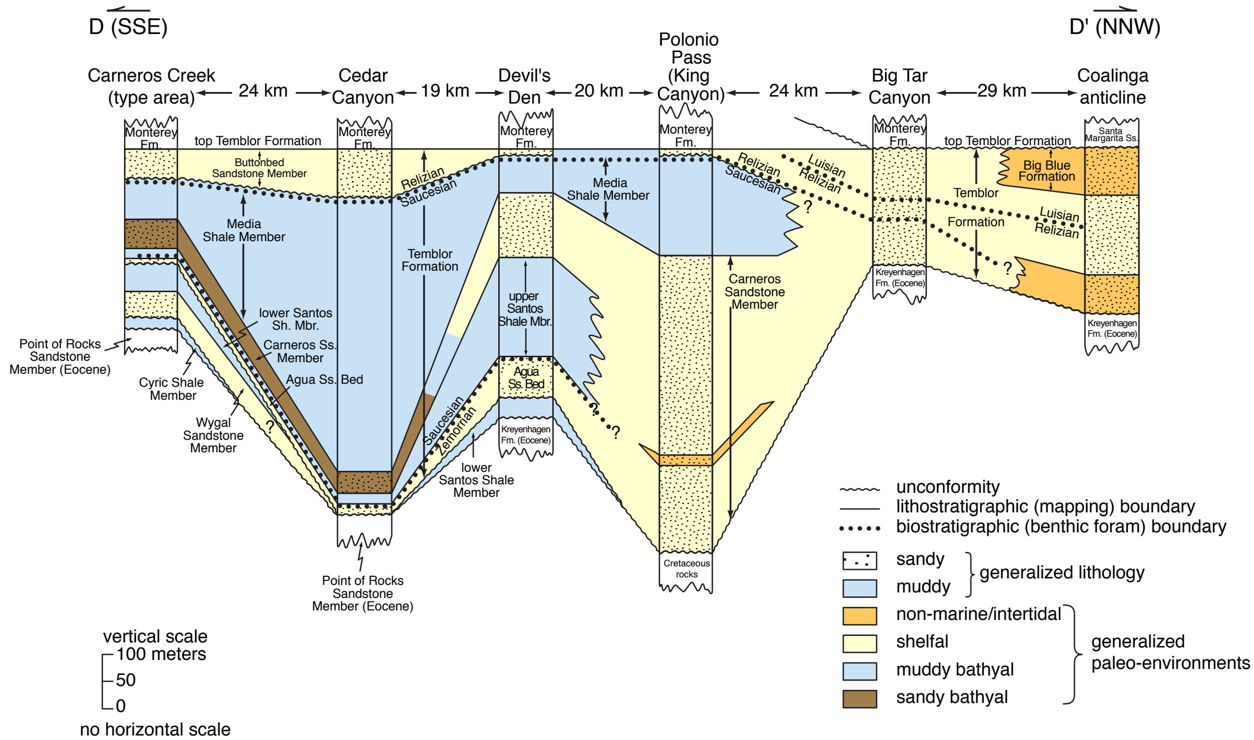


**Fig. 6.5.** General stratigraphic and paleoenvironmental relations of Temblor Formation strata from the west-side of the San Joaquin Basin (D-D' of fig. 6.1). Modified from Graham (1985).

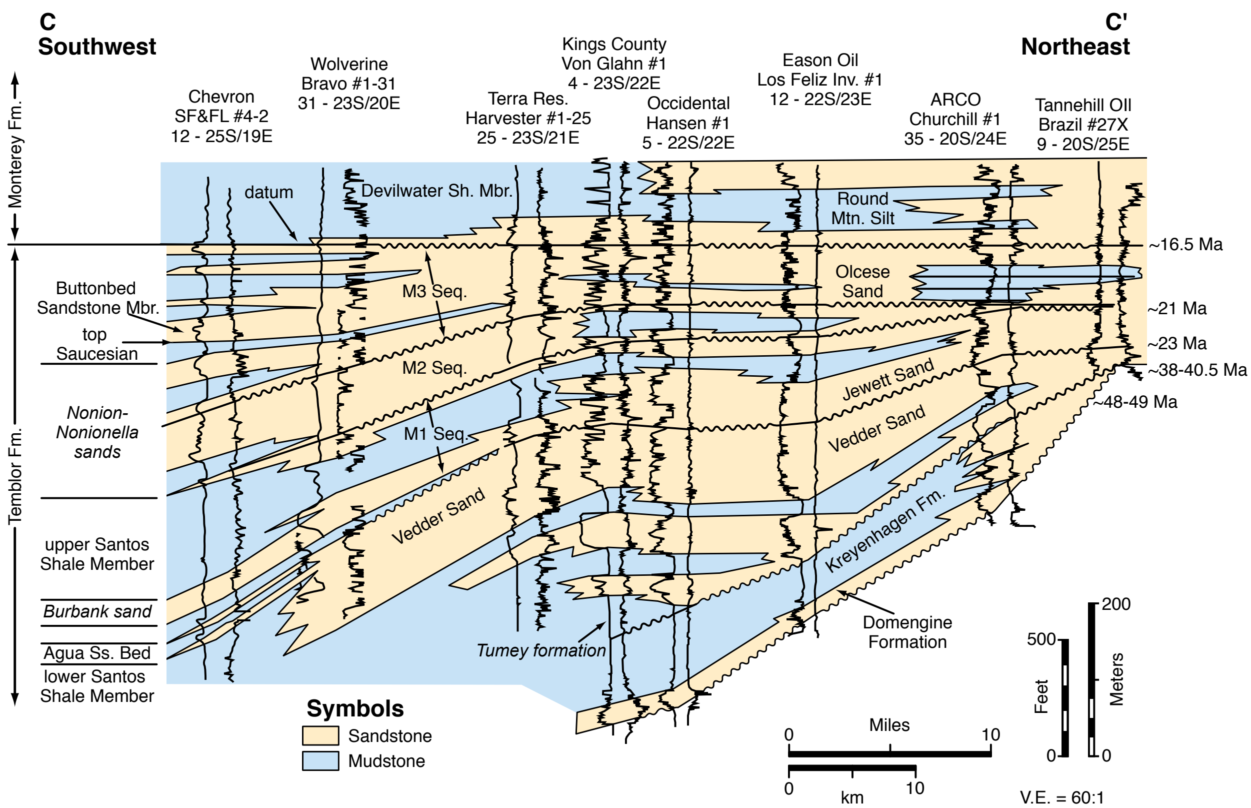


**Fig. 6.6.** Electrical log cross section from Kettleman Hills South Dome to the eastern edge of the San Joaquin Basin, showing relations between Miocene Olcese Sand (east-side) and Temblor Formation strata (west-side). Figure from Bloch (1991b) with the author's permission; M1-M2-M3 refer to Miocene sequences of Bloch (1991b), as discussed in the text. Formation names in italics are informal; references for these appear in text and table 6.1.

quences span about 35 to 17 Ma, with attendant uncertainty of 1 to 2 m.y. at the top and base of the section. This correlation is supported, in part, by strontium-isotope ages (23.5±1 Ma; Olson, 1988a,b) derived from mollusk shells in the eastern San Joaquin Basin. Bloch's (1991a,b) correlations indicate that strata of the Vedder and Olcese Sands are roughly equivalent to the lower Saucesian Agua Sandstone Bed of the Santos Shale Member and to the upper Santos Shale Member of the Temblor Formation in the western San Joaquin Basin. Recent magnetostratigraphic studies further constrain Zemorrian strata at the type section of the Temblor Formation. Prothero and Resseguie (2001) reported that lower to upper Zemorrian strata at the type section (Cymric Shale Member through Agua Sandstone Bed) span approximately 34 to 24 Ma, but noted that the Zemorrian record at the type section is very incomplete, with only 2 to 3 m.y. of the total time span represented in the rock record.

### Type-Section Stratigraphy

At its type section, the Temblor Formation consists of three unconformity-bounded sequences (figs. 6.4 and 6.5) plus one partial sequence. The uppermost Buttonbed Sandstone Member is the basal transgressive sandstone underlying the composite highstand sequence of the Monterey Formation. Paleobathymetric curves underscore the significance of Temblor Formation stratigraphy by highlighting rapid shifts in paleowater depth (Carter, 1985). These paleobathymetric interpretations should be viewed in light of the following comments. Early to middle Miocene benthic-foraminiferal faunas have long been classified by comparison to modern faunas in the eastern Pacific Ocean (Bandy and Arnal, 1969). More recent studies of foraminiferal biofacies, calibrated by clinoform seismic geometries, suggest that previous paleobathymetric assignments may have overestimated water depth (Olson, 1988a,b). Foraminiferal-biofacies groups have been recalibrated in the southeastern San Joaquin Basin (Olson, 1988a,b), but not yet along the westside outcrops. Thus, although Carter (1985) used benthic-foraminiferal data to assign paleobathymetry in the type Temblor Formation, we emphasize the relative rather than absolute changes in water depth indicated by these data. The following summary of Temblor Formation members at the type area derives from Carter (1985).

*Lower Zemorrian sequence*, *Cymric Shale Member*.—The basal member of the Temblor Formation, the lower Zemorrian Cymric Shale Member (subsurface Salt Creek shale of Foss and Blaisdell, 1968), consists of 0 to 18 m of generally massive, silty mudstone at the type section. Carter (1985) inferred minimum lower-middle-bathyal water depths of 1,500 to 2,000 m based on a limited foraminiferal assemblage. This basal member overlaps rocks as young as the Refugian Tumey formation. Thus, the Cymric Shale Member rests unconformably on Eocene bathyal shale and turbidite units, but no regressive sequence is preserved below the unconformity, nor is a transgressive sequence reported above (Carter, 1985).

*Zemorrian sequence, Wygal Sandstone Member/lower Santos Shale Member*.— The Wygal Sandstone Member (subsurface Phacoides sandstone of Curran, 1943, hereafter referred to as Phacoides sandstone; Foss and Blaisdell, 1968) comprises the lower sandy unit of the Temblor Formation. It rests unconformably on the Cymric Shale Member and progressively older units in the subsurface (Carter, 1985). In outcrop, the Wygal Sandstone Member thins to the north from about 68 m at Temblor Creek to less than 10 m at Stone Corral Canyon (Carter, 1985). It thickens to more than 300 m in subsurface sections to the northeast (Carter, 1985). Sedimentologic and faunal evidence indicates an inner-neritic depositional environment for the basal sandstone (fig. 6.5), which likely deepens upward to outer-shelf or upper-slope paleoenvironments on the basis of foraminiferal biofacies in the glauconitic/phosphatic upper sandstone unit.

In the subsurface, "Phacoides" nomenclature variably includes up to three sandstone members separated by thin shale units—the Gibson and Bloemer sands of Williams (1938) and the Belridge 64 sand of Foss and Blaisdell (1968) (hereafter referred to as the Gibson, Bloemer, and Belridge 64 sands), which collectively thicken eastward to at least 350 m at Lost Hills anticline (Carter, 1985). Foss and Blaisdell (1968) proposed that the Wygal Sandstone Member correlates only to the uppermost unit of the Bloemer sand. This interpretation is suggested at Beer Nose oil field, where the Bloemer sand may overlap a gentle angular unconformity with the Belridge 64 and Gibson sands, which are interpreted as part of the Cymric Shale Member sequence. Carter (1985) also indicated that the Belridge 64 sand may be a deep-marine turbidite package related to deposition of the Cymric Shale Member sequence, and that the Bloemer sand is the shallow-marine subsurface equivalent to the regressive Wygal Sandstone Member. Farther east at the Semitropic field, no Phacoides sandstone is present, and the lower Santos Shale Member rests on the Vedder Sand (Carter, 1985). Thus, many questions remain regarding the depositional environments of subsurface Phacoides sandstone units, their internal correlation and relationship to Wygal Sandstone Member outcrops of the Temblor Range, and the relationship between Phacoides sandstone and Vedder Sand to the east.

The overlying lower Santos Shale Member is separated from the Wygal Sandstone Member by a glauconitic and phosphatic condensed section and is about 60 m thick at the type area, thickening to 150 m southeast in the subsurface. Carter (1985) described the lower Santos Shale Member as generally massive and fine-grained, with pelletal phosphorite interpreted as displaced and transported by turbidity currents. Abundant foraminifera in the lower Santos Shale Member suggest environments as deep as lower bathyal (2,000+ m) immediately overlying the Wygal Sandstone Member (fig. 6.5). The lower Santos Shale Member shoals in the upper part of the section to upper-bathyal (150 to 500 m) paleoenvironments. The transitions to deep water at the base of the unit, and to shallower water paleoenvironments in the upper part of the unit, likely reflect the influence of tectonism, because the magnitude of bathymetric change exceeds that possible by eustatic sea-level changes (Carter, 1985).

*Saucesian sequence, Agua Sandstone Bed of the Santos Shale Member/upper Santos Shale Member/Carneros Sandstone Member/Media Shale Member.*—A third unconformity within the Temblor Formation lies at the base of the uppermost Zemorrian (earliest Miocene, about 23 to 24 Ma) Agua Sandstone Bed, which truncates and overlaps progressively older members of the Temblor Formation to middle Eocene Point of Rocks Sandstone Member of the Kreyenhagen Formation toward the northwest. At its thickest near Stone Corral Canyon (as much as 30 m), the Agua Sandstone Bed contains *in situ* oyster reefs, requiring paleowater depth of less than 35 m (Carter, 1985). The Agua Sandstone Bed thins abruptly to the southeast from 0 m to 100 m over a lateral distance of less than five km (fig. 6.5). This thinning accompanies a distinct facies change to primarily phosphatic and glauconitic sandstone, which reflects the transition to a starved outer shelf and slope, probably no deeper than about 500 m (Carter, 1985). This transition is also indicated by foraminifera at the Cymric oil field, which suggest shelf-edge to upper-bathyal paleoenvironments (Carter, 1985). Thus, uplift in the Temblor Range that preceded deposition of the Agua Sandstone Bed established a shelf-edge-to-slope transition during early Miocene time. The overlying, conformable upper Santos Shale Member likely accumulated in a middle-bathyal setting, based on foraminiferal biofacies (Carter, 1985) and sedimentary structures such as low-density turbidites.

The Carneros Sandstone Member is a deep-marine deposit (fig. 6.5) characterized by Bouma sequences, flame structures, flute casts, and lenticular sand bodies, suggesting a turbidite-fan complex, possibly with inner-to-middle-fan paleoenvironments (Carter, 1985). The Carneros Sandstone Member is as thick as 460 m in the subsurface, with four discrete sandstone bodies separated by shale beds (Carter, 1985). The sudden influx of coarse-grained material transported toward the southeast represented by the Carneros Sandstone Member may coincide with a relative sea-level fall in the early Miocene, but more likely reflects tectonism associated with the San Andreas Fault system to the west (Graham and others, 1989). The Carneros Sandstone Member is overlain by the Media Shale Member, a massive burrowed shale with minor laminated intervals, which ranges from 100 to 700 m thick. Foraminifera from the Media Shale Member suggest a middle-bathyal setting (500 to 2,000 m), with a possible slight shoaling in the upper part of the member (Carter, 1985). Shoaling during the late Saucesian likely signaled onset of an erosional hiatus prior to deposition of the Buttonbed Sandstone Member.

*Relizian sequence, Buttonbed Sandstone Member and overlying lower Monterey Formation.*—The unconformity at the top of the Media Shale Member signals the base of a fourth depositional sequence in the Temblor Formation, which was deposited during Relizian time (figs. 6.4 and 6.5). The overlying bathyal shale is mapped as the lowest member of the Monterey Formation, although from a sequence-stratigraphic perspective, this shale is the highstand sequence formed after the transgressive Buttonbed Sandstone Member (Graham and Williams, 1985). The Buttonbed Sandstone Member is a shallow-marine sandstone that crops out in the Temblor Range, where it includes a coquinoid lithofacies with button-like echinoids. Carter (1985) described upward-shoaling paleoenvironments within the Buttonbed Sandstone Member ranging from at least 25 m of water to only about 6 m depth in the coquinoid facies. The uppermost part of the Buttonbed Sandstone Member transitions to an outer-shelf or upper-slope setting, signaling a major transgression to bathyal Monterey Formation facies. Highly lenticular in outcrop, the Buttonbed Sandstone Member ranges from 0 to 245 m thick, and extends for about 31 km from Zemorra Creek to Packwood Creek in outcrop. The Buttonbed Sandstone Member occurs only about as far east in the subsurface as Lost Hills anticline, and as far south in outcrop as Chico Martinez Creek (Carter, 1985). The unconformity at the base of the Buttonbed Sandstone Member, called the "sub-Buttonbed unconformity," represents a major uplift/erosion event along the western basin outcrop belt. Carter (1985) reported 300 m of erosional relief within one km of the Temblor Formation type section at Temblor Creek; further, the Buttonbed Sandstone Member progressively overlaps rocks as old as the middle Eocene Point of Rocks Sandstone Member of the Kreyenhagen Formation. At Antelope Hills, the Buttonbed Sandstone Member laps out on the crest of an anticline (Dibblee, 1973), indicating a folding event during Relizian time.

### Temblor Formation of the Northern Temblor Range and Southern Diablo Range

The type section of the Temblor Formation generally reflects basinal environments relative to a paleo high to the northwest in the present southern Diablo Range. This feature is inferred to have been emergent, at least periodically, during most of Oligocene and early Miocene time. Basal Temblor Formation strata also are younger toward the northwest, and Zemorrian/Saucesian units are present only south of King Canyon. An outcrop correlation section from NW to SE along the Temblor Range (fig. 6.5) reveals the overall northwestward transition throughout most of the Temblor Formation to shelf and eventually nonmarine facies (fig. 6.4) (Pence, 1985). The Agua Sandstone Bed, upper Santos Shale Member, and Carneros Sandstone Member all pinch out in the vicinity of Cedar Canyon, where the Media Shale Member is thickest at over 500 m, implying the presence of a local slope basin and perhaps structurally controlled sediment ponding during late Saucesian time (Pence, 1985).

From Reef Ridge northward to beyond Coalinga, a relatively thin, young Temblor Formation rests unconformably on middle Eocene portions of the Kreyenhagen Formation or older strata (figs. 6.4 and 6.5). The Temblor Formation is shallow marine at Reef Ridge (Cooley, 1982) but includes nonmarine members northward at Coalinga (Bate, 1985). Changes in water depth recorded in these sections likely signal higher-order stratigraphic sequences (Cooley, 1982). Kuespert (1985) correlated the Coalinga and Reef Ridge outcrop sections of the Temblor Formation to deltaic and nonmarine facies in the subsurface at Kettleman North Dome, where a separate subsurface stratigraphic nomenclature applies to the Relizian-Luisian Temblor Formation (figs. 6.3 and 6.4). These northern sections of the Temblor Formation are referable to the “Temblor” California provincial molluscan stage based on abundant megafauna, and the youngest member is Luisian (Bate, 1985), indicating that the upper Temblor Formation at Coalinga is equivalent to the bathyal shale of the lower Monterey Formation of the Temblor Range (fig. 6.5). Thus, the northern Temblor Formation consists of an overall retrogradational stack of systems tracts.

## Oligocene-Miocene Stratigraphic Sequences of the Southeastern San Joaquin Basin

Sand-rich units in the Oligocene through middle Miocene sequences of the eastern San Joaquin Basin include the Vedder Sand, Jewett Sand, and Olcese Sand (Bartow and McDougall, 1984). An unconformity between the Oligocene Vedder Sand and the Eocene Tumey formation is not well documented, but seems likely based on apparent erosional thinning of the Tumey formation eastward (Bloch, 1991a). Bloch (1991a) described three pulses of westward-prograding sand units in the Eocene through Oligocene Tumey formation-Vedder Sand sequence, which transition into shale to the west. The age of the Vedder Sand is constrained by the age of the underlying Tumey formation (CP16 nannofossil zone of Bukry, 1981) at the type section north of Devil’s Den described by Dumoulin (1984), and by correlation south of the Bakersfield Arch, where the basal transgressive sandstone of the unit unconformably overlying the Vedder Sand is 23.5 ± 1 Ma (Olson, 1988a,b). Thus, the Vedder Sand was deposited from 33 to 23 Ma and correlates to the Zemorrian stage, which includes the Cymric Shale Member, Wygal Sandstone Member, lower Santos Shale Member, and Agua Sandstone Bed of the Temblor Formation on the west side of the San Joaquin Basin.

At Kettleman North Dome, the upper Zemorrian stage correlates to the Whepley shale of Dodd and Kaplow (1933) and part of the Burbank sand of Sullivan (1966) (hereafter referred to as the Burbank sand) (Kuespert, 1985). Bloch (1991a) proposed that distal shale facies associated with the Vedder Sand encase the Bloemer sand turbidite(?) member, which is roughly equivalent to the Agua Sandstone Bed and Wygal Sandstone Member and may lie on a sequence boundary over shallow-marine Belridge 64 sand that correlates to the sub-Agua Sandstone Bed unconformity in outcrop. Alternatively, the Agua Sandstone Bed may be equivalent to the transgressive Rio Bravo sand of Noble (1940) (hereafter referred to as the Rio Bravo sand) (Bloch, 1991a), which apparently is of uppermost Zemorrian age at the oldest. These uncertainties in correlation remain to be resolved in the subsurface of the basin center.

The lower to middle Miocene Olcese Sand was divided into three sequences based on well-log and seismic-reflection studies along seismic line WSJ-6 by Bloch (1991a,b; fig. 6.6). These sequences generally consist of a basal “restricted” unit, a middle transgressive unit, and an upper prograding unit, correlated by Bloch (1991a) to lowstand-, transgressive-, and highstand-systems tracts. Bloch’s (1991a) M1 sequence is defined by transgression of the Rio Bravo sand and Jewett Sand, which are overlain by a marine flooding shale unit. Bloch (1991a) inferred that “shelf sands” of the lower Olcese Sand form the progradational highstand part of this sequence, and correlated the M1 sequence to the Burbank sand and lower Felix siltstone of Dodd and Kaplow (1933) in the central part of the basin (the basal unit is 23.5±1 Ma; Olson, 1988a,b). M1 units are apparently upper Zemorrian to earliest Saucesian in age, and therefore, correlate best to the Agua Sandstone and upper Santos Shale Members of the Temblor Formation in the Temblor Range. The M2 sequence defined by Bloch (1991a) is upper Saucesian in age, and correlates to the Carneros Sandstone and Media Shale Members, as well as to transgressive parts of the Nonion-Nonionella sands of Bloch (1991b) at northern Lost Hills. The Media Shale Member may also be related to M3 progradation (upper Olcese Sand). Although transgressive and (or) highstand sequences of the Oligocene through Miocene Olcese Sand and Vedder Sand can be generally correlated to the western basin section, the sub-Buttonbed unconformity observed in the Temblor Range and nearby subsurface is clearly out of sequence with eastside stratigraphy (fig. 6.2) (Bloch 1991b). The Saucesian-Relizian boundary is associated with major uplift and erosion on the west side of the basin, but it most closely correlates to the M3 transgressive and prograding units on the east side, which represent maximum transgression in this depositional sequence (Bloch, 1991a).

# Summary

Sequence-stratigraphic methods can be successfully applied to the complex fill of the tectonically active San Joaquin Basin. Basin-margin unconformities, flooding surfaces, and lowstand and highstand depositional systems are identifiable. These features permit definition of third-order stratigraphic sequences in the Eocene through Miocene basin fill, which in turn, provide context for the study of petroleum source and reservoir units of the region from the Bakersfield Arch to north of Coalinga. Using similar methods, Callaway (1990) recognized 12 unconformity-bounded sequences between ~60 and 15 Ma, whereas we define 9 sequences that we regard as particularly important for understanding basin evolution and petroleum resource potential. We emphasize that the ages of middle Tertiary sequence boundaries of the San Joaquin Basin are in general known with certainty only within a few million years. In contrast, Callaway (1990) assumed that sequence boundaries in the basin temporally align with the global sea-level curve of Haq and others (1988) (the “Haq curve”) and therefore assigned precise age values to each major sequence-stratigraphic surface. As in many basins (for example, Miall, 1997), San Joaquin Basin sequence boundaries can be correlated within uncertainty to the Haq curve, implying that eustatic control on sequence development is possible. On the other hand, pronounced angularity across some unconformities, and unconformities clearly out of phase with the Haq curve (for example, the sub-Buttonbed unconformity), indicate tectonic controls on stratigraphic packaging. Thus, the sequence-stratigraphic analyses reported here form the basis not only for interpretation of genetic controls on sequence development, but also provide motivation for further investigations of the basin fill. Most pressing is the need for significantly improved age resolution of sequence-stratigraphic architectural elements.

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## References Cited

Addicott, W.G., 1970, Miocene gastropods and biostratigraphy of the Kern River area, California: U.S. Geological Survey Professional Paper 642, 174 p.

Addicott, W.G., 1973, Oligocene molluscan biostratigraphy and paleontology of the lower part of the type Temblor Formation, California: U.S. Geological Survey Professional Paper 791, 48 p.

Almgren, A.A., Filewicz, M.V., and Heitman, H.L., 1988, Lower Tertiary foraminiferal and calcareous nannofossil zonation of California—An overview and recommendation, *in* Filewicz, M.V., and Squires, R.L., eds., Paleogene stratigraphy, west coast of North America: Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 58, p. 83-106.

Anderson, F.M., 1905, A stratigraphic study in the Mount Diablo Range of California: Proceedings of the California Academy of Science, Third Series, Geology, v. 2, no. 2, p. 155-248.

Anderson, K.S., 1998, Facies architecture of two Paleogene structurally controlled turbidite systems, central California: Stanford, Calif., Stanford University, Ph.D. dissertation, 391 p.

Armentrout, J.M., 1981, Correlation and ages of Cenozoic chronostratigraphic units in Oregon and Washington, *in* Armentrout, J.M., ed., Pacific Northwest Cenozoic biostratigraphy: Boulder, Colo., Geological Society of America Special Paper 184, p. 137-148.

Atwill, E.R., 1935, Oligocene Tumey Formation of California: Bulletin of the American Association of Petroleum Geologists, v. 19, no. 8, p. 1192-1204.

Bandy, O.L., and Arnal, R.E., 1969, Middle Tertiary basin development, San Joaquin Valley, California: Geological Society of America Bulletin, v. 80, p. 783-819.

Barron, J.A., and Isaacs, C.M., 2001, Updated chronostratigraphic framework for the California Miocene, *in* Isaacs, C.M., and Rullkotter, J., eds., The Monterey Formation—From rocks to molecules: New York, Columbia University Press, p. 393-395.

Bartow, J.A., 1991, The Cenozoic evolution of the San Joaquin Valley, California: U.S. Geological Survey Professional Paper 1501, 40 p.

Bartow, J.A., and McDougall, K., 1984, Tertiary stratigraphy of the southeastern San Joaquin Valley, California: U.S. Geological Survey Bulletin 1529-J, 41 p.

Bate, M.A., 1985, Depositional sequence of Temblor and Big Blue formations, Coalinga Anticline, California, *in* Graham, S.A., ed., Geology of the Temblor Formation, western San Joaquin Basin, California: Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 44, p. 69-86.

Bent, J.V., 1985, Provenance of upper Oligocene-middle Miocene sandstones of the San Joaquin Basin, California, *in* Graham, S.A., ed., Geology of the Temblor Formation, western San Joaquin Basin, California: Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 44, p. 97-120.

Berggren, W.A., and Aubert, J., 1983, Paleogene benthic foraminiferal biostratigraphy and paleobathymetry of the central Coast Ranges of California, *in* Brabb, E.E., ed., Studies in Tertiary stratigraphy of the California Coast Ranges: U.S. Geological Survey Professional Paper 1213, p. 4-21.

Bishop, C.C., and Davis, J.F., comps., 1984, Central California province correlation chart, *in* Correlation of Stratigraphic Units in North America [COSUNA], Correlation chart series: Tulsa, Okla., American Association of Petroleum Geologists, 1 sheet.

Bloch, R.B., 1991a, San Andreas Fault to Sierra Nevada Range, Sheet 3 of 3, *in* Bloch, R.B., and Graham, S.A., coords., West coast regional cross section: Tulsa, Okla., American Association of Petroleum Geologists, 1 sheet.

Bloch, R.B., 1991b, Studies of the stratigraphy and structure of the San Joaquin Basin, California: Stanford, Calif., Stanford University, Ph.D. dissertation, 319 p.

Bukry, D., 1981, Synthesis of silicoflagellate stratigraphy for Maestrichtian to Quaternary marine sediment, *in* Warme, J.E., Douglas, R.G., and Winterer, E.L., eds., The Deep Sea Drilling Project—A decade of progress: Tulsa, Okla., Society of Economic Paleontologists and Mineralogists Special Publication No. 32, p. 433-444.

Callaway, D.C., 1990, Organization of stratigraphic nomenclature for the San Joaquin Basin, California, *in* Kuespert, J.G., and Reid, S.A., eds., Structure, stratigraphy, and hydrocarbon occurrences of the San Joaquin Basin, California: Bakersfield, Calif., Pacific Sections, Society of Economic Paleontologists and Mineralogists and Association of Petroleum Geologists, v. 64, p. 5-21.

Callaway, D.C., and Rennie, E.W., Jr., 1991, San Joaquin basin, California, *in* Gluskoter, H.J., Rice, D.D., and Taylor, R.B., eds., Economic geology, U.S.: Boulder, Colo., Geological Society of America, The Geology of North America, v. P-2, p. 417-430.

Carter, J.B., 1985, Depositional environments of the type Temblor Formation, Chico Martinez Creek, Kern County, California, *in* Graham, S.A., ed., Geology of the Temblor Formation, western San Joaquin Basin, California: Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 44, p. 5-18.

Clarke, S.H., Jr., 1973, The Eocene Point of Rocks Sandstone—Provenance, mode of deposition, and implications for the history of offset along the San Andreas Fault in central California: Berkeley, Calif., University of California, Ph.D. dissertation, 302 p.

Coe, A.L., 2003, ed., The sedimentary record of sea-level change: Cambridge, Cambridge University Press, 288 p.

Cooley, S.A., 1982, Depositional environments of the lower and middle Miocene Temblor Formation of Reef Ridge and vicinity, Fresno and King Counties, California: Stanford, Calif., Stanford University, M.S. thesis, 89 p.

Curran, J.F., 1943, Eocene stratigraphy of Chico Martinez Creek area, Kern County, California: Bulletin of the American Association of Petroleum Geologists, v. 27, no. 10, p. 1361-1386.

Dibblee, T.W., Jr., 1973, Stratigraphy of the southern Coast Ranges near the San Andreas Fault from Cholame to Maricopa, California: U.S. Geological Survey Professional Paper 764, 45 p.

Dodd, H.V., and Kaplow, E.J., 1933, Kettleman North Dome and Kettleman Middle Dome fields—Progress in development, *in* Summary of operations, California oil fields: San Francisco, Annual Report of the State Oil and Gas Supervisor, v. 18, no. 4, p. 5-20 [also available *in* California Division of Oil and Gas, Summary of Operations, 1915-1999: California Division of Conservation, Division of Oil, Gas, and Geothermal Resources, Publication No. CD-3, and at ftp://ftp.consrv.ca.gov/pub/oil/Summary_of_Operations/1933/].

Dumoulin, J.A., 1984, Silicoflagellate biostratigraphy and paleoecology of the upper Kreyenhagen Formation (Eocene-Oligocene), California, *in* Blueford, J.R., ed., Kreyenhagen Formation and related rocks: Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 37, p. 29-49.

Edwards, E.C., 1943, Kern Front area of the Kern River oil field, *in* Jenkins, O.P., ed., Geologic formations and economic development of the oil and gas fields of California: San Francisco, State of California, Department of Natural Resources, Division of Mines Bulletin No. 118, p. 571-574.

Emery, D., and Myers, K., 1996, Sequence stratigraphy: Oxford, Blackwell Science, 297 p.

Foss, C.D., 1972a, Lower Eocene to Upper Cretaceous stratigraphy, central San Joaquin Valley, *in* Rennie, E.W., Jr., ed., Guidebook, Geology and oil fields, West side central San Joaquin Valley, 47th Annual Meeting: Pacific Sections, American Association of Petroleum Geologists, Society of Exploration Geophysicists, and Society of Economic Paleontologists and Mineralogists, p. 59-63.

Foss, C.D., 1972b, A preliminary sketch of the San Joaquin Valley stratigraphic framework, *in* Rennie, E.W., Jr., ed., Guidebook, Geology and oil fields, West side central San Joaquin Valley, 47th Annual Meeting: Pacific Sections, American Association of Petroleum Geologists, Society of Exploration Geophysicists, and Society of Economic Paleontologists and Mineralogists, p. 40-49.

Foss, C.D., and Blaisdell, R., 1968, Stratigraphy of the west side southern San Joaquin Valley, *in* Karp, S.E., ed., Guidebook, Geology and oil fields, West side southern San Joaquin Valley: Pacific Sections, American Association of Petroleum Geologists, Society of Exploration Geophysicists, Society of Economic Paleontologists and Mineralogists, 43rd Annual Meeting, p. 33-43.

Galloway, W.E., 1989, Genetic stratigraphic sequences in basin analysis I—Architecture and genesis of flooding-surface bounded depositional units: American Association of Petroleum Geologists Bulletin, v. 73, p. 125-142.

Goudkoff, P.P., 1943, Correlation of oil field formations on west side of San Joaquin Valley, *in* Jenkins, O.P., ed., Geologic formations and economic development of the oil and gas fields of California: San Francisco, State of California, Department of Natural Resources, Division of Mines Bulletin No. 118, p. 247-252.

Goudkoff, P.P., 1945, Stratigraphic relations of Upper Cretaceous in Great Valley, California: Bulletin of the American Association of Petroleum Geologists, v. 29, p. 956-1007.

Graham, S.A., 1978, Role of Salinian Block in evolution of San Andreas Fault system, California: American Association of Petroleum Geologists Bulletin, v. 62, p. 2214-2231.

Graham, S.A., 1985, Introduction, *in* Graham, S.A., ed., Geology of the Temblor Formation, western San Joaquin Basin, California: Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 44, p. 1-3.

Graham, S.A., 1987, Tectonic controls on petroleum occurrence in central California, *in* Ingersoll, R.V., and Ernst, W.G., eds., Cenozoic basin development of coastal California: Englewood Cliffs, N.J., Prentice-Hall, Rubey Volume VI, p. 47-63.

Graham, S.A., and Berry, K.D., 1979, Early Eocene paleogeography of the central San Joaquin Valley—Origin of the Cantua Sandstone, *in* Armentrout, J.M., Cole, M.R., and TerBest, H., Jr., eds., Cenozoic paleogeography of the western United States: Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists, Pacific Coast Paleogeography Symposium 3, p. 119-127.

Graham, S.A., and Johnson, C.L., 2004, Stratigraphic megasequences of the San Joaquin Basin—Origins, characteristics, and petroleum occurrence [abs.], *in* Programs and Abstracts, American Association of Petroleum Geologists, Society of Economic Mineralogists and Paleontologists, and Society of Exploration Geophysicists, 2004 Pacific Section Convention, p. A10-A11: American Association of Petroleum Geologists Bulletin, v. 88, no. 13 (Supplement).

Graham, S.A., Stanley, R.G., Bent, J.V., and Carter, J.B., 1989, Oligocene and Miocene paleogeography of central California and displacement along the San Andreas Fault: Geological Society of America Bulletin, v. 101, p. 711-730.

Graham, S.A., and Williams, L.A., 1985, Tectonic, depositional, and diagenetic history of Monterey Formation (Miocene), central San Joaquin Basin, California: American Association of Petroleum Geologists Bulletin, v. 69, p. 385-411.

Haq, B.U., Hardenbol, J., and Vail, P.R., 1988, Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change, *in* Wilgus, C.K., Hastings, B.S., Ross, C.A., Posamentier, H., Van Wagoner, J., and Kendall, C.G.St.C. eds., Sea-level changes—An integrated approach: Tulsa, Okla., Society of Economic Paleontologists and Mineralogists Special Publication 42, p. 72-108.

Hardenbol, J., Thierry, J., Farley, M.B., de Graciansky, P.-C., and Vail, P.R., 1998, Mesozoic and Cenozoic sequence chronostratigraphic framework of European basins, *in* de Graciansky, P.-C., Hardenbol, J., Thierry, J., and Vail, P.R., eds., Mesozoic and Cenozoic sequence stratigraphy of European basins: Tulsa, Okla., Society for Sedimentary Geology Special Publication 60, p. 3-13.

Harun, H., 1984, Distribution and deposition of lower to middle Eocene strata in central San Joaquin Valley, California: Stanford, Calif., Stanford University, M.S. thesis, 100 p.

Hewlett, J.S., and Jordan, D.W., 1993, Stratigraphic and combination traps within a seismic sequence framework, Miocene Stevens turbidites, Bakersfield Arch, California, *in* Weimer, P., and Posamentier, H.W., eds., Siliciclastic sequence stratigraphy—Recent developments and applications: American Association of Petroleum Geologists Memoir 58, p. 135-162.

Hubbard, R.J., 1988, Age and significance of sequence boundaries on Jurassic and Early Cretaceous rifted continental margins: American Association of Petroleum Geologists Bulletin, v. 72, p. 49-72.

Kuespert, J., 1985, Depositional environments and sedimentary history of the Miocene Temblor Formation and associated Oligo-Miocene units in the vicinity of Kettleman North Dome, San Joaquin Valley, California, *in* Graham, S.A., ed., Geology of the Temblor Formation, western San Joaquin Basin, California: Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 44, p. 53-67.

Mallory, V.S., 1959, Lower Tertiary biostratigraphy of the California Coast Ranges: Tulsa, Okla., American Association of Petroleum Geologists, 416 p.

McGuire, D.J., 1988a, Depositional framework of the Upper Cretaceous-lower Tertiary Moreno Formation, central San Joaquin Basin, California, *in* Graham, S.A., and Olson, H.C., eds., Studies of the geology of the San Joaquin Basin: Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists, book 60, p. 173-188.

McGuire, D.J., 1988b, Stratigraphy, depositional history and hydrocarbon source-rock potential of the Upper Cretaceous-Lower Tertiary Moreno Formation, central San Joaquin Basin, California: Stanford, Calif., Stanford University, Ph.D. dissertation, 240 p.

Miall, A.D., 1997, The geology of stratigraphic sequences: Berlin, Springer-Verlag, 433 p.

Milam, R.W., 1984, Late early to late middle Eocene planktonic foraminiferal zonations in California, *in* Blueford, J.R., ed., Kreyenhagen Formation and related rocks: Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 37, p. 51-66.

Milam, R.W., 1985, Biostratigraphy and sedimentation of the Eocene and Oligocene Kreyenhagen Formation, central California: Stanford, Calif., Stanford University, Ph.D. dissertation, 240 p.

Mitchum, R.M., Vail, P.R., and Thompson, S.I., 1977, Seismic stratigraphy and global changes of sea level, part 2—The depositional sequence as a basic unit for stratigraphic analysis, *in* Payton, C.E., ed., Seismic stratigraphy—Applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 53-62.

Nilsen, T.H., Reid, S.A., and Boote, D.R., 2004, Late Cretaceous and early Tertiary sequence stratigraphy, depositional systems, tectonic framework, and paleogeography of the southern San Joaquin Basin, California [abs.], *in* Programs and Abstracts, American Association of Petroleum Geologists, Society of Economic Mineralogists and Paleontologists, and Society of Exploration Geophysicists, 2004 Pacific Section Convention, p. A23: American Association of Petroleum Geologists Bulletin, v. 88, no. 13 (Supplement).

Noble, E.B., 1940, Rio Bravo oil field, Kern County, California: Bulletin of the American Association of Petroleum Geologists, v. 24, no. 7, p. 1330-1333.

Okada, H., and Bukry, D., 1980, Supplementary modification and introduction of code numbers to the low-latitude coccolith biostratigraphic zonation (Bukry, 1973; 1975): Marine Micropaleontology, v. 5, no. 6, p. 321-325.

Olson, H.C., 1988a, Middle Tertiary stratigraphy, depositional environments, paleoecology, and tectonic history of the southeastern San Joaquin Basin, California: Stanford, Calif., Stanford University, Ph.D. dissertation, 353 p.

Olson, H.C., 1988b, Oligocene-middle Miocene depositional systems north of Bakersfield, California—Eastern basin equivalents of the Temblor Formation, *in* Graham, S.A., and Olson, H.C., eds., Studies of the geology of the San Joaquin Basin: Los Angeles, Pacific Section, Society of Economic

Paleontologists and Mineralogists, book 60, p. 189-205.

Payton, C.E., 1977, Seismic stratigraphy—Applications to hydrocarbon exploration: Tulsa, Okla., American Association of Petroleum Geologists Memoir 26, 516 p.

Pence, J.J., 1985, Sedimentology of the Temblor Formation in the northern Temblor Range, California, *in* Graham, S.A., ed., Geology of the Temblor Formation, western San Joaquin Basin, California: Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 44, p. 19-34.

Posamentier, H.W., and Allen, G.P., 1999, Siliciclastic sequence stratigraphy—Concepts and applications: Tulsa, Okla., Society for Sedimentary Geology Concepts in Sedimentology and Paleontology, v. 7, 210 p.

Prothero, D.R., 2001a, Magnetic stratigraphy of the lower-middle Eocene Domengine, Avenal, and Yokut sandstones, western San Joaquin Basin, Fresno and Kings counties, California, *in* Prothero, D.R., ed., Magnetic stratigraphy of the Pacific Coast Cenozoic: Pacific Section, Society of Economic Paleontologists and Mineralogists, book 91, p. 45-55.

Prothero, D.R., 2001b, Magnetic stratigraphy of the middle Eocene Point of Rocks Sandstone (Ulatisian and type Narizian stages), western San Joaquin Basin, California, *in* Prothero, D.R., ed., Magnetic stratigraphy of the Pacific Coast Cenozoic: Pacific Section, Society of Economic Paleontologists and Mineralogists, book 91, p. 65-74.

Prothero, D.R., and Resseguie, J.L., 2001, Magnetic stratigraphy of the Oligocene type Zemorrian Stage, Temblor Formation, Kern County, California, *in* Prothero, D.R., ed., Magnetic stratigraphy of the Pacific Coast Cenozoic: Pacific Section, Society of Economic Paleontologists and Mineralogists, book 91, p. 210-223.

Prothero, D.R., and Sutton, J., 2001, Magnetic stratigraphy of the upper Eocene Wagonwheel Formation, Kern County, California, *in* Prothero, D.R., ed., Magnetic stratigraphy of the Pacific Coast Cenozoic: Pacific Section, Society of Economic Paleontologists and Mineralogists, book 91, p. 136-143.

Prothero, D.R., and Thompson, M., 2001, Magnetic stratigraphy of the type Refugian Stage (late Eocene-early Oligocene), western Santa Ynez Range, Santa Barbara County, California, *in* Prothero, D.R., ed., Magnetic stratigraphy of the Pacific Coast Cenozoic: Pacific Section, Society of Economic Paleontologists and Mineralogists, book 91, p. 119-135.

Reid, S.A., Boote, D.R., and Nilsen, T.H., 2004, The petroleum systems of the San Joaquin Basin—Using a sequence-stratigraphic framework to describe the origin of hydrocarbon accumulations in a structurally active basin [abs.]: *in* Programs and Abstracts, American Association of Petroleum Geologists, Society of Economic Mineralogists and Paleontologists, and Society of Exploration Geophysicists, 2004 Pacific Section Convention, p. A21-A22: American Association of Petroleum Geologists Bulletin, v. 88, no. 13 (Supplement).

Schulein, B.J., 1993, Sedimentology and tectonics of the upper lower to lower middle Eocene Domengine Formation, Vallecitos syncline, California: Stanford, Calif., Stanford University, M.S. thesis, 343 p.

Sullivan, J.C., 1963, Guijarral Hills oil field, *in* Summary of operations, California oil fields: San Francisco, Annual Report of the State Oil and Gas Supervisor, v. 48, no. 2, p. 37-51 [also available *in* California Division of Oil and Gas, Summary of Operations, 1915-1999: California Division of Conservation, Division of Oil, Gas, and Geothermal Resources, Publication No. CD-3, and at ftp://ftp.consrv.ca.gov/pub/oil/Summary_of_Operations/1962/].

Sullivan, J.C., 1966, Kettleman North Dome oil field, *in* Summary of operations, California oil fields: Sacramento, Annual Report of the State Oil and Gas Supervisor, v. 52, no. 1, p. 6-21 [also available *in* California Division of Oil and Gas, Summary of Operations, 1915-1999: California Division of Conservation, Division of Oil, Gas, and Geothermal Resources, Publication No. CD-3, and at ftp://ftp.consrv.ca.gov/pub/oil/Summary_of_Operations/1966/].

Thorup, R.R., 1943, Type locality of the Vaqueros Formation, *in* Jenkins, O.P., ed., Geologic formations and economic development of the oil and gas fields of California: San Francisco, State of California, Department of Natural Resources, Division of Mines Bulletin No. 118, p. 463-466.

Tye, R.S., Hewlett, J.S., Thompson, P.R., and Goodman, D.K., 1993, Integrated stratigraphic and depositional-facies analysis of parasequences in a transgressive systems tract, San Joaquin Basin, California, *in* Weimer, P., and Posamentier, H.W., eds., Siliciclastic sequence stratigraphy—Recent developments and applications: American Association of Petroleum Geologists Memoir 58, p. 99-133.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., and Rahmanian, V.D., 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops—Concepts for high-resolution correlation of time and facies: Tulsa, Okla., American Association of Petroleum Geologists Methods in Exploration Series, v. 7, 55 p.

Wilkinson, E.R., 1960, Vallecitos field, *in* Summary of operations, California oil fields: San Francisco, Annual Report of the State Oil and Gas Supervisor, v. 45, no. 2, p. 17-33 [also available *in* California Division of Oil and Gas, Summary of Operations, 1915-1999: California Division of Conservation, Division of Oil, Gas, and Geothermal Resources, Publication No. CD-3, and at ftp://ftp.consrv.ca.gov/pub/oil/Summary_of_Operations/1959/].

Williams, R.N., Jr., 1938, Recent developments in the North Belridge oil field, *in* Summary of operations, California oil fields: San Francisco, Annual Report of the State Oil and Gas Supervisor, v. 21, no. 4, p. 5-16 [also available *in* California Division of Oil and Gas, Summary of Operations, 1915-1999: California Division of Conservation, Division of Oil, Gas, and Geothermal Resources, Publication No. CD-3, and at ftp://ftp.consrv.ca.gov/pub/oil/Summary_of_Operations/1936/].