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

Chapter 5

Age, Distribution, and Stratigraphic Relationship of Rock Units in the San Joaquin Basin Province, California

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Contents

Introduction

The San Joaquin Basin is a major petroleum province that forms the southern half of California's Great Valley, a 700-km-long, asymmetrical basin that originated between a subduction zone to the west and the Sierra Nevada to the east. Sedimentary fill and tectonic structures of the San Joaquin Basin record the Mesozoic through Cenozoic geologic history of North America's western margin. More than 25,000 feet (>7,500 meters) of sedimentary rocks overlie the basement surface and provide a nearly continuous record of sedimentation over the past ~100 m.y. Further, depositional geometries and fault structures document the tectonic evolution of the region from forearc setting to strike-slip basin to transpressional margin. Sedimentary architecture in the San Joaquin Basin is complicated because of these tectonic regimes and because of lateral changes in depositional environment and temporal changes in relative sea level. Few formations are widespread across the basin. Consequently, a careful analysis of sedimentary facies is required to unravel the basin's depositional history on a regional scale.

At least three high-quality organic source rocks formed in the San Joaquin Basin during periods of sea level transgression and anoxia. Generated on the basin's west side, hydrocarbons migrated into nearly every facies type in the basin, from shelf and submarine fan sands to diatomite and shale to nonmarine coarse-grained rocks to schist. In 2003, the U.S. Geological Survey (USGS) completed a geologic assessment of undiscovered oil and gas resources and future additions to reserves in the San Joaquin Valley of California (USGS San Joaquin Basin Province Assessment Team, this volume, chapter 1). Several research aims supported this assessment: identifying and mapping the petroleum systems, modeling the generation, migration, and accumulation of hydrocarbons, and defining the volumes of rock to be analyzed for additional resources. To better understand the three-dimensional relationships between hydrocarbon source and reservoir rocks, we compiled a database consisting of more than 13,000 well picks and of one-mile resolution seismic grids. Both the well picks and the seismic grids characterize the depths to the top of key stratigraphic units. This database formed the basis of subsequent numerical modeling efforts, including the construction of a three-dimensional geologic model (Hosford Scheirer, this volume, chapter 7) and simulation of the petroleum systems in space and time (Peters, Magoon, Lampe, and others, this volume, chapter 12). To accomplish this modeling, we synthesized the age, geographic distribution, lithology, and petroleum characteristics of hydrocarbon source and reservoir rocks in the basin. The results of that synthesis are presented in this paper in the form of new stratigraphic correlation columns for the northern, central, and southern San Joaquin Valley (fig. 5.1; note that all figures are at the back of this report, following the References Cited).

The stratigraphic relationships and ages published here draw heavily on published and unpublished studies of the San Joaquin Basin. The stratigraphy presented in each of the columns necessarily idealizes the subsurface geology over a relatively large area, instead of representing the specific geology at an individual well, oil and gas field, or outcrop. In this paper we present the background rationale for defining the geographic divisions of the basin (inset map, fig. 5.1), the paleontological time scales used for assigning absolute ages to rock units (figs. 5.2 and 5.3), and the supporting maps illustrating the geographic distribution of each rock type included in the stratigraphic column (figs. 5.4 through 5.64).

Geographic Definitions

The San Joaquin Valley extends from the buried Stockton Arch to the foothills of the Tehachapi and San Emigdio Mountains and from the San Andreas Fault and Coast Ranges to the foothills of the Sierra Nevada (inset, fig. 5.1). The boundaries of the San Joaquin Basin Province as defined by the USGS Energy Resources Program in prior assessments (Beyer and Bartow, 1987; Gautier and others, 1996) differs slightly from the "geologic" definition (for example, Bartow, 1991) in that the northern boundary coincides with the border between Stanislaus and San Joaquin Counties rather than with the Stockton Arch.

For this study, we divided the San Joaquin Basin Province into three geographic zones—northern, central, and southern—based on the locations of major changes in subsurface stratigraphy. The boundary between the northern and central zones corresponds to the approximate northern edge of marine deposition in the mid-Miocene (for example, Bartow, 1991). The boundary between the central and southern San Joaquin Basin corresponds approximately to the deposition of undifferentiated Temblor Formation (and equivalents) to the north of the boundary and the deposition of discrete, interbedded mud and sand of the Temblor Formation (and equivalents) to the south. This facies distinction occurs between the Pyramid Hill (PH, fig. 5.1) and Devils Den (DD, fig. 5.1) oil fields on the basin's west side and between Dudley Ridge (DR, fig. 5.1) and Trico (T, fig. 5.1) gas fields in the central basin. On the basin's east side, the division between a complete section of Temblor Formation-equivalent rocks and undifferentiated, middle Miocene rocks occurs between Jasmin (J, fig. 5.1) and Deer Creek (DC, fig. 5.1) fields, but on the basis of the mapped distribution of rock types, we modified the boundary to lie north of Deer Creek, North field (DCN, fig. 5.1) (for example, see distribution of Olcese Sand, fig. 5.46). The southern boundary of the stratigraphic column corresponds to the surface trace of the White Wolf Fault (WWF, fig. 5.1). The region south of the fault, known as the Tejon embayment (Goodman and Malin, 1992), is poorly characterized by well and seismic data in our database and therefore is not included in this compilation. See DeCelles (1988) and Goodman (1989) for detailed treatments of subsurface geology in the southernmost San Joaquin Basin.

The division of the San Joaquin Basin into three geographic zones matches the distribution of rock types quite well—most wells for a given geologic unit fall entirely within one or two of the geographic zones. Only three units in our database occur in all three subregions: basement rocks, Kreyenhagen Formation, and Santa Margarita Sandstone. Several of the Cretaceous units probably lie within the three subregions as well, but they lie too deeply beneath the southwestern margin of the San Joaquin Basin to be penetrated by hydrocarbon exploration wells.

Stratigraphic Column

The stratigraphic column presents subsurface geology of the San Joaquin Basin dating from the Late Cretaceous to the present (fig. 5.1). The time scale and stages shown in figure 5.1 derive from figure 4.3 of McDougall (this volume, chapter 4), which utilized the international time scales of Gradstein and others (2004) and Gradstein and Ogg (2005). Correlated with these international time scales are the tectonic megasequences of Graham and Johnson (2004), which chronicle the major tectonic events affecting the California margin and control, together with relative changes in sea level, the stratigraphic architecture of San Joaquin Basin sedimentary fill.

The stratigraphic column shows the gross lithology, depositional environment, and hydrocarbon properties of each source and reservoir rock (fig. 5.1). Lithologic symbols indicate whether a unit is coarse grained of nonmarine origin, coarse grained of marine origin, or predominantly mud rich or biosiliceous. Hydrocarbon source rocks are further symbolized with red (gas) or green (oil) icons denoting the principal type of generated hydrocarbon, regardless of source rock maturity (see Peters, Magoon, Lampe, and others, this volume, chapter 12, for a discussion of source rock maturity). Reservoir rocks are similarly shaded by whether they predominantly contain gas or oil, according to thresholds used for this assessment (Gautier and others, this volume, chapter 2)—reservoir rocks containing 0.5 million barrels of oil (MMBO) or greater are shaded green and reservoir rocks containing 3 billion cubic feet (BCF) of gas or greater are depicted in red (see also table 5.1); some oil reservoir rocks, shaded in green, are depicted with red-colored "gas caps" to indicate that those rocks exceed these criteria for both oil and gas. Reservoir rocks containing minor volumes of hydrocarbons are shaded yellow (fig. 5.1). See Magoon and others (this volume, chapter 8) for more on hydrocarbon reservoir rocks in the San Joaquin Basin Province. Within each of the geographic subregions, geologic relationships are displayed relative to a dashed vertical line indicating the schematic position of the basin axis. The basin axis generally separates those rocks deposited on the basin's tectonically active west side from those deposited on its more stable eastern flank.

Although initially inspired by previously published stratigraphic correlations, such as those of Bartow (1991) and Callaway and Rennie (1991), the correlation columns presented here are customized on the basis of a number of factors. First, the geographic distribution and prevalence of each rock unit in the well database guided their inclusion in the columns; generally we selected rock units based on their widespread occurrence in at least one of the subregions of the San Joaquin Basin Province. A frequency threshold of about 10 identifications in the database per rock unit guided this geographic requirement, but was overlooked if an important unit appeared in only a few wells (for example, Kern River Formation, fig. 5.59). Further, we included on the correlation columns all proven or prospective hydrocarbon source and reservoir rocks in the basin; Lillis and Magoon (this volume, chapter 9) describe these source rocks, and Magoon and others (this volume, chapter 8) discuss the reservoir rocks (in particular, their table 8.1).

A key element of the stratigraphic columns is the consistent usage of geologic names. Nomenclatural inconsistency pervades the literature of the San Joaquin Basin. These inconsistencies, summarized by Callaway and Rennie (1991), arise from a myriad of factors, including more than 100 years of exploration (resulting in a large number of geologists describing the rocks), pronounced facies variations within nearly every rock unit, inconsistent application of outcrop nomenclature to subsurface stratigraphy, and muddled usage of biostratigraphic, lithostratigraphic, and chronostratigraphic descriptors. In this compilation, rock unit names that have been formally described are used as indicated in the geologic names lexicon of the USGS national geologic map database (http://ngmdb.usgs.gov/Geolex/geolex_home.html); these names appear in plain text in figure 5.1. In contrast, rock unit names lacking formal geologic description (italic text in fig. 5.1) are referred to in the context of a definitive citation. Typically, informally described rock units consist of (1) hydrocarbon reservoirs that are areally restricted to a few oil or gas fields (for example, the Nozu sand of Kasline, 1942; fig. 5.47); (2) geologic units that are confined to the subsurface and therefore lack a definitive and (or) easily accessible type section (for example, the Stevens sand of Eckis, 1940; fig. 5.53); and (3) horizons within a unit that are easily identified and correlated by the presence of a dominant fauna (for example, the Leda sand of Sullivan, 1963; fig. 5.29).

Absolute ages of each rock unit were determined by extensive review of published and unpublished literature. Ages for many units derive from biostratigraphic and magnetostratigraphic studies of outcrop sections. Although these studies typically leave the correlation between exposures and the subsurface unspecified, we use these ages with the caveat that facies change between outcrop and buried sections introduces uncertainty in absolute ages.

Age assignments for Cretaceous rocks proved challenging because most studies of these rocks date them by referring to the benthic foraminiferal zones of Goudkoff (1945) without reference to a geologic time scale. Consequently, we used the study of Williams (1997; fig. 5.2), which correlates those paleontologic zones with absolute ages for the Sacramento Valley. To our knowledge, this study is the only one available for central-northern California that ties industry paleontology reports and published subsurface correlations with the international time scale (note, however, that this figure uses the time scale of Gradstein and others, 1994; we did not attempt to update this work to a more recent time scale). A further complication is that the correspondence between biostratigraphic boundaries and lithostratigraphic boundaries often is unspecified in the literature. In the absence of more specific information, we assumed a one-to-one correspondence between the biostratigraphic boundaries and the lithostratigraphic ones. Because most of the benthic foraminiferal zones of Goudkoff (1945) span a time of less than 2 m.y. (and none exceeds 4 m.y. duration), the error introduced by equating biostratigraphic and lithostratigraphic units probably averages less than 2 m.y.

Age assignments for Cenozoic rocks followed similar principles—for studies that cite only the planktonic or benthic foraminiferal zones or calcareous nannofossil zones without correlation to the global geologic time scale, we used the time scale of McDougall (this volume, chapter 4; fig. 5.3) to pinpoint the unit's depositional age. Again, error in these age assignments derives from uncertainties in relative stratigraphic positions of the biostratigraphic zones and the rock section. The foraminiferal zones of Laiming (1940) similarly required correlation with the geologic time scale. To that end, we used the correlation of Bartow (1992) for southern California between the emended Laiming zones of Almgren and others (1988) and the calcareous nannofossils zones, which we subsequently correlated with the time scale shown in figure 5.3. We also used studies of mammalian fossils within the various stratigraphic units of the San Joaquin Basin. Ages of North American mammalian stages derive from the GeoWhen Database of the International Commission on Stratigraphy (http://www.stratigraphy.org/geowhen/index.html).

Because of uncertainties related to equating biostratigraphic zones with lithostratigraphic boundaries and for simpler drafting of the stratigraphic columns, we rounded most ages to the nearest half-million years, except for ages pinpointed by tightly constrained radiometric dates (for example, Tulare Formation, fig. 5.64).

Table 5.2 summarizes the salient features of each rock unit that appears on the correlation columns, including geologic names usage, lower and upper ages, and number of well picks and unique wells containing identifications of the unit.

Distribution Maps

To supplement the stratigraphic correlation columns (fig. 5.1), we present maps illustrating the geographic distribution of each rock unit, as defined by our well database, considered in the three regions (figs. 5.4 through 5.64); more than 95% of the entries in the well database derive from annual reports of the California Department of Conservation, Division of Oil, Gas, and Geothermal Resources (http://www.consrv.ca.gov/dog/pubs_stats/annual_reports/annual_reports.htm) and in published compilations of prospect wells (CDOG, 1982). The longitude and latitude for each well, obtained from databases provided by the Division of Oil, Gas, and Geothermal Resources, is plotted at the center of a blue-filled circle. Each distribution map displays all well picks for a given unit in the database; we did not attempt to exclude outliers for this effort, although extensive analyses of incompatible formation locations were performed for the compilation of the three-dimensional geologic model (see Hosford Scheirer, this volume, chapter 7).

Hosford Scheirer (this volume, chapter 7) describes the data sources, compilation procedures, and quality control required to assemble the well database, which contains more than 13,000 well picks in about 3,200 wells and encompasses nearly 600 uniquely named units. To enhance the utility of this database, rock units were combined by formation so that members, sand zones, faunal horizons, and the like are grouped into a single distribution map. For example, the distribution map for the Moreno Formation (fig. 5.17) incorporates identifications of 15 different members, which in turn are specified in the well database by 35 different names. Any combination of these members may be identified in a single well. Accordingly, each well symbol on a distribution map may represent more than one well pick. We report in the title of each map and in table 5.2 the total number of well picks for each formation, as well as the unique number of wells in which the formation and its members appear. Because the ages of each rock unit are discussed from oldest to youngest, the distribution maps and accompanying figure captions are ordered such that individual members of a formation appear prior to the formation itself; the geographic distribution map of the formation thereby summarizes the prior group of plots.

The locations of geographic features or places that are important to the discussion of each rock type are indicated on the distribution maps by filled black triangles and abbreviated names; these abbreviations are defined in the figure captions. The displayed locations of oil and gas fields correspond to the centroid of the productive limits of the fields. The locations of most other place names, such as outcrop sections or sample locations, derive from a database of geographic names obtained from the Geographic Names Information System of the USGS (http://geonames.usgs.gov). If possible, these locations were updated to the coordinates of particular outcrop sections. The locations of specific oil and gas wells mentioned in the discussion of a given rock type are highlighted on its distribution map by open red circles. The American Petroleum Institute (API) numbers of these reference wells appear in the text. We report only the central 8 digits of each API number, omitting the first two digits ("04") that indicate the well was drilled in California and the 11th through 14th digits indicat-

Table 5.1. Principal reservoir rocks in the San Joaquin Basin Province.

[Reservoir rocks containing greater than 0.5 million barrels of oil are shaded green in the table and in figure 5.1; reservoir rocks containing more than 3 billion cubic feet of gas are shaded red. Mbo, thousands of barrels of oil; MMcfg, millon cubic feet of gas; GOR, gas-oil ratio; cf/bo, cubic feet per barrel of oil; BOE, barrels of oil-equivalent; Mboe, thousands of barrels of oil-equivalent; na, not applicable. Columns are sorted numerically by known recoverable oil]

Reservoir rock[1]	Age	Known Recoverable Oil (Mbo)	Oil (%)	Known Recoverable Gas (MMcfg)	GOR (cf/bo)	Gas (%)	BOE (Mboe)	BOE (%)
Undesignated[2]	undesignated	3,664,917	25.11	823,622	225	4.39	3,802,187	21.45
Kern River Formation	late Miocene	2,076,205	14.23	19,308	9	0.10	2,079,423	11.73
Stevens sand of Eckis (1940)	middle to late Miocene	1,971,754	13.51	9,245,757	4,689	49.23	3,512,714	19.82
Temblor Formation	Oligocene to middle Miocene	1,632,436	11.19	3,181,502	1,949	16.94	2,162,686	12.20
Tulare Formation	Pliocene to Pleistocene	1,343,187	9.20	843,597	628	4.49	1,483,787	8.372
Reef Ridge Shale Member of Monterey Formation	late Miocene	888,932	6.09	126,136	142	0.67	909,955	5.134
Etchegoin Formation	Pliocene	819,575	5.62	655,439	800	3.49	928,815	5.241
Lodo Formation	Paleocene to Eocene	556,759	3.82	1,662,694	2,986	8.85	833,875	4.705
Chanac Formation	late Miocene	457,593	3.14	164,567	360	0.88	485,021	2.737
Jewett Sand	early Miocene	442,060	3.03	56,505	128	0.30	451,478	2.547
Vedder Sand	Oligocene	291,973	2.00	462,894	1,585	2.46	369,122	2.083
McLure Shale Member of Monterey Formation	late Miocene	102,684	0.70	403,026	3,925	2.15	169,855	0.958
Zilch formation of Loken (1959)	Oligocene to middle Miocene	79,773	0.55	69,715	874	0.37	91,392	0.516
Santa Margarita Sandstone	late Miocene	55,354	0.38	15,460	279	0.08	57,931	0.327
Leda sand of Sullivan (1963)	late Eocene	33,942	0.23	55,462	1,634	0.30	43,186	0.244
Tumey formation of Atwill (1935)	late Eocene	32,059	0.22	95,061	2,965	0.51	47,903	0.27
Vaqueros Formation	Oligocene	27,341	0.19	49,126	1,797	0.26	35,529	0.20
Olcese Sand	early Miocene	25,160	0.17	20,948	833	0.11	28,651	0.162
San Emigdio Formation[2]	Eocene	24,347	0.17	58,663	2,409	0.31	34,124	0.193
Domingene Formation	Eocene	23,555	0.16	76,540	3,249	0.41	36,312	0.205
Point of Rocks Sandstone Member of Kreyenhagen Formation	Eocene	15,069	0.10	45,935	30,718	0.24	28,901	0.16
Antelope shale of Graham and Williams (1985)	late Miocene	9,646	0.07	49,800	5,163	0.27	17,946	0.101
Round Mountain Silt	middle Miocene	8,556	0.06	5,219	610	0.03	9,426	0.053
Yokut Sandstone	Eocene	5,351	0.04	5,622	1,051	0.03	6,288	0.035
San Joaquin Formation	early to late Pliocene	2,335	0.02	354,203	151,693	1.89	61,369	0.346
Basalt[2]	Miocene	1,384	0.01	18,742	13,542	0.10	4,508	0.025
Kreyenhagen Formation	Eocene	761	0.01	848	1,114	0.00	902	0.005
Tejon Formation[2]	early to late? Eocene	204	0.00	2,488	12,196	0.01	619	0.003
Moreno Formation[3]	Late Cretaceous to Paleocene	118	0.00	4,742	40,186	0.03	908	0.005
Walker Formation	Oligocene	71	0.00	0	na	0.00	71	<0.1
Schist[2]	Jurassic(?)	18	0.00	0	na	0.00	18	0
Nortonville sand of Frame (1950)[2]	Eocene	0	0.00	74,067	na	0.39	12,345	0.07
Panoche Formation[3]	Late Cretaceous	0	0.00	59,864	na	0.32	9,977	0.056

[1] Reservoir rocks are designated by CDOGGR (2004), and have been updated to comply with USGS geologic names standards.
[2] These formations do not appear in figure 5.1 but are included for completeness with data presented by Magoon and others (this volume, chapter 8).
[3] The Moreno and Panoche Formations remain unshaded in figure 5.1 because it is unclear in CDOGGR (2004) which specific units within those formations are productive.

ing the sidetrack code and number of operations on the well (for example, see explanation at http://www.spwla.org/library_info/api_codes/apitechnical.htm).

The remainder of the text summarizes the absolute age and geographic distribution of each rock unit shown in figure 5.1.

Jurassic to Cretaceous

Basement rocks: 160 Ma (Coast Range ophiolite of Bailey and Blake, 1974) and 120 Ma (Sierra Nevada granite) (fig. 5.4)

The nature of basement rock in the San Joaquin Basin is a question of long-standing scientific inquiry, focusing chiefly on the spatial relationships of westward-dipping Sierra Nevada granite, eastward-dipping Coast Range ophiolite of Bailey and Blake (1974; hereafter referred to as Coast Range ophiolite), and rocks of the Franciscan Complex (see for example, Wentworth and others, 1984; Jachens and others, 1995; Dickinson, 2002). For the purposes of resource exploration and assessment, basement consists of the base of hydrocarbon prospective sediments, regardless of the composition of that foundation (for example, Callaway and Rennie, 1991). However, we focused some effort on discerning the nature of the basement surface beneath the San Joaquin Basin because of extensive data available to us for modeling the basin in three dimensions (see Hosford Scheirer, this volume, chapter 7), and because fractured schist forms a hydrocarbon reservoir at Mountain View (MV, fig. 5.4) (Park, 1966) and Edison (E, fig. 5.4) (White, 1955) oil fields. Further, numerical modeling of the petroleum systems in the San Joaquin Basin Province revealed that the composition of basement rocks plays an important role in determining basal heat flow, which in turn influences the volume of generated petroleum (see Peters, Magoon, Lampe, and others, this volume, chapter 12). Although a detailed examination of basement rocks exceeds the scope of this study, we present here a brief overview of the age of the top of basement rocks in the San Joaquin Valley.

The Coast Range ophiolite predates the other two basement types in the San Joaquin Basin. Hopson and others (1981) present the geologic relations, petrology, and age of 23 remnants of the Coast Range ophiolite spanning a 700-km-long transect along California's coast and Great Valley; four of these sites occur near the western border of the San Joaquin Basin Province. Uranium-lead dating of zircon grains from an ophiolite remnant exposed in Bitterwater Canyon (BC, fig. 5.4) yields ages of 165 to 163 Ma (each with error ranges of ± 2 Ma) (Hopson and others, 1981). A section of ophiolite exposed in Del Puerto Canyon (DC, fig. 5.4) of the northern Diablo Range preserves a nearly complete section of oceanic crust and overlying pelagic sediment; radiometric analyses on this section suggest a younger age of 155 ± 2 Ma, although the crosscutting plagiogranite dike from which the samples were taken appear to post-date the dioritic host rock. Potassium-argon analyses of hornblende from stratigraphically deeper levels of the ophiolite at Del Puerto Canyon yield ages of 160 ± 0.8 Ma (Lanphere, 1971), which are more compatible with the age of the ophiolite at Bitterwater Canyon. For the purposes of numerical modeling (see Peters, Magoon, Lampe, and others, this volume, chapter 12), we use an age of 160 Ma for the top of the Coast Range ophiolite.

Abundant age control exists for the granitoid rocks of the Sierra Nevada, which constitutes the eastern substrate of the San Joaquin Basin, extending at least as far east as the Coast Ranges and the San Andreas Fault (Jachens and others, 1995). Uranium-lead dating on zircon and sphene from granitoid rocks collected between 36°N and 38°N suggest that emplacement of granitic plutons occurred between 120 and 80 Ma (Chen and Moore, 1982). Further, plots of these dates along northeast-southwest trending profiles (dashed lines labeled C-C' and D-D' in fig. 5.4) indicate a steady migration of plutonism from west to east during this time period, with the oldest rocks occurring on the margin of the San Joaquin Valley and the youngest rocks appearing on the eastern flank of the Sierra Nevada (Chen and Moore, 1982). Note that the cessation of plutonism at about 80 Ma predates by about 5 m.y. the beginning of the flat slab subduction megasequence of Graham and Johnson (2004) (fig. 5.1). Potassium-argon analyses of hornblende and biotite from Sierran granite by Evernden and Kistler (1970) corroborate the age progression noted by Chen and Moore (1982); two northeast-southwest oriented transects at about 38.25° and 37.25°N (dashed lines labeled A-A' and B-B', respectively, in fig. 5.4) reveal that Sierran basement rocks at the eastern margin of the Great Valley date to about 120 Ma. We thus use an age of 120 Ma for the top of granitic basement beneath the San Joaquin Basin.

Assigning a single age to the top of the Franciscan Complex is somewhat arbitrary, as the complex encompasses a varied assemblage of sedimentary, igneous, and metamorphic rocks emplaced in diverse tectonic settings (Mattinson, 1988). Geochronologic analyses of metamorphic rocks of the Franciscan Complex reveal a spread of ages ranging from 165 to 70 Ma; this large age range encompasses two clusters of high-grade metamorphic rocks (150 to 165 Ma and 100 to 115 Ma) and one group of lower-grade rocks spanning the entire array (Mattinson, 1988). However, because the age and geometry of the Franciscan Complex at depth in the San Joaquin Basin remain uncertain, we neglect the Franciscan Complex in numerical flow models of the basin's petroleum systems.

In summary, for the purposes of this regional compilation and for numerical analyses, we assume upper depositional ages of 160 Ma for the Coast Range ophiolite and 120 Ma for Sierran granite. Figure 5.4 shows 470 identifications of "basement," "Franciscan," and schist.

Table 5.2. Summary of geologic names, ages, total number of identifications, and number of unique wells for each of the rock units in figure 5.1.
[An "x" in the data columns labeled North/Central/South indicates in which column(s) of figure 5.1 that rock unit appears. Italic text denotes informally named geologic units; see text for more information on informal formation names]

Figure Number	Name as appearing on stratigraphic section	Name as appearing on distribution map	Age at base (Ma)	Age at top (Ma)	Number of picks	Number of wells	North	Central	South
5.4	*Basement rocks*	Basement rocks	N/A	160/120	470	470	x	x	x
5.5	*Forbes fm*	Forbes formation of Kirby (1943)	83.5	78	72	69	x	—	—
5.6	*Sacramento shale*	Sacramento shale of Callaway (1964)	78	77	78	77	x	—	—
5.7	*Lathrop sd*	Lathrop sand of Callaway (1964)	77	73.5	469	288	x	—	—
5.8	Joaquin Ridge Ss Mbr	Joaquin Ridge Sandstone Member of Panoche Formation	77	73.5	14	14	—	x	—
5.9	Panoche Fm	Panoche Formation	83.5	73.5	619	385	x	x	—
5.10	*Sawtooth shale*	Sawtooth shale of Hoffman (1964)	73.5	73	342	342	x	—	—
5.11	*Tracy sds*	Tracy sands of Hoffman (1964)	73	72	342	267	x	—	—
5.12	*Brown Mtn ss*	Brown Mountain sandstone of Bishop (1970)	73	72	42	42	—	x	—
5.13	Ragged Valley silt	Ragged Valley silt of Hoffman (1964)	73 (north)/ 74 (central)	71.5 (north)/ 73 (central)	490	485	x	x	—
5.14	*Starkey sands*	Starkey sands of Hoffman (1964)	75	71.5	527	202	x	—	—
5.15	*Blewett sds*	Blewett sands of Hoffman (1964)	71.5	68	773	464	x	—	—
5.16	Garzas Ss/*Wheatville sd*	Garzas Sandstone Member of Moreno Formation/Wheatville sand of Callaway (1964)	64.5	61	588	529	x	x	—
5.17	Moreno Fm	Moreno Formation	73.5	61	2511	810	x	x	—
5.18	San Carlos sand	Sand Carlos sand of Wilkinson (1960)	58.5	55.5	81	80	—	x	—
5.19	Cantua Ss Mbr	Cantua Sandstone Member of Lodo Formation	53	51.5	51	40	—	x	—

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Figure Number	Name as appearing on stratigraphic section	Name as appearing on distribution map	Age at base (Ma)	Age at top (Ma)	Number of picks	Number of wells	North	Central	South
5.20	Arroyo Hondo Sh Mbr	Arroyo Hondo Shale Member of Lodo Formation	51.5	49.5	148	132	—	x	—
5.21	*Gatchell sd*	Gatchell sand of Goudkoff (1943)	50	49.5	93	88	—	x	—
5.22	Lodo Fm	Lodo Formation	58.5	49.5	305	218	—	x	—
5.23	Yokut Ss	Yokut Sandstone	49.5	49	31	31	—	x	—
5.24	Domengine Fm	Domengine Formation	49	48.5	538	538	x	x	—
5.25	Canoas Slts Mbr	Canoas Siltstone Member of Kreyenhagen Formation	48.5	45.5	38	38	—	—	x
5.26	Point of Rocks Ss Mbr	Point of Rocks Sandstone Member of Kreyenhagen Formation	45.5	40.5	80	69	—	—	x
5.27	Kreyenhagen Fm	Kreyenhagen Formation	48.5	37	1384	1157	x	x	x
5.28	*Oceanic sand*	Oceanic sand of McMasters (1948)	37	35	19	19	—	—	x
5.29	*Leda sd*	Leda sand of Sullivan (1963)	34	33.5	42	42	—	x	—
5.30	*Tumey formation*	Tumey formation of Atwill (1935)	37	33.5	250	219	—	x	x
5.31	*Famoso sand*	Famoso sand of Edwards (1943)	49	33.5	103	101	—	x	x
5.32	Cymric Shale Mbr	Formation	33	32	22	20	—	—	x
5.33	Wygal Ss Mbr	Wygal Sandstone Member of Temblor Formation	30	29	69	61	—	—	x
5.34	Santos Sh Mbr	Santos Shale Member of Temblor Formation	29	20	19	16	—	—	x
5.35	Agua Ss Bed	Agua Sandstone Bed of the Santos Shale Member of Temblor Formation	25	24	38	37	—	—	x
5.36	Walker Fm	Walker Formation	34	25	48	48	—	—	x
5.37	Vedder Sand	Vedder Sand	33.5	25	165	150	—	—	x
5.38	Vaqueros Fm	Vaqueros Formation	33.5	24	37	36	—	x	—
5.39	PH [Pyramid Hill Sd Mbr]	Pyramid Hill Sand Member of Jewett Sand	25	24	64	62	—	—	x
5.40	*Rio Bravo sd*	Rio Bravo sand of Noble (1940)	25	24	15	15	—	—	x
5.41	Jewett Sand	Jewett Sand	25	21	69	66	—	—	x
5.42	Freeman Silt	Freeman Silt	24	19	44	44	—	—	x

Table 5.2. Summary of geologic names, ages, total number of identifications, and number of unique wells for each of the rock units in figure 5.1.

[An "x" in the data columns labeled North/Central/South indicates in which column(s) of figure 5.1 that rock unit appears. Italic text denotes informally named geologic units; see text for more information on informal formation names]— Continued.

Figure Number	Name as appearing on stratigraphic section	Names as appearing on distribution map	Age at base (Ma)	Age at top (Ma)	Number of picks	Number of wells	North	Central	South
5.43	Carneros Ss Mbr	Carneros Sandstone Member of Temblor Formation	20	17.5	58	42	—	—	x
5.44	Media Sh Mbr	Media Shale Member of Temblor Formation	17.5	16.5	35	35	—	—	x
5.45	B [Buttonbed Ss Mbr]	Buttonbed Sandstone Member of Temblor Formation	16.5	16	33	33	—	—	x
5.46	Olcese Sand	Olcese Sand	21	16.5	130	129	—	—	x
5.47	*Nozu sd*	Nozu sand of Kasline (1942)	15	14.5	31	31	—	—	x
5.48	*Zilch fm*	Zilch formation of Loken (1959)	30	14	293	293	x	x	—
5.49	Temblor Fm	Temblor Formation	33 (south)/ 18 (central)	16 (south)/ 14 (central)	1036	703	—	x	x
5.50	Round Mtn Silt	Round Mountain Silt	16	13.5	41	41	—	—	x
5.51	Devilwater Sh Mbr/Gould Sh Mbr, undiff.	Gould Shale and Devilwater Shale Members of Monterey Fm, undiff.	16	13.5	62	59	—	—	x
5.52	McDonald Sh Mbr	McDonald Shale Member of Monterey Formation	13.5	10	109	108	—	—	x
5.53	*Stevens sd*	Stevens sand of Eckis (1940)	9.5	7	232	188	—	—	x
5.54	*Fruitvale shale*	Fruitvale shale of Miller and Bloom (1939)	13.5	6.5	41	39	—	—	x
5.55	McLure Shale Mbr	McLure Shale Member of Monterey Formation	12	6.5	279	279	—	x	—
5.56	*Antelope sh*	Antelope shale of Graham and Williams (1985)	10	6.5	171	168	—	—	x
5.57	Santa Margarita Ss	Santa Margarita Sandstone	11	6.5	471	448	x	x	x
5.58	Chanac Fm	Chanac Formation	11	6	58	46	—	—	x
5.59	KR [Kern River Fm]	Kern River Formation	8	6	3	3	—	—	x
5.60	Reef Ridge Sh Mbr	Reef Ridge Shale Member of Monterey Formation	6.5	5.5	265	248	—	x	x
5.61	Monterey Fm	Monterey Formation	16 (south)/12 (central)	5.5 (south)/5.5 (central)	1356	860	—	x	x
5.62	Etchegoin Fm	Etchegoin Formation	5.5	4.5	459	371	—	x	x
5.63	San Joaquin Fm	San Joaquin Formation	4.5	2.5	288	280	—	x	x
5.64	Tulare Fm	Tulare Formation	2.5	0.6	92	86	—	—	x
Total					16633	12261			

Cretaceous

[Begin Panoche Formation]

Forbes formation of Kirby (1943): 83.5 to 78 Ma (fig. 5.5)

The Forbes formation of Kirby (1943), hereafter referred to as the Forbes formation, contains benthic foraminifers from the F-1 and F-2 zones (Almgren, 1986; Williams, 1997), indicating deposition from about 83.5 to 78 Ma. This formation is restricted to the northern San Joaquin Basin. Figure 5.5 shows 72 identifications in 69 wells of "Forbes" and "F-zone."

Sacramento shale of Callaway (1964): 78 to 77 Ma (fig. 5.6)

The Sacramento shale of Callaway (1964), hereafter referred to as the Sacramento shale, contains benthic foraminifers of the lower E zone (Almgren, 1986; Williams, 1997), indicating deposition from about 78 to 77 Ma. Identified in 77 wells in our database (fig. 5.6), the Sacramento shale exhibits a subsurface distribution very similar to that of the underlying Forbes formation (fig. 5.5).

Lathrop sand of Callaway (1964): 77 to 73.5 Ma (fig. 5.7)

According to previously published stratigraphic correlations (Callaway, 1964; Edmondson and others, 1964), the Lathrop sand of Callaway (1964; hereafter referred to as Lathrop sand) contains benthic foraminifers from a bit above the lower E zone interval (77 Ma) to near the boundary between the E and D-2 zones (73.5 Ma). Deposition of this sand thus occurred from somewhat later than 77 Ma to about 73.5 Ma. The 469 entries of this unit in 288 wells (fig. 5.7) are variously labeled as "Lathrop," "Lathrop sand," "upper Lathrop," "middle Lathrop," and "lower Lathrop" as well as "top upper Lathrop," "top middle Lathrop," and "base middle Lathrop."

Note that a large number of these wells lie north of the San Joaquin Basin Province boundary; these wells, which derive from a proprietary study referred to by Nilsen and Moore (1997), lie south of the Stockton Arch, the natural geologic division between the Sacramento Basin to the north and the San Joaquin Basin to the south.

Joaquin Ridge Sandstone Member of the Panoche Formation: 77 to 73.5 Ma (fig. 5.8)

The Joaquin Ridge Sandstone Member contains benthic foraminifers of E-zone age (Almgren, 1986), implying deposition from about 77 to 73.5 Ma. Occurring mainly in the Coalinga area (C, fig. 5.8) of the central San Joaquin Basin Province, the Joaquin Ridge Sandstone is time-correlative with the Lathrop sand (Trumbly, 1990). Although overlying units are often included in the Panoche Formation, we follow the convention of Huey (1948), who considers the Joaquin Ridge Sandstone to be the uppermost member of the Panoche Formation in the Coalinga area. The well-top database contains 14 picks of this geologic unit (fig. 5.8).

Panoche Formation: 83.5 to 73.5 Ma (fig. 5.9)

Although use of the terms Moreno Formation and Panoche Formation more accurately classify outcrop geology than subsurface geology (Bartow and Nilsen, 1990), we retain them in this classification because well picks labeled as "Moreno" and "Panoche" persist in the data sources that comprise the well-top database. Well-top picks classified as Panoche Formation in this compilation include those described for the Forbes formation, the Sacramento shale, the Lathrop sand, and the Joaquin Ridge Sandstone Member, as well as identifications labeled "first Panoche sand," "second Panoche sand," "third Panoche sand," "fourth Panoche sand," "Panoche," and "Panoche sand." Following the convention of Huey (1948) and Bishop (1970), we consider the Lathrop sand and the Joaquin Ridge Sandstone as the top members of the Panoche Formation in the subsurface of the northern and central San Joaquin Basin, respectively. Accordingly, the top of the Panoche Formation is assigned an age of 73.5 Ma. Because our well database contains no identifications of geologic units older than the Forbes formation, we nominally use an age of 83.5 Ma for the base of the Panoche Formation, but note that stratigraphic charts (for example, Edmondson and others, 1964) indicate a G zone, Santonian age unit called the Dobbins shale of Hoffman (1964) beneath the Forbes formation in the San Joaquin Basin. The Panoche Formation and its members appear in 385 wells in our database (fig. 5.9).

[End Panoche Formation]

[Begin Moreno Formation]

Sawtooth shale of Hoffman (1964): 73.5 to 73 Ma (fig. 5.10)

According to stratigraphic correlations of Almgren (1986), the Sawtooth shale of Hoffman (1964; hereafter referred to as Sawtooth shale) coincides with the lower half of benthic foraminiferal zone D-2, implying deposition from about 73.5 to 73 Ma. Our well-top database contains 342 identifications of this unit (fig. 5.10).

Tracy sands of Hoffman (1964): 73 to 72 Ma (fig. 5.11)

Deposition of the Tracy sands of Hoffman (1964; hereafter referred to as Tracy sands) coincided with most of benthic foraminiferal zone D-2 (73.5 to 72 Ma) (Almgren, 1986). Well-top picks in our database are labeled as "Tracy," "first Tracy," "Tracy sand," "middle Tracy marker," and "base first Tracy." Our database includes 267 wells with 342 picks of this geologic unit (fig. 5.11).

Brown Mountain sandstone of Bishop (1970): 73 to 72 Ma (fig. 5.12)

The Brown Mountain sandstone of Bishop (1970), hereafter referred to as the Brown Mountain sandstone, is the time-stratigraphic equivalent (73 to 72 Ma) in the central San Joaquin Basin of the Tracy sands in the northern basin (Almgren, 1986; Trumbly, 1990). Identifications of this unit in our database are labeled as "Brown Mountain" and "base Brown Mountain." The well database contains 42 identifications of this geologic unit; these appear clustered in the vicinities of Coalinga (C, fig. 5.12), Riverdale (R, fig. 5.12), and Cheney Ranch (CR, fig. 5.12) fields. Although some authors assign this unit to the Panoche Formation (for example, Anderson, 1972), we follow the convention of Huey (1948), which includes the Brown Mountain sandstone in the Moreno Formation, and the convention of Bishop (1970), which includes units of benthic foraminiferal zone D-2 in the Moreno Formation.

Ragged Valley silt of Hoffman (1964): 73 to 71.5 Ma (north) and 74 to 73 Ma (central) (fig. 5.13)

The Ragged Valley silt of Hoffman (1964; hereafter referred to as Ragged Valley silt) is a time-transgressive unit. In the northern San Joaquin Basin, the Ragged Valley silt contains benthic foraminifers of the D-2 and D-1 zones (Almgren, 1986), with the contact between the zones occurring near the top of the silt (Hoffman, 1964), implying an upper age somewhat younger than 72 Ma. In the northern San Joaquin Basin, this unit overlies the Tracy sands and underlies the Blewett sands of Hoffman (1964) (Bartow and Nilsen, 1990). We use an age of 73 to 71.5 Ma for the Ragged Valley silt in the northern San Joaquin Basin.

Although the Ragged Valley silt is identified in only 3 wells in the central San Joaquin Basin, we include it in the correlation chart for the central region because of its intervening position between the better characterized Brown Mountain sandstone (above) and Joaquin Ridge Sandstone (below) (Bartow and Nilsen, 1990). Typically, the silt in the Coalinga area (C, fig. 5.13) contains fauna from the D-2 and upper E foraminiferal zones (Almgren, 1986). Thus, the Ragged Valley silt was deposited between about 73 and 74 Ma in the central basin. This unit occurs in 485 wells in our database (fig. 5.13).

Starkey sands of Hoffman (1964): 75 to 71.5 Ma (fig. 5.14)

The Starkey sands of Hoffman (1964; hereafter referred to as Starkey sands) comprise three main sand units that have coeval relationships with the Sawtooth shale, the Tracy sands, and the Ragged Valley silt, and possibly with the Blewett sands of Hoffman (1964) (Callaway, 1990). Nilsen and Moore (1997) indicate a coeval relationship of the lowermost of the Starkey sands with the Lathrop sand as well. The second and third of these sands contain benthic foraminifers from zone D-2, and possibly from zone E (Nilsen and Moore, 1997; Williams, 1997), whereas the first sand contains foraminifers from the lower D-1 zone (Callaway, 1990). Thus, the Starkey sands were deposited from about 75 to 71.5 Ma.

Identifications of this unit in our database are labeled "first Starkey sand," "second Starkey sand," "third Starkey sand," "fourth Starkey sand," "Starkey," and "base Starkey." The database also contains three interformational markers identified by Nilsen and Moore (1997). Figure 5.14 shows the locations of 202 wells with identifications of the Starkey sands; this number may be artificially low as Philbrick (1997) reports that early developers of gas fields in the northern San Joaquin Basin named the east side shelf sands as first through fourth Panoche sands; wells with those picks were included with the distribution map for the Panoche Formation (fig. 5.9).

Incidentally, based on its age and east-side provenance, the Starkey sands belong neither to the Moreno nor Panoche Formations, but we include it in this section describing the subsurface members of the Moreno Formation because of its coeval relationship with many of those members (for example, the Blewett sands of Hoffman, 1964).

Blewett sands of Hoffman (1964): 71.5 to 68 Ma (fig. 5.15)

According to stratigraphic correlations of Almgren (1986), the Blewett sands of Hoffman (1964; hereafter referred to as Blewett sands) encompass all of foraminiferal zone D-1 (72 to 68 Ma). Because of the age of the underlying Ragged Valley silt, we use an age of 71.5 to 68 Ma for the Blewett sands. Well-top identifications include picks for "Blewett," "Blewett sand," "upper Blewett," and "lower Blewett." The database contains 464 wells with 773 picks of this unit (fig. 5.15).

Cretaceous to Paleocene

Garzas Sandstone Member of the Moreno Formation and Wheatville sand of Callaway (1964): 64.5 to 61 Ma (fig. 5.16)

Nearly 600 identifications of the Garzas Sandstone Member, "base Garzas," and "Wheatville sand" in more than

500 wells characterize the widespread geographic distribution of this uppermost (subsurface) member of the Moreno Formation. The correlative sand in the central San Joaquin Basin is the Wheatville sand of Callaway (1964). Members of the Moreno Formation are generally better dated in outcrop than in subsurface sections (for example, McGuire, 1988b). These age constraints are difficult to apply to subsurface sections, however, because of different nomenclature between the two settings—whereas subsurface members of the Moreno Formation include the Sawtooth shale, the Tracy sands, the Ragged Valley silt, and the Blewett sands (for example, Bishop, 1970), outcrop sections of the Moreno Formation are divided into the Dosados Sandstone and Shale, the Tierra Loma Shale, the Marca Shale, and the Dos Palos Shale (Payne, 1951). However, these latter subdivisions of the Moreno Formation generally are not identified in the subsurface because of variations in lithology and biostratigraphic control (McGuire, 1988a). In fact, in our well database these members are identified in only 28 wells.

In outcrop at Oat Gulch (OG, fig. 5.16), the Garzas Sandstone Member contains benthic foraminifers from the A-2 zone (Goudkoff, 1945). At the type section of the Moreno Formation in Escarpado Canyon (EC, fig. 5.16), McGuire (1988a) associates the A-2 zone with the middle to upper Dos Palos Shale Member and the Cima Sandstone Lentil. Together these two units correlate to an unnamed "upper sandy interval" in the Cheney Ranch 1 well (API number 01900190; open red circle, fig. 5.16) located about 6 miles east of the outcrop section. If this upper sandy unit correlates with the Garzas Sandstone Member, age constraints derived by McGuire (1988b) pinpoint its age—in both the Escarpado Canyon section and Cheney ranch well, fauna characteristic of planktonic foraminiferal zone P1b and benthic foraminiferal zone A-2 (or Cheneyian Stage of Loeblich, 1958) indicate a basal age somewhere within the range of 64.5 to 62.5 Ma. The youngest absolute age established by McGuire (1988b) for the upper Dos Palos Shale at Escarpado Canyon occurs at a stratigraphic position located 55 meters below the contact with the overlying Lodo Formation, at which diagnostic planktonic fauna define the base of zone P3a (61.1 Ma). In the absence of more specific age information, we use an age of 64.5 (base) to 61 (top) Ma for the Garzas Sandstone Member of the Moreno Formation.

Moreno Formation: 73.5 to 61 Ma (fig. 5.17)

More than 2,500 identifications in 810 wells define the widely occurring Moreno Formation in the northern and central San Joaquin Basin. These identifications include those described for the Sawtooth shale, Tracy sands, Brown Mountain sandstone, Ragged Valley silt, and the Starkey and Blewett sands, as well as the Cima Sandstone Lentil, Dos Palos Shale, "Dos Palos equivalent," "lower Dos Palos," "Moreno," and "base Moreno."

The most specific determination of the absolute age of the Moreno Formation comes from detailed analysis by McGuire (1988b) at its type section in Escarpado Canyon (EC, fig. 5.17). The upper age (61 Ma), as discussed above, is constrained by planktonic foraminifers of zone P3a in the upper Dos Palos Shale Member in outcrop and in the upper sandy interval in the Cheney Ranch 1 well (API number 01900190; open red circle, fig. 5.17) (McGuire, 1988b). The age of the base of the Moreno Formation derives in our study from age constraints for the Sawtooth shale, which contains benthic foraminifers from the lower part of zone D-2 (73.5 to 73 Ma); this definition implies a correlation between the base of the Moreno Formation and the boundary between zones D-2 and E (73.5 Ma). In contrast, McGuire (1988b) associates the base of the Moreno Formation in his study area with the boundary between zones C and D-1, or 68 Ma. This apparent discrepancy in the age of the base of the Moreno Formation is consistent with the observation by McGuire (1988b) that the age of the Moreno Formation in outcrop increases from the Panoche Hills (PH, fig. 5.17) northward, becoming increasingly older as the unconformity at the top of the Moreno Formation cuts down section (McGuire, 1988b). Because most well picks in our database lie north of the Escarpado Canyon section studied by McGuire (1988b), for this compilation we use the ages of the individual members of the Moreno Formation for its depositional age (73.5, base, to 61, top, Ma).

[End Moreno Formation]

Paleocene

[Begin Lodo Formation]

San Carlos sand of Wilkinson (1960): 58.5 to 55.5 Ma (fig. 5.18)

The basal sandstone of the Lodo Formation is commonly known as the San Carlos sand of Wilkinson (1960; hereafter referred to as San Carlos sand). In our database, this unit is most commonly identified as the Martinez Formation, but this geologic name more accurately refers to a formal geologic unit with a defined type section in Contra Costa County (northwest of the San Joaquin Valley). The Martinez Formation in the San Joaquin Basin is better considered as the basal sandstone of the Lodo Formation (Wilkinson, 1960; Anderson, 1998). Thus, for the distribution map (fig. 5.18) we combine well picks labeled as Martinez Formation with well picks labeled as San Carlos sand. Additional well picks include "Meganos-Martinez" and "main San Carlos sand."

In the Sacramento Basin, the Martinez Formation ranges in age from above the base of planktonic foraminiferal zone P4 to the lower part of zone P5 (about 58 to 56 Ma) (Almgren, 1984). The San Carlos sand in the San Joaquin Basin is essentially coeval with the more northerly Martinez Formation; in the Vallecitos area (V, fig. 5.18), the San Carlos sand overlies unnamed shale containing flora of nannoplankton zone CP4

(58.5 to 60 Ma) and underlies the Cerros Shale, which contains flora of nannoplankton zones CP8b and CP9b (about 55.5 to 53 Ma) (Anderson, 1998). We thus use an age of 58.5 (base) to 55.5 (top) Ma for this basal sand member of the Lodo Formation. Our well database contains 80 wells containing 81 picks of the Martinez Formation and the San Carlos sand.

Eocene

Cantua Sandstone Member of the Lodo Formation: 53 to 51.5 Ma (fig. 5.19)

The Cantua Sandstone Member extends in the subsurface from Vallecitos oil field (V, fig. 5.19) to Salt Creek (SC, fig. 5.19). Outcrop sections of the Cantua Sandstone Member at Cantua Creek (CC, fig. 5.19) and Ciervo Hills (CH, fig. 5.19) contain fauna from Laiming's (1940) benthic foraminiferal zone C, which correlates with calcareous nannoplankton zones NP11 through mid-NP12 (Bartow, 1992), or about 54 to 51.8 Ma. Additionally, Stinemeyer (1974) reports fauna from the lower to middle part of Laiming's (1940) zone B-4 in the upper part of the Cantua Sandstone in outcrop at Salt Creek; this zone correlates with the middle to top part of nannoplankton zone NP12 (Bartow, 1992), or about 51.8 to 50.5 Ma. Because only the lower part of zone B-4 is represented at Salt Creek, the Cantua Sandstone is no younger than about 51 Ma at that location. In outcrop at New Idria (NI, fig. 5.19), Poore (1976) reports flora from calcareous nannoplankton zone *Discoaster lodoensis*, which Almgren and others (1988) equate to zone CP11 (50.5 to 49.5 Ma). Finally, recent analyses of calcareous nannoplankton from the Cantua Sandstone in the Vallecitos area indicate flora from zones CP9b (53.5 to 52.8 Ma) to mid-CP10 (51.5 Ma) (Anderson, 1998). Because the underlying Cerros Shale Member of the Lodo Formation also contains flora from zone CP9b (Anderson, 1998), the basal age of the Cantua Sandstone Member is closer to 53 Ma than to 53.5 Ma. Integrating all of these constraints, we use an age of 53 (base) to 51.5 (top) Ma for the Cantua Sandstone Member of the Lodo Formation. Our database contains 40 wells containing 51 picks labeled "Cantua," "Cantua sand," and "Cantua shale."

Arroyo Hondo Shale Member of the Lodo Formation: 51.5 to 49.5 Ma (fig. 5.20)

Defined by 132 wells in our database, the Arroyo Hondo Shale Member occupies a geographically restricted area in the subsurface of the west-central San Joaquin Basin, but extends over a larger overall range than the underlying Cantua Sandstone. Well picks are labeled "Arroyo," "Arroyo Hondo," "Arroyo Hondo shale," "Hondo," "Hondo shale," "upper Arroyo Hondo," and "lower Arroyo Hondo."

In outcrop at Salt Creek (SC, fig. 5.20), the Arroyo Hondo Shale contains fauna from Laiming's (1940) foraminiferal zones B-2 through mid-B-4, whereas in Shell Core Hole 2 (API number 01906246; open red circle, fig. 5.20) the unit contains fauna only from zones B-3 through mid-B-4 (Stinemeyer, 1974). As explained above, the middle of zone B-4 corresponds to about 51 Ma, whereas zone B3 correlates to nannoplankton zone NP13, or 50.5 to 49.5 Ma. The lower part of the outcrop section at New Idria (NI, fig. 5.20) contains flora referable to the upper part of calcareous nannoplankton zone *Discoaster lodoensis* (Poore, 1976), or middle to upper CP11 (50 to 49.5 Ma). Finally, Anderson (1998) constrains the age of the Arroyo Hondo Shale in the Vallecitos area (V, fig. 5.20) from mid-CP10b (51.5 Ma) to the base of zone CP12a (49.5 Ma). We utilize an age of 51.5 (base) to 49.5 (top) Ma for the Arroyo Hondo Shale Member in the subsurface of the San Joaquin Basin.

Gatchell sand of Goudkoff (1943): 50 to 49.5 Ma (fig. 5.21)

The Gatchell sand of Goudkoff (1943; hereafter referred to as Gatchell sand) and the equivalent (Harun, 1984) lower McAdams sandstone of Sullivan (1963; hereafter referred to as McAdams sandstone) occur in 88 wells in our database. Like the Arroyo Hondo Shale Member of the Lodo Formation, the Gatchell sand is distributed throughout the west-central San Joaquin Basin. In the "nose" area of Coalinga oil field (C, fig. 5.21), the Gatchell sand contains fauna from Laiming's (1940) foraminiferal zone B-3 (50.5 to 49.5 Ma). North of the Coalinga area in the vicinity of Turk Anticline oil field (TA, fig. 5.21), the Gatchell sand merges with the underlying Cantua Sandstone, indicating partial time equivalence (Ryall, 1974; Graham and Berry, 1979); well picks in that area are labeled as "Gatchell-Cantua," reflecting the undifferentiated character of the two units. Because the Gatchell sand appears to correlate with the upper part of the Arroyo Hondo Shale (Callaway, 1990), we assign an age of 50 (base) to 49.5 (top) Ma to the sand.

Lodo Formation: 58.5 to 49.5 Ma (fig. 5.22)

The Lodo Formation covers a broad swath of the subsurface of the central San Joaquin Basin. The northernmost age determination of the Lodo Formation is at Escarpado Canyon (EC, fig. 5.22), where McGuire (1988b) determined that a particular species of nannoplankton immediately overlying the Moreno Formation corresponds to benthic foraminiferal zone NP8 (57.5 to 56.5 Ma). According to Poore (1976) and Warren (1983), less than 5 miles to the southeast at its type section in Lodo Gulch (LG, fig. 5.22), the formation spans nannoplankton zones *Discoaster lodoensis* through *Discoaster mohleri*; Almgren and others (1988) equate these zones to calcareous nannoplankton zones CP11 to CP6 (57.7 to 49.5 Ma). Anderson (1998) summarized the ages of the members of the Lodo Formation in the Vallecitos area (V, fig. 5.22), where the basal San Carlos sand overlies shale of calcareous nannofossil zone CP4 (60 to 58.5 Ma) and the Arroyo Hondo Shale Member underlies Domengine Sandstone containing flora of zone CP12a (49.5 to 48.5 Ma). About 30 miles due east at Cantua Creek (CC, fig. 5.22), as well as at Coalinga (C, fig. 5.22), outcrop sections of the Lodo Formation contain fauna from the base of Laiming's (1940) benthic foraminiferal zone C (54 Ma) to the top of zone B-2 (49.5 Ma); the same faunal zones occur in outcrop at Salt Creek (SC, fig. 5.22) and in Shell Core Hole 2 (API number 01906246; open red circle, fig. 5.22) (Stinemeyer, 1974). These ages are generally consistent with age determinations, summarized by Moxon (1990), of exposures of the Lodo Formation at Media Agua Creek (MAC, fig. 5.22) and Devils Den (DD, fig. 5.22), although paleontological assemblages indicate that the formation becomes older southward (Warren, 1983; Almgren and others, 1988). However, because our database lacks subsurface identifications of the Lodo Formation basinward of these outcrop sections, we use the more northerly age determinations of 58.5 (base) to 49.5 (top) Ma for the Lodo Formation.

Although no information on a depositional hiatus underlying the Lodo Formation is available for subsurface sections, both Warren (1983) and McGuire (1988b) document a hiatus beneath the formation in outcrop at Lodo Gulch and Escarpado Canyon, respectively. The difference between the upper age of the Moreno Formation (61 Ma) and the basal age of the Lodo Formation (58.5 Ma) indicates a hiatus of about 2.5 m.y. duration. This hiatus may not have been regionally widespread, however, as the unnamed shale beneath the San Carlos sand in the Vallecitos area appears not to be a member of the Moreno Formation and contains flora from zone CP4 (60 to 58.5 Ma) (Anderson, 1998). If this shale is indeed a member of the Lodo Formation, the basal age of the formation is closer to 60 Ma and the depositional hiatus is on the order of 1 m.y.

The Lodo Formation and its members are identified in 218 wells in our database. Identifications include those discussed for the San Carlos sand, Cantua Sandstone, Arroyo Hondo Shale, and Gatchell sand, as well as the Cerros Shale, "lower Lodo sandstone," "McAdams," and "McAdams sand."

Incidentally, we exclude the Cerros Shale Member on the stratigraphic columns and on a geographic distribution map because only 2 wells in our database identify the Cerros Shale. Occurring between the underlying San Carlos sand and the overlying Cantua Sandstone Member, the Cerros Shale contains calcareous nannoplankton from zones CP8b and CP9b (55.5 to 53 Ma). We also disregard the east-side facies of the Lodo Formation—the Tule River sandstone, Tule River shale, and Mushrush sandstone, all of Reid (1988)—because of uncertain correlations with west-side members of the formation.

[End Lodo Formation]

Yokut Sandstone: 49.5 to 49 Ma (fig. 5.23)

Although the Yokut Sandstone is undifferentiated from the Domengine Formation in the Vallecitos Syncline (V, fig. 5.23) (Dibblee and Nilsen, 1974), the Yokut Sandstone at its type area at Domengine Creek (DC, fig. 5.23) lies above shale of the Lodo Formation and beneath a pebble bed at the base of the Domengine Formation (White, 1940). Sedimentologic and electric-log characteristics appear to place the two sandstones into different stratigraphic sequences; whereas the Yokut Sandstone is of fluvial-deltaic origin (Anderson, 1998) exhibiting regressive electric-log character (Callaway, 1990), the Domengine Sandstone is a thin, shallow marine transgressive unit (Callaway, 1990) underlain by a regional unconformity marking major tectonic reorganization of the San Joaquin Basin (Schulein, 1993). Magnetic characteristics similarly support distinction between the two units, as the magnetic polarities change from positive to negative in the middle of the Yokut Sandstone at Domengine Creek and remain negative throughout the overlying Domengine Formation (Prothero, 2001a). Because of these demonstrated differences between the Domengine Formation and Yokut Sandstone, we display them separately on the correlation chart (fig. 5.1) and assign different ages.

Although the basal section of the Yokut Sandstone in outcrop at Salt Creek (SC, fig. 5.23) lacks microfossils, Stinemeyer (1974) assigns it to the lower to middle part of the B-1 zone of Laiming (1940), immediately overlying the Arroyo Hondo Shale Member of the Lodo Formation of B-2 zone age. According to Bartow (1992), the base of Laiming's (1940) B-1 zone correlates with the base of calcareous nannoplankton zone NP14, or 49.5 Ma, whereas the top of zone B-1 lies somewhere in the lower to middle of zone NP14, or about 48.5 Ma. Prothero (2001a) conducted magnetostratigraphic analyses of the type section of the Yokut Sandstone at Domengine Creek, where it overlies the Arroyo Hondo Shale. In that area the Yokut Sandstone correlates with the younger part of magnetic chron C22n, or about 49.5 to 49 Ma; this is the age we use in our stratigraphic column for the Yokut Sandstone. Our database contains 31 wells with identifications labeled as "Yokut," "Yokut sand," "third Yokut sand," and "Yokut-Loescher;" this latter label indicates that Yokut Sandstone appears undifferentiated from Loescher sands of Callaway (1990) in those wells.

Domengine Formation: 49 to 48.5 Ma (fig. 5.24)

The Domengine Formation and its equivalent southeast of Jacalitos oil field (J, fig. 5.24), the Avenal Sandstone, blanket much of the northern and central San Joaquin Basin. Outcrop sections of the Avenal Sandstone at Garzas Creek (GC, fig. 5.24) and of the Domengine Sandstone at Lodo Gulch (LG, fig. 5.24) and in the Oil City area of Coalinga field (C, fig. 5.24) contain flora from calcareous nannoplankton zone CP12a (49.5 to 48.5 Ma), whereas the overlying basal Kreyenhagen Shale contains flora from zone CP12b (48.5 to 47.5 Ma) (Almgren and others, 1988). At Salt Creek (SC, fig. 5.24), the Domengine Formation is conformable with the underlying Yokut Sandstone and contains fauna no older than the middle of Laiming's (1940) B-1 zone (49 Ma) (Stinemeyer, 1974). Outcrop of the Domengine Formation at Silver Creek

(SiC, fig. 5.24) similarly contains fauna from the B-1 zone (Schulein, 1993). Outcrop at Griswold Canyon (GrC, fig. 5.24) pinpoints the upper age of the Domengine Formation; Schulein sampled flora of zone CP12b (48.5 to 47.5 Ma) less than one meter above the contact with the overlying Kreyenhagen Formation. Finally, Prothero (2001a) sampled the type section of the Domengine Formation at Domengine Creek (DC, fig. 5.24), where he correlated the Domengine Formation, the Avenal Sandstone, and the lower Kreyenhagen Formation with magnetic chron C21r (49 to 47.9 Ma). The conformity in that area with the underlying Yokut Sandstone implies a basal age for the Domengine Formation of 49 Ma; the magnetic data constrain the top of the Domengine Formation to be somewhat older than about 48 Ma. We thus assign an age of 49 (base) to 48.5 (top) Ma to the Domengine Formation. Note that although Warren (1983) provides age constraints on the Avenal Sandstone at Media Agua Creek (MAC, fig. 5.24) and Devils Den (DD, fig. 5.24), subsurface occurrences of the Domengine Formation lie north of these exposures. Consequently, we exclude the Domengine Formation on the correlation chart for the southern San Joaquin Basin.

Our database contains 538 identifications of “Domengine,” “Domengine-Yokut,” “Avenal,” and “Avenal sand.”

[Begin Kreyenhagen Formation]

Canoas Siltstone Member of the Kreyenhagen Formation: 48.5 to 45.5 Ma (fig. 5.25)

In the subsurface of the San Joaquin Basin, 38 wells in our database document the lowermost member of the Kreyenhagen Formation, the Canoas Siltstone. This geologic unit is confined in the subsurface to a narrow zone located between Antelope Hills oil field (AH, fig. 5.25) in the southeast to Pyramid Hills oil field (PH, fig. 5.25) in the northwest. The northernmost age constraint for the Gredal Shale Member (equivalent to the Canoas Siltstone) derives from core material of the lower 50 feet of the Kreyenhagen Formation in North Coalinga Oil Company 1 well (API 01900437; open red circle, fig. 5.25), which contains calcareous nannoplankton from the *Rhabdosphaera inflata* sub-zone of the *Discoaster sublodoensis* zone (Milam, 1985). Warren (1983) correlates this nannoplankton zone with calcareous nannoplankton zone NP14b, indicating an age for the base of the Gredal Shale (and thus the Canoas Siltstone) somewhere in the range of 48.5 to 47.3 Ma. The age of the base of the unit is further constrained in outcrop at Reef Ridge (RR, fig. 5.25), where the contact between the Canoas Siltstone and the underlying Avenal Sandstone lies just below the boundary between calcareous nannofossil zones CP12a and CP12b (48.5 Ma) (Morelan, 1988). The upper age of the Canoas Siltstone is constrained at Reef Ridge by the presence of fauna from the upper part of nannoplankton zone *Nannotetrina quadrata* (Morelan, 1988). Warren (1983) equates this zone to nannoplankton zone NP15, implying an age of about 45 to 43.5 Ma for the upper Canoas Siltstone. Nearby at Garzas Creek (GC, fig. 5.25) on Reef Ridge, Almgren and others (1988) correlate the Canoas Siltstone with all of zone CP12b to the middle of zone CP13b, or about 49.5 to 45.5 Ma. Farther south at Devils Den (DD, fig. 5.25), the Gredal Shale appears to be somewhat older, spanning all of zone CP12 time and extending into lower zone CP13 (49.5 to 47 Ma) (Almgren and others, 1988). Warren (1983) indicates a larger depositional time span in this location, where nannofossils suggest that deposition occurred from about 50.5 to 44.5 Ma; at Devils Den the Gredal Shale thus appears to be partially age equivalent with the underlying Avenal Sandstone. Finally, at Media Agua Creek (MAC, fig. 5.25) the Gredal Shale spans nannofossil zone CP12a (49.6 to 48.5 Ma) (Almgren and others, 1988); in this area the lower Kreyenhagen Formation is coeval with the Domengine Formation farther north at Lodo Gulch (LG, fig. 5.25) and Coalinga (C, fig. 5.25).

For consistency with age determinations for the underlying Domengine Sandstone and overlying Point of Rocks Sandstone Member, we use an age of 48.5 (base) to 45.5 (top) Ma for the Canoas Siltstone Member of the Kreyenhagen Formation.

Point of Rocks Sandstone Member of the Kreyenhagen Formation: 45.5 to 40.5 Ma (fig. 5.26)

The Point of Rocks Sandstone Member is confined in the subsurface to a narrow belt between Belgian Anticline (BA, fig. 5.26) and Pyramid Hills (PH, fig. 5.26) oil fields. Our database includes 69 wells with identifications of the first, second, and third Point of Rocks Sandstone. Age constraints on the Point of Rocks Sandstone derive from outcrop sections at Devils Den (DD, fig. 5.26), near the northern end of its subsurface extent, and at Media Agua Creek (MAC, fig. 5.26), located in the middle of its subsurface range. Biostratigraphic sampling of the type section of the Point of Rocks Sandstone Member at Devils Den indicates that the contact between the sand body and the underlying Gredal Shale Member corresponds to the boundary between calcareous nannoplankton zones NP15b and NP15c, or 44.5 Ma (Warren, 1983). Almgren and others (1988) confirm this basal age but do not clearly indicate the upper age of the sandstone. Milam (1985) constrains the age of the Point of Rocks Sandstone at Devils Den with biostratigraphic control on the underlying Gredal Shale Member and the overlying Welcome Shale Member; microfossil data imply a time span of 5 m.y. (45.5 to 40.5 Ma) between the members. Finally, Prothero (2001b) sampled the upper part of the Point of Rocks Sandstone at Devils Den, where the sandstone is in contact with the overlying Welcome Shale Member. Because of uncertain correlations between the stratigraphic position of his sample and biostratigraphic control, Prothero proposed an upper age boundary correlative with either the top of chron C20n (42.5 Ma) or the top of chron C21n (46.5 Ma). The former correlation seems more consistent with the above constraints.

Deposition of the Point of Rocks Sandstone appeared to occur several million years earlier farther south at Media Agua Creek. Prothero (2001b) correlates the base of the sandstone where it is in contact with the underlying Gredal Shale Member to the lower parts of calcareous nannofossil zone CP12 and magnetic chron C22r, or about 50 Ma. Warren (1983) refines this basal age, indicating that the boundary with the underlying Gredal Shale Member corresponds to the zone NP14a-NP14b boundary, or about 48.5 Ma. Although the upper Point of Rocks Sandstone is not shown in the biostratigraphic studies of Warren (1983) and Almgren and others (1988), the sandstone must be at least as young as 44 Ma, as the latter study shows the middle Point of Rocks Sandstone at Media Agua Creek extending into zone CP13 (47 to 44 Ma).

For consistency with the age of the underlying Canoas Siltstone, we assume that deposition of the Point of Rocks Sandstone Member generally occurred between 45.5 and 40.5 Ma.

Kreyenhagen Formation: 48.5 to 37 Ma (fig. 5.27)

The Kreyenhagen Formation is one of three geologic units shown on our stratigraphic column (fig. 5.1) (with basement rocks and Santa Margarita Sandstone) that lie within the three geographic subregions of the San Joaquin Basin. The well database contains 1,157 wells containing nearly 1,400 picks of the Kreyenhagen Formation and its members, including those discussed for the Canoas Siltstone and Point of Rocks Sandstone, as well as the Nortonville Shale (equivalent to the Canoas Siltstone in the central part of the basin), “Kreyenhagen,” and “base Kreyenhagen.” The base of the Kreyenhagen Formation corresponds to the base of the Canoas Siltstone Member and its equivalent in outcrop, the Gredal Shale. Using the biostratigraphic constraints discussed above, the basal age of the Kreyenhagen Formation is about 48.5 Ma. The upper portion of the Kreyenhagen Formation, though unnamed in the subsurface, is known as the Welcome Shale Member in outcrop. The top of the Welcome Shale Member at Devils Den (DD, fig. 5.27) contains calcareous nannofossils from the middle of zone CP15b (about 37 Ma) (Milam, 1985). These upper and lower age determinations are consistent with correlation charts for equivalent sections at Coalinga (C, fig. 5.27), Cantua Creek (CC, fig. 5.27), and Ciervo Hills (CH, fig. 5.27), which show benthic fauna from Laiming’s (1940) zones A-1 and A-2 (48.5 to 37 Ma) (Laiming, 1940). We thus use an age of 48.5 (base) to 37 (top) Ma for the age of the Kreyenhagen Formation. Note that in the northern San Joaquin Basin, where Miocene rocks overlie the Kreyenhagen Formation (Loken, 1959; Hill, 1962), the top of the formation is probably older due to erosion of late Eocene through early-middle Miocene rocks.

[End Kreyenhagen Formation]

[Begin Tumey formation]

Oceanic sand of McMasters (1948): 37 to 35 Ma (fig. 5.28)

In outcrop at Arroyo Ciervo (AC, fig. 5.28), the Tumey formation of Atwill (1935; hereafter referred to as Tumey formation) consists of a basal sandstone, an intermediate shale, and an upper sandstone (Atwill, 1935). Though unnamed in this outcrop section, this basal sand probably corresponds to the subsurface Oceanic sand of McMasters (1948; hereafter referred to as Oceanic sand). Identified in 19 wells as “Oceanic” and “Oceanic/Wagonwheel” in our database, the Oceanic sand conformably and unconformably overlies the Kreyenhagen Formation (Foss and Blaisdell, 1968). The Oceanic sand occupies a zone on the basin’s southwest margin that resembles, in map view, the subsurface distribution of the older Point of Rocks Sandstone Member of the Kreyenhagen Formation (fig. 5.26). The age of the Oceanic sand is derived from stratigraphic superposition; the unit lies between the underlying Narizian-age upper shale member of the Kreyenhagen Formation and the overlying Refugian-age shale member of the Tumey formation. Milam (1985) provides firmer, if somewhat indirect, biostratigraphic control for this sand at Devils Den (DD, fig. 5.28), where the top of the underlying Welcome Shale Member of the Kreyenhagen Formation was deposited at about 37 Ma and the base of the overlying shale of the Wagonwheel Formation, which is equivalent to the shale of the Tumey formation, contains flora from the lower part of nannofossil zone CP15b (35 Ma). Prothero and Sutton (2001) correlate this biostratigraphic zone with magnetostratigraphic analyses of the Wagonwheel Formation at Devils Den. Their results indicate that the upper boundary of the basal sand member correlates with the upper boundary of magnetic chron C15r (35 Ma). Because of its conformable relationship with both underlying and overlying strata, we assign an age of 37 (base) to 35 (top) Ma to the Oceanic sand.

Leda sand of Sullivan (1963): 34 to 33.5 Ma (fig. 5.29)

The Leda sand of Sullivan (1963), hereafter known as Leda sand, lies near the top of the shale portion of the Tumey formation (Cushman and Simonson, 1944; Callaway, 1990). Defined by 42 wells in our database, the Leda sand is confined to a ~10-mile-long by ~6-mile-wide region centered on Guijarral Hills (GH, fig. 5.29) and Pleasant Valley (PV, fig. 5.29) oil fields on the western margin of the central San Joaquin Basin. Direct age constraints on the Leda sand are sparse; Kuespert (1985) considers the Leda sand to predate the Vaqueros Formation (33.5 to 24 Ma; discussed below), whereas Cooley (1985) considers the sand as middle to early Zemorrian in age (about 33.5 to 29 Ma). On the basis of its unconformable relationship with the overlying Cymric Shale Member of the Temblor Formation (33 to 32 Ma; discussed below) and its facies relationship with the shale of the Tumey formation (35 to 33.5 Ma; discussed below), we consider the Leda sand to be the uppermost member of that formation and assign an age of 34 (base) to 33.5 (top) Ma.

Tumey formation of Atwill (1935): 37 to 33.5 Ma (fig. 5.30)

The Tumey formation, equivalent to the Wagonwheel Formation in outcrop, and its Oceanic and Leda sand members, are identified in 219 wells and are distributed over much of the southern and central subregions of the San Joaquin Basin. As discussed above, biostratigraphic data at Devils Den (DD, fig. 5.30) indicate an age of 35 Ma at the base of the shale member of the Wagonwheel Formation. Biostratigraphic analyses of the shale member of the Tumey formation at Tumey Gulch (TG, fig. 5.30) indicate an upper age within, or near the top of, nannofossil zone CP16a (34 to 33.5 Ma) (Milam, 1985), which also corresponds to the boundary between the Refugian and the Zemorrian Stages. Given this biostratigraphic control, Prothero and Sutton (2001) correlate the upper part of the Wagonwheel Formation at Devils Den to magnetic chron C13r (34.7 to 33.5 Ma). Taken together, age constraints indicate an age of 35 to 33.5 Ma for the upper shale member of the Tumey formation and a total age of 37 to 33.5 Ma for the entire Tumey formation.

[End Tumey formation]

Famoso sand of Edwards (1943): 49 to 33.5 Ma (fig. 5.31)

The Famoso sand of Edwards (1943), hereafter referred to as Famoso sand, is identified in 101 wells in our database as “Famoso,” “base Famoso,” and “Famoso-Domengine.” The Famoso sand is confined to the east side of the southern and central San Joaquin Basin. Primary age control on this unit comes from paleontological analyses in the Gulf KCL-B 45 and Shell Fuhrman 1 wells (API numbers 02906949 and 02926316, respectively, from west to east; open red circles, fig. 5.31); these analyses indicate that the upper Famoso sand contains benthic foraminifers from the late Refugian Stage (33.5 Ma) (Bartow and McDougall, 1984). The upper portion of this unit, which grades into the lower Walker Formation, thus correlates in time with the upper portion of the Tumey formation. The lower part of the Famoso sand correlates with the Domengine Formation to the west (Reid, 1988), indicating an age for the base of the sand of about 49 Ma. Deposition of the Famoso sand thus occurred from about 49 to 33.5 Ma in the southeastern San Joaquin Basin.

Oligocene

[Begin Temblor Formation and equivalents]

Cymric Shale Member of the Temblor Formation: 33 to 32 Ma (fig. 5.32)

The Cymric Shale Member, also known as the Salt Creek shale of Foss and Blaisdell (1968), is defined by 20 wells in our database; included in this distribution map are well picks for the Gibson sand of Williams (1938), which lies near the top of the Cymric Shale in the vicinity of North Belridge oil field (NB, fig. 5.32). Absolute age dating of this basal member of the Temblor Formation proves difficult, because diagnostic microfossils are either sparse (Carter, 1985b) or absent (Tipton and others, 1974) in outcrop and subsurface sections. Near the top of the Cymric Shale within the type Temblor Formation at Chico Martinez Creek (CMC, fig. 5.32), Addicott (1973) reports the collection of small mollusks, which he characterizes as late Refugian age. However, Tipton and others (1973) advise caution in interpreting the particular species collected by Addicott (1973) as Refugian age, based in part on the identification of foraminifers from the lower Zemorrian Stage by Kleinpell (1938) within the Cymric Shale at Zemorra Creek (ZC, fig. 5.32). This latter conclusion appears consistent with magnetic stratigraphy studies of the Cymric Shale at Zemorra Creek by Prothero and Resseguie (2001), if their unreferenced report of nannofossils from zones CP16b and CP16c (33.4 to 31.4 Ma) in the Cymric Shale is correct. That paleontological constraint, coupled with entirely reversed magnetic polarity throughout the Cymric Shale section, implies a correlation with magnetic chron C12r (33 to 31 Ma). Because the basal part of the overlying Wygal Sandstone Member of the Temblor Formation is also reversed polarity and contains fossils from the same zone (Prothero and Resseguie, 2001), the Cymric Shale Member must have been deposited during the early part of that chron, or between about 33 and 32 Ma. The boundary between the Refugian and Zemorrian Stages thus occurs at or just below the base of the Cymric Shale at Zemorra Creek. A regionally extensive unconformity at the base of the Cymric Shale (Carter, 1985b) likewise marks the end of the Eocene in the southwestern San Joaquin Basin.

Wygal Sandstone Member of the Temblor Formation: 30 to 29 Ma (fig. 5.33)

This distribution map displays 69 identifications in 61 wells of the Wygal Sandstone Member, the correlative Phacoides sandstone of Curran (1943; hereafter referred to as Phacoides sandstone), and their approximate temporal equivalents (Foss and Blaisdell, 1968; Bishop and Davis, 1984), the Bloemer sand of Williams (1938) and the Belridge 64 sand of Foss and Blaisdell (1968). All of these units are confined in the subsurface to the southwestern margin of the San Joaquin Basin. Tipton and others (1973) failed to find diagnostic fauna in the Wygal Sandstone in the T.H. Purman Cymric 1 well (API number 02939376; open red circle, fig. 5.33), but Kleinpell (1938) designated the Wygal Sandstone in outcrop at nearby

Zemorra Creek (ZC, fig. 5.33) as part of his type sequence of the early Zemorrian Stage. Prothero and Resseguie (2001) cite the presence of early Zemorrian fossils within the Wygal Sandstone at Zemorra Creek and fauna from zones P19 and P20 (32 to 29.5 Ma) and CP18 (31.5 to 30 Ma) at San Lorenzo River (located off the map) as their method of correlating its negatively magnetized samples with the late part of magnetic chron C12r (32 to 31 Ma). In contrast, both Addicott (1973) and Tipton and others (1973) present evidence of microfauna and megafauna in the Phacoides sandstone that seem to be younger than early Zemorrian. Bloch (1991) suggests that the age of the Wygal Sandstone approximates the boundary between nannofossil zones CP18 and CP19, or 30 Ma. Finally, the base of the Wygal Sandstone appears to correlate with a global fall in sea level that occurred about 30 Ma (Carter, 1985b). If this latter supposition is correct, the Wygal Sandstone correlates better with C11r (30.5 to 30 Ma) than with chron C12r as concluded by Prothero and Resseguie (2001). We assign a late early Zemorrian age of 30 to 29 Ma to the Wygal Sandstone Member of the Temblor Formation, but note that this leaves a 2 m.y. gap between the Wygal Sandstone and Cymric Shale.

Santos Shale Member of the Temblor Formation: 29 to 20 Ma (fig. 5.34)

Although the Santos Shale Member is nearly always discussed in the literature as the upper Santos Shale and the lower Santos Shale (for example, Foss and Blaisdell, 1968; Tipton and others, 1973; Carter, 1985b), we combine our discussion of the upper and lower parts of the Santos Shale because only 5 wells in our database identify the lower part of the unit. The 16 wells in our database that contain picks of the Santos Shale indicate that it is confined to a narrow zone on the basin's southwest margin.

Both the upper and lower Santos Shale contain abundant benthic foraminifers in the T.H. Purman Cymric 1 well (API number 02939376; open red circle, fig. 5.34) (Tipton and others, 1973). In that well, foraminifers from the base of the Santos Shale, immediately overlying the Phacoides sandstone, correlate to the *Uvigerinella sparsicostata* zone, or late Zemorrian. Magnetostratigraphic analyses on outcrop samples from Zemorra Creek (ZC, fig. 5.34) indicate that the lowermost Santos Shale is reversely magnetized whereas the remainder of the lower Santos Shale to its contact with the Agua Sandstone Bed of the Santos Shale Member exhibits positive magnetic polarity (Prothero and Resseguie, 2001). Citing nannofossils from zone CP19 within the lower Santos Shale, Prothero and Resseguie (2001) correlate their magnetic results with chron C6Cr (24.7 to 24.1 Ma) and the lower part of chron C6Cn (24.1 to 23.3 Ma). Because the underlying Wygal Sandstone Member at Zemorra Creek contains early Zemorrian fossils, Prothero and Resseguie (2001) conclude that an unconformity of several million years duration underlies the lower Santos Shale. However, because nannofossil zone CP19 contains several reversed-polarity intervals (for example, fig. 5.3) and because Foss and Blaisdell (1968) cite lower Zemorrian fauna within the lower Santos Shale, we use caution in interpreting these magnetic results and extend the basal age of the lower Santos Shale Member to 29 Ma. Further evidence supporting an older basal age of the lower Santos Shale comes from stratigraphic studies by Pence (1985) and Carter (1985b), who indicate no unconformity between the underlying Wygal Sandstone Member and the Santos Shale.

Age constraints for the upper Santos Shale Member in the Purman well include benthic fauna from the lower part of the *Siphogenerina transversa* zone at the top of the underlying Agua Sandstone Bed of the Santos Shale Member and from the upper part of the *Plectofrondicularia miocenica* zone at the top of the Santos Shale (Tipton and others, 1973). Using the timescale of Bartow (1992), these fauna indicate ages of about 24 Ma for the top of the Agua Sandstone Bed and about 19 or 20 Ma for the top of the Santos Shale. Taken together, deposition of the Santos Shale Member of the Temblor Formation occurred about 29 to 25 Ma (lower) and about 24 to 20 Ma (upper). The boundary between the Oligocene Zemorrian and the Miocene Saucesian Stages thus coincides with the contact between the Agua Sandstone and the upper Santos Shale.

Agua Sandstone Bed of the Santos Shale Member of the Temblor Formation: 25 to 24 Ma (fig. 5.35)

Paleontological control on the age of the Agua Sandstone Bed, discussed above, indicates that the Agua Sandstone Bed was deposited between about 25 and 24 Ma (Tipton and others, 1973). Our database contains 37 wells (fig. 5.35) with identifications labeled "Agua," "upper Agua," and "lower Agua."

Walker Formation: 34 to 25 Ma (fig. 5.36)

Stratigraphic relationships provide the only age control for the nonmarine Walker Formation, which occurs in the subsurface on the southeast margin of the San Joaquin Basin and is identified in 48 wells in our database. These relationships differ, however, north and south of the Bakersfield Arch (broad gray shading, BA, fig. 5.36). North of the arch, the Walker Formation lies unconformably on basement; basinward the upper Walker Formation interfingers with Zemorrian-aged Vedder Sand, whereas the lower section grades into Refugian-aged Famoso sand (Bartow and McDougall, 1984). Strontium isotope analyses of the overlying Pyramid Hill Sand, which overlies the correlative Vedder Sand, restrict the upper age of the Walker Formation to about 25 Ma north of the arch (Olson, 1988a,b). In contrast, the Walker Formation appears to be somewhat younger south of the Bakersfield Arch, where a rhyolite tuff located 365 meters below the top of the Walker Formation yields a potassium-argon date of 21.4 ± 0.6 Ma and the lower part of the unit grades into Zemorrian-aged Vedder Sand (Bartow and McDougall, 1984). In this location, the upper Walker Formation is partially coeval with the Jewett Sand and lower Freeman Silt. Because the majority of our well samples lie north of the Bakersfield Arch, we depict in figure 5.1 an age of 34 to 25 Ma for the Walker Formation.

Vedder Sand: 33.5 to 25 Ma (fig. 5.37)

The Vedder Sand occurs in the subsurface of the eastern San Joaquin Basin within a broad swath extending from the Tejon embayment (Te, fig. 5.37) in the far southern part of the basin to Township 20 South, or a distance of more than 80 miles. This unit is identified in 150 wells in our database; these are labeled “Vedder,” “first Vedder,” “second Vedder,” “third Vedder,” “fourth Vedder,” “base Vedder,” “upper Vedder,” and “lower Vedder.” The distribution map also includes identifications of the Cantleberry sand of Hluza (1959), which is a productive sand lens at the base of the Vedder Sand in Jasmin field (J, fig. 5.37) (Hluza, 1959). Although it conformably overlies the Walker Formation in outcrop, the Vedder Sand is the lateral equivalent of the upper Walker Formation in the subsurface (Bartow and McDougall, 1984). Biostratigraphic studies of Vedder Sand samples in the Gulf KCL-B 45, Chevron 33-1, Shell Fuhrman 1, and Chevron 24-35 wells (API numbers 02906949, 02930973, 02926316, and 02906398, respectively, from west to east; open red circles, fig. 5.37) yield microfossils of Zemorrian age, although some fauna suggest that the Vedder Sand could be as young as Saucesian (Bartow and McDougall, 1984). However, strontium isotope data from the base of the overlying Pyramid Hill Sand at Pyramid Hill (PH, fig. 5.37) constrain the top of the Vedder Sand to be no younger than 23 ± 1 Ma (Olson, 1988a). Similar to the Vaqueros Formation on the basin’s west side (discussed below), the Vedder Sand appears to span the entire Zemorrian Stage, or about 33.5 to 25 Ma. Based on these ages, the Vedder Sand correlates with the Cymric Shale, Wygal Sandstone, and lower Santos Shale Members of the Temblor Formation of the southwestern San Joaquin Basin.

Vaqueros Formation: 33.5 to 24 Ma (fig. 5.38)

The Vaqueros Formation as defined in our database is confined in the subsurface to the west-central portion of the San Joaquin Basin Province near Kettleman North Dome (KND, fig. 5.38) and Coalinga (C, fig. 5.38) oil fields. Identified in 36 wells, picks of the Vaqueros Formation are variously labeled as “Vaqueros,” “Temblor-Vaqueros,” “upper Vaqueros,” “lower Vaqueros,” and “Vaqueros zone.” Absolute age control on this sandy unit is undocumented in the San Joaquin Basin, probably in part because of a long history of inconsistent use of the term “Vaqueros” in the basins bordering the San Andreas Fault and because of its use in paleontology as the name of a molluscan stage; see Woodring and others (1940) and Graham (1985) for summaries of nomenclature issues involving the Vaqueros Formation. Because of the longstanding confusion between lithologically similar strata labeled as Temblor Formation and Vaqueros Formation on both sides of the San Andreas Fault, Dibblee (1973) advocated that the lithostratigraphic Vaqueros Formation (as opposed to the biostratigraphic “Vaqueros” Stage) be restricted to the west side of the fault in accordance with the location of its type section in the Salinas Basin (for example, Thorup, 1943). However, use of the Vaqueros Formation as a lithostratigraphic term in the San Joaquin Basin persists; the California Division of Oil, Gas, and Geothermal Resources (2004) reports past and present production from oil pools labeled “Vaqueros” at Coalinga East Extension, Kettleman North Dome, Kettleman City, Kettleman Middle Dome, and Tulare Lake oil fields. Moreover, two of the wells in our database containing picks of the Vaqueros Formation were drilled as recently as 1992. Rather than eliminating usage of the term “Vaqueros” in the San Joaquin Basin, Foss and Blaisdell (1968) suggest that in places where both Vaqueros and Temblor Formations occur, “Temblor Formation” should refer to beds of Saucesian age and younger and (or) those containing gastropods of the *Turritella ocoyana* zone, whereas “Vaqueros Formation” should refer to Zemorrian-age strata or beds containing gastropods of the *Turritella inezana* zone. Clearly this is a difficult criterion to apply in the absence of preserved specimens or paleontological analyses.

The correlation chart of Bishop and Davis (1984) assumes a Zemorrian age for the Vaqueros Formation in the San Joaquin Basin; at Kettleman Hills (KH, fig. 5.38) the unit represents most of Zemorrian time, or about 35 to 24 Ma. A comprehensive sequence stratigraphic analysis of the San Joaquin Basin by Bloch (1991) considers the Vaqueros Formation within the late Eocene to late Oligocene sequence, also about 35 to 24 Ma, and cites partial equivalency with the Vedder Sand (34 to 24 Ma) on the east side of the basin. Finally, Callaway (1990) confines the Vaqueros Formation in the San Joaquin Basin to a narrow age range centered on a sea-level transgression at 30 Ma. In this compilation, the time span of 30 to 24 Ma is represented by informal members of the Temblor Formation, including the Allison sand of Sullivan (1963) and the Whepley shale of Dodd and Kaplow (1933).

Although coupled magnetostratigraphy and micropaleontology studies provide definitive age control in outcrop sections of the Vaqueros Formation in the Santa Cruz Mountains (for example, McDougall, 1983; Prothero and others, 2001), we follow Foss and Blaisdell (1968) and assign a Zemorrian age of 33.5 (base) to 24 (top) Ma to the Vaqueros Formation in the San Joaquin Basin.

Pyramid Hill Sand Member of the Jewett Sand: 25 to 24 Ma (fig. 5.39)

The basal member of the Jewett Sand, the Pyramid Hill Sand, is reported in 62 wells in our database, with picks labeled as “Pyramid Hill,” “first Pyramid Hill,” and “second

Pyramid Hill." Although a few wells lie within the Midway-Sunset oil field (MS, fig. 5.39), these are probably misidentified or mislocated because the Pyramid Hill Sand is a facies of the southeastern San Joaquin Basin (Callaway, 1990). The basal age of the Pyramid Hill Sand, 23 ± 1 Ma, is determined from strontium isotope analyses of pectens from outcrop at Pyramid Hill (PH, fig. 5.39) (Olson, 1988a); within error this age straddles the boundary between the Zemorrian and Saucesian Stages. Micropaleontology data on subsurface sections of the Pyramid Hill Sand reveal diagnostic Zemorrian fauna within the lower part of the Jewett Sand (Bartow and McDougall, 1984); assuming that these species derive from the Pyramid Hill Sand Member, this unit was probably deposited in latest Oligocene times, with the boundary between the Zemorrian and Saucesian Stages (~24 Ma) occurring at or near the top of the section. Because stratigraphic correlation charts (Bartow and McDougall, 1984; Olson, 1988a) indicate a depositional interval of about 1 m.y. duration for the Pyramid Hill Sand Member, we use an age of 25 (base) to 24 (top) Ma for this geologic unit.

Rio Bravo sand of Noble (1940): 25 to 24 Ma (fig. 5.40)

The Rio Bravo sand of Noble (1940), hereafter referred to as the Rio Bravo sand, is identified in 15 wells in our database; these are variously labeled as "Rio Bravo," "Rio Bravo equivalent," and "Rio Bravo-Vedder." At Rio Bravo oil field (RB, fig. 5.40), this unit is either the local equivalent of (Bartow and McDougall, 1984), or slightly older than (Callaway, 1990), the shelfal Pyramid Hill Sand Member of the Jewett Sand to the east. Immediately to the southeast at Greeley field (G, fig. 5.40), Welge (1970) asserts equivalency between the Rio Bravo sand and the Pyramid Hill Sand. Although Bartow and McDougall (1984) report the presence of mollusks within the Rio Bravo sand, these appear to be undated. In contrast, benthic foraminiferal assemblages in the Gulf KCL-B 45 and Chevron 33-1 wells (API numbers 02906949 and 02926316, respectively, from west to east; open red circles, fig. 5.40) generally indicate an upper Zemorrian age (Bartow and McDougall, 1984). In the absence of specific age data on this unit, we use the same age for the Rio Bravo sand as for the Pyramid Hill Sand Member (and coincidentally, as the Agua Sandstone Bed of the Santos Shale Member of the Temblor Formation), or 25 (base) to 24 (top) Ma.

Miocene

Jewett Sand: 25 to 21 Ma (fig. 5.41)

Although identified in only 7 wells in our database (open blue circles, fig. 5.41), the Jewett Sand is an oil reservoir in the southeastern San Joaquin Basin, with past and present production in Ant Hill (AH, fig. 5.41), Edison (E, fig. 5.41), Kern River (KR, fig. 5.41), and Round Mountain (RM, fig. 5.41) oil fields (CDOGGR, 2004). The total well count increases to nearly 70 with inclusion of the basal Pyramid Hill Sand Member (filled blue circles, fig. 5.41). Though shallow-water facies of the Jewett Sand in outcrop lack diagnostic faunal assemblages, deeper-water facies in the subsurface contain foraminifers of lower Saucesian age (Chevron 24-35 well, API number 02906398; open red circle, fig. 5.41) (Bartow and McDougall, 1984). Although specific data on the age of the top of the Jewett Sand are lacking, stratigraphic correlation columns (Bartow and McDougall, 1984; Olson, 1988a) suggest that the contact between the Jewett Sand and overlying Freeman Silt occurs at about 21 Ma. The Jewett Sand exclusive of the Pyramid Hill Sand Member was thus deposited from about 24 to 21 Ma. Including the basal Pyramid Hill Sand Member, the age of the Jewett Sand ranges from 25 to 21 Ma.

Freeman Silt: 24 to 19 Ma (fig. 5.42)

Identifications of the Freeman Silt in our well database include entries labeled "Freeman-Jewett." In outcrop the Freeman Silt overlies the Jewett Sand but in the subsurface, the mudstone interfingers with the Jewett Sand, indicating partial time equivalency between the two units (Bartow and McDougall, 1984). The "Freeman-Jewett" label, then, reflects the replacement basinward of the coarse-grained Jewett Sand with the finer-grained Freeman Silt (Bartow and McDougall, 1984). Age control on the Freeman Silt derives both from the stratigraphic relationship between it and the Jewett Sand and from outcrop and subsurface sections containing paleontological fauna of the Saucesian Stage (Gulf KCL-B 45, Chevron 33-1, Shell Fuhrman 1, and Standard Jeppi-Camp 67-8 wells, API numbers 02906949, 02930973, 02926316, and 02906412, respectively, from west to east; open red circles, fig. 5.42) (Bartow and McDougall, 1984). Bartow and McDougall (1984) allow for the possibility of Relizian aged nannofossils within the Freeman Silt but found none in their subsurface samples, whereas Olson (1988a) precludes the possibility of a Relizian age for the Freeman Silt based on strontium isotope data for the overlying Olcese Sand. On the basis of these constraints and on the stratigraphic correlations of Olson (1988a) and Callaway (1990), we use an early to mid-Saucesian age for the Freeman Silt, or about 24 to 19 Ma. The Freeman Silt and Jewett Sand thus correlate stratigraphically with the upper Santos Shale and the Carneros Sandstone Members of the Temblor Formation in the southwestern San Joaquin Basin. Our database contains 44 identifications of the Freeman Silt.

Carneros Sandstone Member of the Temblor Formation: 20 to 17.5 Ma (fig. 5.43)

Identifications of the Carneros Sandstone Member within 42 wells in our database are labeled as "Carneros," "first Carneros," "second Carneros," and "third Carneros." In outcrop, the Carneros Sandstone consists of two sand bodies and an intervening shale, whereas subsurface sections may contain up to four sand bodies interbedded with shale (Carter, 1985b; Pence, 1985). The age of the Carneros Sandstone is broadly constrained by calcareous nannoplankton from zones CN2 to CN3 (19.2 to 15.5 Ma) collected within the shale interbed in outcrop at Alex Cook Springs (AC, fig. 5.43) (Pence, 1985). A shale interbed at Chico Martinez Creek (CMC, fig. 5.43) contains benthic foraminifers characteristic of the *Plectofrondicularia miocenica* zone (Carter, 1985a), which Bartow (1992) equates with the N5 and N6 calcareous nannofossil zones (21.5 to 17 Ma). Pence (1985) shows the upper boundary of the Carneros Sandstone coincident with the upper boundaries of the "Vaqueros" molluscan stage and the *Plectofrondicularia miocenica* zone, or about 17 Ma, but Tipton and others (1973) report fauna in the T.H. Purman Cymric 1 well (API number 02939376; open red circle, fig. 5.43) from the same zone in the overlying Media Shale Member of the Temblor Formation. On the basis of this paleontological control point and on the upper age of the underlying Santos Shale Member, we use an age of 20 (base) to 17.5 (top) Ma for the Carneros Sandstone Member.

Media Shale Member of the Temblor Formation: 17.5 to 16.5 Ma (fig. 5.44)

The distribution map for the Media Shale Member shows 35 wells that contain identifications of this unit. All but five of these wells are confined to the San Joaquin Basin's southwest margin; the outliers likely represent misidentifications because the Media Shale is properly considered as a facies confined to the southwest margin of the basin (Callaway, 1990). Tipton and others (1973) report benthic foraminifers in the T.H. Purman Cymric 1 well (API number 02939376; open red circle, fig. 5.44) from the *Plectofrondicularia miocenica* zone (21.5 to 17 Ma) within the lower part of the section and fauna from the *Uvigerinella obesa* zone (17 to 16.5 Ma) within the upper part. They also cite a Relizian Stage assemblage located 50 feet above the uppermost Saucesian sample, although other studies (Carter, 1985b; Pence, 1985) of outcrop sections place the boundary between the Relizian and Saucesian Stages (17 Ma) at the top of the Media Shale Member. On the basis of these limited data and on a conformable relationship with the underlying Carneros Sandstone Member (Carter, 1985b; Pence, 1985), we assign an age of 17.5 (base) to 16.5 (top) Ma to this unit.

Buttonbed Sandstone Member of the Temblor Formation: 16.5 to 16 Ma (fig. 5.45)

The Buttonbed Sandstone is typically considered to be the uppermost member of the Temblor Formation at its type section at Chico Martinez Creek (CMC, fig. 5.45) but may be more accurately considered as the basal member of the Monterey Formation (Foss and Blaisdell, 1968) or, in sequence stratigraphic terms, as the basal member of the Monterey Formation depositional sequence (Carter, 1985b). Most of the 33 wells in our database with identifications of this unit lie within a narrow belt between Cymric (C, fig. 5.45) and Lost Hills (LH, fig. 5.45) oil fields. Biostratigraphic age constraints for the Buttonbed Sandstone are sparse but generally indicate a Relizian age (Addicott, 1972b). Foss and Blaisdell (1968) report foraminifers from the *Siphogenerina hughesi* zone, which Bartow (1992) correlates to most of magnetic chron C5Cn (16.6 to 15.9 Ma). In addition to the button-like echinoids that give this unit its name (Addicott, 1972b), the Buttonbed Sandstone contains planktonic foraminifers of the N7 zone (17.2 to 16.5 Ma) (Pence, 1985). Taken together, these constraints suggest that the Buttonbed Sandstone was deposited between about 16.5 and 16 Ma. An unconformity underlying the Buttonbed Sandstone Member, called the "pre-Relizian" (Graham and others, 1989) or "sub-Buttonbed" (Bloch, 1991) unconformity, indicates a period of uplift and erosion on the southwestern margin of the San Joaquin Basin just prior to its deposition (Carter, 1985b).

Olcese Sand: 21 to 16.5 Ma (fig. 5.46)

The Olcese Sand covers much of the southeastern San Joaquin Basin, from the Tejon embayment (Te, fig. 5.46) in the far south to north of Trico gas field (T, fig. 5.46). It is identified in 129 wells in our database most frequently as "Olcese," and rarely as "upper Olcese," "lower Olcese," and "base Olcese." Although the Olcese Sand is entirely of marine origin in the subsurface of the San Joaquin Basin, in outcrop the Olcese Sand consists of an upper and lower marine sandstone and an intervening nonmarine bed (Bartow and McDougall, 1984). Abundant age control for the Olcese Sand exists both in outcrop and subsurface sections. Olson (1988a) dated several stratigraphic sections of the upper Olcese Sand at Nickel Cliff (NC, fig. 5.46) and Upper Olcese Creek (UOC, fig. 5.46). Strontium isotope analyses of a variety of fossils near the top of the section yield dates of about 16.5 Ma. Similar analyses of oysters located just above the contact between the upper and middle Olcese Sands yield dates of 18 ± 1 Ma (Olson, 1988a). Age constraints on the middle Olcese Sand derive from a pumiceous sandstone near the middle of the unit; fission-track data yield an age of 15.5 ± 1.7 Ma, whereas potassium-argon (K-Ar) analyses indicate ages of 19.0 ± 0.8 and 21.8 ± 0.6 Ma (Bartow and McDougall, 1984). Although the fission-track age appears too young given the strontium isotope analyses of the overlying sand unit, within error it is compatible with the strontium analyses and with the K-Ar results. Paleontological analyses indicate abundant benthic foraminifers within the Olcese Sand in the Chevron 33-1, Shell Fuhrman 1, and Chevron 24-35 wells (API numbers 02930973, 02926316, and 02906398, respectively, from west to east; open red circles, fig. 5.46), but these tend toward long-ranging species; only one age-diagnostic species confirms a Relizian or Luisian age (Bartow and McDougall, 1984). No direct age data are available for the lower Olcese Sand, but in the subsurface it interfingers with the underlying Freeman Silt, indicating partial age equivalency (Bartow and McDougall, 1984; Bloch and Olson, 1990). In summary, we use an age of 21 to 19 Ma for the lower Olcese Sand, 19 to 17 Ma for the middle Olcese Sand, and 17 to 16.5 Ma for the upper Olcese Sand.

Nozu sand of Kasline (1942): 15 to 14.5 Ma (fig. 5.47)

Though regionally restricted, the Nozu sand of Kasline (1942) (open blue circles, fig. 5.47) in the Bakersfield Arch area (broad gray shading, BA, fig. 5.47) and its temporal equivalent in the Tejon embayment (Te, fig. 5.47), the Valv sandstone of MacPherson (1978) (filled blue circles, fig. 5.47), together have produced about 4.5 MMBO (CDOGGR, 2004). Both units represent mid-Luisian time (MacPherson, 1978; Callaway, 1990), or about 15 to 14.5 Ma. Incidentally, Bloch (1991) notes that the two sand bodies are either temporal equivalents or separated by an unconformity, with the Nozu sand of Kasline (1942) being the deep-water turbidite facies of the shallower-water Valv sandstone of MacPherson (1978).

Zilch formation of Loken (1959): 30 to 14 Ma (fig. 5.48)

The Zilch formation of Loken (1959), hereafter referred to as the Zilch formation, is identified in 293 wells in our database. Initially deposited during a worldwide regression that resulted in extensive deposition of nonmarine rocks in central and southern California (Bartow, 1987), the Zilch formation occurs over a fairly narrow, northwest-southeast oriented band from southwest of Riverdale oil field (R, fig. 5.48) in the central San Joaquin Basin to Chowchilla gas field (C, fig. 5.48) in the northern basin. Typically the Zilch formation lies unconformably above the Eocene Kreyenhagen Formation or Tumey formation and unconformably below the Miocene Santa Margarita Sandstone or McLure Shale Member of the Monterey Formation (Loken, 1959; Bishop and Davis, 1984; Callaway, 1990).

Characterized by Loken (1959) as a lower to middle Miocene continental deposit, the Zilch formation remains undated despite its importance as a hydrocarbon reservoir (~80 MMBO and ~70 BCF; table 5.1). Accordingly, uncertainty remains regarding its absolute age, as various sources extend the basal Zilch formation into early Oligocene (PS-AAPG, 1957; Callaway, 1990) and even into early Eocene (Bishop and Davis, 1984) times. Bartow (1987) considers the Zilch formation as the nonmarine equivalent of mid-Zemorrian (~30 to 27 Ma) units of the lower Temblor Formation on the basin's southwest side. Although absolute ages for the Zilch formation are lacking, numerical modeling of the subsidence history of the Great Valley by Moxon (1990) provides some guidelines; he used an upper age for the Zilch formation of 12 Ma just north of Raisin City oil field (RC, fig. 5.48) and 15 Ma near Helm (H, fig. 5.48) and Riverdale fields. Accordingly, we consider the nonmarine deposits of the Zilch formation to range in age from middle Oligocene to middle Miocene, or about 30 to 14 Ma. Neither of these ages is particularly well determined; either date could be incorrect by several millions of years.

Temblor Formation: 33 to 16 Ma (south) and 18 to 14 Ma (central) (fig. 5.49)

The distribution map for the Temblor Formation illustrates its widespread distribution in the subsurface of the southern and central San Joaquin Basin. The well database includes 703 wells containing more than 1,000 picks of the Temblor Formation and its members, including the Cymric Shale, Wygal Sandstone, Santos Shale, Carneros Sandstone, Media Shale, and Buttonbed Sandstone. The map also includes wells with identifications of various electric-log markers within the formation ("Temblor A point," "Temblor B point," and "Temblor E point"), as well as identifications of the Pioneer sand of Barnes (1961). In the southern San Joaquin Basin where all or most of these members crop out in the Temblor Range (TR, fig. 5.49) and extend into the subsurface, the age of the Temblor Formation ranges from the basal age of the Cymric Shale Member to the upper age of the Buttonbed Sandstone Member, or 33 to 16 Ma.

The Temblor Formation in the central San Joaquin Basin exhibits markedly different stratigraphy than in the southern part of the basin (Graham and others, 1989). Stratigraphic correlation charts indicate an undifferentiated Temblor Formation near Vallecitos (V, fig. 5.49), Coalinga Anticline (C, fig. 5.49), and Reef Ridge (RR, fig. 5.49) (Cooley, 1985; Callaway, 1990; Bartow, 1991); in these areas, the nomenclature of stratigraphic horizons within the Temblor Formation tends to be unique to each oil field and outcrop. Further, the Temblor Formation in these central areas spans late Saucesian through at least mid-Luisian time, indicating a far younger section than the type Temblor Formation to the south (Bent, 1985). In the stratigraphic column (fig. 5.1), we use an age of 18 to 14 Ma for the Temblor Formation in the central basin and 33 to 16 Ma for the Temblor Formation in the southern San Joaquin Basin.

[End Temblor Formation and equivalents]

[Begin Monterey Formation and equivalents]

Round Mountain Silt: 16 to 13.5 Ma (fig. 5.50)

Identified in 41 wells in our database, the Round Mountain Silt extends from the Tejon embayment (Te, fig. 5.50) to north of Jasmin oil field (J, fig. 5.50). The age of the Round

Mountain Silt is determined by both paleontological and geochemical methods. Bartow and McDougall (1984) document Luisian benthic fauna near the base of the section in outcrop near Round Mountain oil field (RM, fig. 5.50) and Luisian diatoms near the top of the section. Diagnostic Luisian species also were identified in the Round Mountain Silt at unspecified stratigraphic levels in the Gulf KCL-B 45, Chevron 33-1, Shell Fuhrman 1, and Standard Jeppi-Camp 67-8 wells (API numbers 02926316, 02906398, 02930973, and 02906412, respectively, from west to east; open red circles, fig. 5.50) (Bartow and McDougall, 1984). Olson (1988a) confirms the middle Miocene age of this unit with strontium isotope analyses of shell material and pectens in outcrop at Miller Gulch (MG, fig. 5.50); estimates for the age of the basal Round Mountain Silt range from 16 to 15 Ma, whereas stratigraphically higher sections yield dates of about 14.5 Ma. Together with paleontological control, these data led Olson (1988a) to conclude that the Round Mountain Silt was deposited between 16 and 14 Ma. These ages are consistent with other studies—Harrison and Graham (1999) indicate an age of 13.8 m.y. at the top of the Round Mountain Silt in the Bakersfield Arch area (broad gray shading, BA, fig. 5.50), whereas Sanchez and Prothero (2004) correlate the base to upper third of the Round Mountain Silt with magnetic chrons C5Bn1r and C5Cn1 (16.2 to 15.0 Ma) in Poso Creek (PC, fig. 5.50) and a nearby locality. For conformity with the overlying Fruitvale shale of Miller and Bloom (1939, discussed below), we extend the upper age of the Round Mountain Silt to the top of the Luisian Stage (13.5 Ma), and use an age of 16 (base) to 13.5 (top) Ma for this unit.

Gould Shale and Devilwater Shale Members of the Monterey Formation, undifferentiated: 16 to 13.5 Ma (fig. 5.51)

Although distinguishable as two individual members in outcrop, the Gould Shale and Devilwater Shale Members of the Monterey Formation are considered together on the stratigraphic column (fig. 5.1) because typically the two units cannot be distinguished on electric logs of subsurface sections (Graham and Williams, 1985). Our well database bears out this observation; only 7 of 59 wells that identify these members specify the Gould Shale separately from the Devilwater Shale. Graham and Williams (1985) consider the “Devilwater-Gould equivalent” section as Relizian and Luisian in age (~17 to 13.5 Ma). Foss and Blaisdell (1968) report Relizian foraminifers in the Gould Shale representative of the *Siphogenerina branneri* zone, which Bartow (1992) equates with the lower to middle part of the N8 planktonic foraminiferal zone (16.5 to 15.5 Ma). The lower Devilwater Shale contains foraminifers representative of the early Luisian *Siphogenerina reedi* zone, whereas the upper part of the section contains fauna characteristic of the late Luisian *Siphogenerina collomi* zone (Foss and Blaisdell, 1968). Together these zones correspond to a time range of about 15.5 to 13.5 Ma. The Gould Shale and Devilwater Shale Members of the Monterey Formation were thus deposited between about 16 and 13.5 Ma.

McDonald Shale Member of the Monterey Formation: 13.5 to 10 Ma (fig. 5.52)

The McDonald Shale Member and its basal Packwood sand of Foss and Blaisdell (1968) are identified in 108 wells in our database (fig. 5.52). Confined to the San Joaquin Basin’s southwest side, the McDonald Shale generally lies between the underlying Devilwater Shale and overlying McLure Shale Members of the Monterey Formation. The lower McDonald Shale contains benthic foraminifers correlative with the *Bolivina modeloensis* zone of the lower Mohnian Stage (Foss and Blaisdell, 1968). According to the timescale of Bartow (1992), this zone ranges in time from the base of planktonic foraminiferal zone N11 to near the base of N12, or about 13 to 12.5 Ma. Assemblages from the *Bulimina uvigerinaformis* zone characterize the upper part of the McDonald Shale (Foss and Blaisdell, 1968); this zone corresponds in time to near the base of zone N12 (12.5 Ma) to the top of calcareous nannoplankton zones NN9 and CN7 (about 9.5 Ma) (Bartow, 1992). Because the relative stratigraphic position between these fauna and the section in which they occur remain unknown and because Calaway (1990) illustrates the upper boundary of the McDonald Shale Member coincident with a sea level transgression at 10 Ma, we use an age of 13.5 (base) to 10 (top) Ma for this geologic unit.

Stevens sand of Eckis (1940): 9.5 to 7 Ma (fig. 5.53)

The Stevens sand of Eckis (1940), hereafter referred to as Stevens sand, as discussed here includes all upper Miocene turbidite fans sourced from the southeastern, southern, and southwestern margins of the San Joaquin Basin. Our database includes 232 identifications in 188 wells of the Stevens sand and equivalents. These include the Monarch, Leutholtz, Republic, and Spellacy sandstones of Webb (1981), the Webster and Moco T sands of Link and Hall (1990), and the Metson sand of Foss and Blaisdell (1968) on the basin’s west side; the Yowlumne sand of Metz and Whitworth (1984) in the Maricopa subbasin, a deep depocenter located just north of the White Wolf Fault (WWF, fig. 5.53); the Coulter sandstone of MacPherson (1978) and upper Western sands of Webb (1981) in the Bakersfield Arch area (broad gray shading, BA, fig. 5.53); and the upper, middle, and lower Stevens sand. Other identifications of the Stevens sand are labeled as “top Stevens,” “first upper Stevens,” “second upper Stevens,” “base upper Stevens,” “main Stevens,” “Stevens F-1,” “Stevens F-1A,” and “Stevens F2.” Intra-formational seismic horizons such as the “O Marker” and “P Marker” (for example, Clark and others, 1996; Harrison and Graham, 1999), represented in the database by about 25 wells, are also included in this distribution plot of the Stevens sand.

Encased in late Miocene-age shales of the Monterey Formation, the Stevens sand and equivalents represent a variety of sediment source terranes and depositional environments (Lamb and others, 2003). Accordingly, no single determination of depositional age accurately reflects the age range encompassed by the various members of this turbidite sand system. Nonetheless, dated horizons at South Coles Levee oil field (SCL, fig. 5.53) constrain the age of the Stevens sand for the purposes of this compilation. In that location, the Stevens sand lies between an unconformity at the base of the Coulter sandstone of MacPherson (1978) dated at 8.7 Ma and a seismic and electric-log marker ("N Marker") within the overlying Monterey Formation dated at 6.5 Ma (Clark and others, 1996). Reid (1995) confirms this basal age of the Stevens sand, reporting that Stevens sand deposition in the southeastern basin began about 8.5 Ma. On the basin's west side, the various members of the Stevens sand range in age from about 9.5 Ma, when their Gabilan Range source was uplifted and the Leutholtz, Williams, and Republic sandstones of Webb (1981) were deposited, to 7 Ma, when the Gabilan Range was eroded (Ryder and Thomson, 1989). We use an age of 9.5 to 7 Ma for the Stevens sand, although we indicate graphically on the stratigraphic column (fig. 5.1) the generally younger Stevens sand (8.5 to 6.5 Ma) in the southeastern San Joaquin Basin.

Fruitvale shale of Miller and Bloom (1939): 13.5 to 6.5 Ma (fig. 5.54)

The Fruitvale shale of Miller and Bloom (1939), hereafter referred to as Fruitvale shale, is the principal shale member of the Monterey Formation in the southeastern San Joaquin Basin. Our database contains 39 wells with identifications of the lower and upper Fruitvale shale. Age diagnostic fauna in the Gulf KCL-B 45 well (API number 02906949; open red circle, fig. 5.54) and a questionable outcrop sample indicate an early to middle Mohnian depositional age for this unit (~13.5 to 10 Ma) (Bartow and McDougall, 1984). Stratigraphic relationships provide additional age control; in the subsurface of the southeastern San Joaquin Basin, the Fruitvale shale rests conformably between the underlying Round Mountain Silt and the overlying Santa Margarita Sandstone (discussed below) (Bartow and McDougall, 1984), indicating a partial age range for the Fruitvale shale in this area of about 13.5 to 10 Ma.

The upper part of the Fruitvale shale must be younger than 10 Ma because in the Bakersfield Arch area (broad gray shading, BA, fig. 5.54) it lies between the older Round Mountain Silt and younger Reef Ridge Shale Member of the Monterey Formation (Harrison and Graham, 1999), wholely encasing the Stevens sand (Webb, 1981). This contradicts the interpretation of Callaway (1990), who regards the Fruitvale shale as the shale facies lying below the Stevens sand and considers the Antelope shale of Graham and Williams (1985) as the shale facies overlying the Stevens sand. However, the well database clearly illustrates that the Antelope shale of Graham and Williams (1985) is confined to the western margin of the San Joaquin Basin (see fig. 5.56) and therefore should be considered separately from the Fruitvale shale. Further, several stratigraphic correlation charts label the shale facies overlying the Stevens sand in the Bakersfield Arch area as the upper Fruitvale shale (Bishop and Davis, 1984; Reid, 1995), a relationship we confirmed by three-dimensional spatial analysis of well picks for upper and lower Fruitvale shale and Stevens sand. We thus consider the upper boundary of the Fruitvale shale to correspond to the "N-Point" electric log marker at the base of the Reef Ridge Shale Member of the Monterey Formation (Harrison and Graham, 1999), which is dated at 6.5 Ma (Clark and others, 1996). In summary, we assume that deposition of the Fruitvale shale occurred between 13.5 and 6.5 Ma.

McLure Shale Member of the Monterey Formation: 12 to 6.5 Ma (fig. 5.55)

The McLure Shale Member of the Monterey Formation occurs principally in the subsurface of the central San Joaquin Basin, where the Antelope shale of Graham and Williams (1985) and McDonald Shale Member typical of the southwest basin margin cannot be differentiated (Foss and Blaisdell, 1968; Graham and Williams, 1985). Although a few scattered identifications of the McLure Shale occur in the southern part of the basin (fig. 5.55), these well picks are probably better identified as McDonald Shale or Fruitvale shale, which are the principal middle members of the Monterey Formation in that location. The basal age of the McLure Shale in the central basin is constrained at Reef Ridge (RR, fig. 5.55) by potassium-argon dating of biotite from a bentonite collected 15 feet above the contact with the underlying Temblor Formation (see Woodring and others, 1940, for a detailed description of the collection site); based on 1977 decay constants this age is 11.8 ± 0.4 m.y (J. Obradovich, written commun.). This age for the base of the McLure Shale suggests a hiatus or loss by erosion of about 2 m.y. of section between the upper Temblor Formation and lower Monterey Formation in the central part of the basin. In the northern part of the central San Joaquin Basin, Bishop and Davis (1984) indicate an age of about 10 to 12 Ma for the McLure Shale Member, where it lies between the overlying Santa Margarita Sandstone and underlying Zilch formation.

Absolute dating of the upper McLure Shale is challenging because of the absence of preserved microfossils in the porcelaneous and siliceous facies and because of a markedly time-transgressive contact with the overlying Reef Ridge Shale Member (Graham and Williams, 1985). This contact marks the cessation of biogenic sedimentation and initiation of clastic sedimentation in the late Mohnian throughout most of the central San Joaquin Basin. In the southwestern basin the contact between the units corresponds to a diagenetic boundary between the opal-A and opal-CT phases of silica (Graham and Williams, 1985). Outside of this localized region, the electric-log marker known as the "N-Point" or "N-Marker" serves well as a proxy for the contact between the McLure Shale and Reef Ridge Shale, because it marks the abrupt change in resistivity associated with the transition from siliceous facies below to clayey facies above (Gruenenfelder, 1987). This electric log marker has been dated biostratigraphically at 6.5 Ma (Clark and others, 1996). Thus, for the purposes of this regional-scale compilation we use an age of 12 (base) to 6.5 (top) Ma for the McLure Shale Member of the Monterey Formation.

The distribution map includes 279 identifications of the McLure Shale and the base McLure Shale, as well as the Escudo Sandstone, which is the basal sand of the McLure Shale at Devils Den oil field (DD, fig. 5.55) (Addicott, 1972a).

Antelope shale of Graham and Williams (1985): 10 to 6.5 Ma (fig. 5.56)

Confined principally to the southwest margin of the San Joaquin Basin, the Antelope shale of Graham and Williams (1985; hereafter referred to as Antelope shale), is identified in 168 wells in our database. These wells are variously labeled as "Antelope-McDonald," "Cahn/Antelope," "lower Antelope," "N Point-Antelope," "upper Antelope," and "McLure-Antelope." Generally, members of the Monterey Formation lack firm temporal control because of a variety of factors, including diagenetic alteration of siliceous microfossils, the time-transgressive nature of benthic foraminifers, and the lack of material for adequate radiometric dating; see Graham and Williams (1985) and Omarzai (1992) for summaries of challenges in dating the Monterey Formation. The Antelope shale generally lies between the 6 Ma and 10 Ma stratigraphic sequence boundaries of Callaway (1990). The lower Antelope shale hosts numerous species of benthic foraminifers and a pecten species of the upper Mohnian Stage (Foss and Blaisdell, 1968). In the Crocker Flat area of the Temblor Range (CF, fig. 5.56), Simonson and Krueger (1942) report sparse assemblages in the upper Antelope shale but diagnostic occurrences of *Bolivina marginata* in the lower part of the section. Graham and Williams (1985) document a diatom flora correlative with the *Denticulopsis hustedii* zone near the upper part of the Antelope shale exposed at Chico Martinez Creek (CMC, fig. 5.56); this diatom zone is dated at 9.2 to 8.3 Ma in basins of southern and central coastal California (Barron and Isaacs, 2001). Other studies define the top of the Antelope shale as the uppermost occurrence of benthic foraminifers *Bolivina vaughani* (Callaway, 1962); this somewhat subjective definition results from the difficulty in differentiating the brown-colored Antelope shale from the overlying, brown-colored Reef Ridge Shale Member. In the Midway-Sunset oil field (MS, fig. 5.56), electric logs confirm the utility of this general definition, because the contact between the two units as defined on a specific potential log occurs just 100 feet above the microfossil zone (Callaway, 1962). The upper age of the Antelope shale is constrained further by the occurrence at its top of the "N-Point" electric marker, which records the transition from biosiliceous to siliciclastic deposition in the southern San Joaquin Basin (Gruenenfelder, 1987). This marker is dated at 6.5 Ma (Clark and others, 1996). On the basis of all of this evidence and on its stratigraphic position between the McDonald Shale Member and the N-Point electric marker, the Antelope shale was deposited between about 10 and 6.5 Ma.

The stratigraphic column (fig. 5.1) summarizes our interpretation of the various shale members of the Miocene Monterey Formation, based on analyses of our well database and on relationships presented in the literature (for example, Foss and Blaisdell, 1968)—in the southwestern San Joaquin Basin, McDonald Shale grades into lower Fruitvale shale eastward and into lower McLure Shale northward, whereas Antelope shale grades into upper Fruitvale shale eastward and into upper McLure Shale northwards. These relationships, elucidated by several hundred well picks, should help clarify persistent nomenclatural confusion involving the members of the Monterey Formation.

Santa Margarita Sandstone: 11 to 6.5 Ma (fig. 5.57)

The Santa Margarita Sandstone occupies a broad swath of the subsurface of the eastern San Joaquin Basin, from the Tejon embayment (Te, fig. 5.57) in the south to Chowchilla gas field (Ch, fig. 5.57) in the north. Subsurface occurrences of the Santa Margarita Sandstone on the basin's west side are confined mainly to Coalinga oil field (C, fig. 5.57), although the unit crops out in the Temblor Range (TR, fig. 5.57) along the southern margin of the western San Joaquin Basin (Ryder and Thomson, 1989). Generally, the Santa Margarita Sandstone refers to upper Miocene, shallow-marine clastic facies located east of the San Andreas Fault that are broadly coeval with the basinal Stevens sand (Goodman, 1989; Harrison and Graham, 1999). Identifications of the Santa Margarita Sandstone, its base, and "transition" (a well pick that appears to mark a zone between the Santa Margarita Sandstone and the Chanac Formation, discussed below) occur in 448 wells in our database.

In the Bakersfield Arch (broad gray shading, BA, fig. 5.57) and Tejon embayment regions of the southeastern San Joaquin Basin, the Santa Margarita Sandstone conformably and unconformably overlies the Fruitvale shale and conformably underlies the nonmarine Chanac Formation in outcrop but grades into the lower part of that unit in the subsurface (Bartow and McDougall, 1984; Goodman and Malin, 1992). Age control derives from strontium isotope analyses of outcrop at Comanche Point (CP, fig. 5.57), where shell material from the middle part of the unit dates to 8.5 Ma (Goodman and Malin, 1992). In the Tejon Hills (TH, fig. 5.57), magnetostratigraphic correlations with early to late Clarendonian (11.8 to 9 Ma) mammals at unspecified stratigraphic levels in the Santa Margarita Sandstone and Chanac Formation correlate with magnetic chrons C5n to C5An (12.4 to 9.8 Ma) (Wilson and Prothero, 1997). Published correlations provide further age control for the Santa Margarita Sandstone in the southeastern San Joaquin Basin—Bishop and Davis (1984) and Reid (1995) depict an age range of about 11 to 8.5 Ma, whereas Callaway (1990) depicts deposition between about 12 and 6 Ma. The large time span indicated by this latter source may reflect the fact that in the Bakersfield Arch area, the Santa Margarita Sandstone consists of several stratigraphic sequences separated by unconformities (Bloch, 1991). In contrast, Bartow and McDougall (1984) illustrate a very short depositional time of about 1 m.y. centered on 10 Ma for the Santa Margarita Sandstone in the Bakersfield Arch area. In summary, because the top of the Santa Margarita Sandstone in the eastern part of the southern San Joaquin Basin appears to be contemporaneous with the upper Fruitvale shale (Bishop and Davis, 1984; Callaway, 1990), we assume that deposition of the Santa Margarita Sandstone occurred between about 11 and 6.5 Ma.

Age constraints on the Santa Margarita Sandstone in the central and northern San Joaquin Basin derive mainly from indirect sources, rather than from biostratigraphic or magnetostratigraphic analyses. Bishop and Davis (1984) indicate an age in the vicinity of Helm (H, fig. 5.57) and Riverdale (R, fig. 5.57) oil fields of about 8.5 to 10 Ma whereas Moxon (1990) utilized an upper age of 6 Ma in the vicinity of Helm field (Amerada Hess Brix et al. 1-16 well, API number 01920771; open red circle, fig. 5.57) for an analysis of basin subsidence. The same study used an age of 8 Ma for the top of the Santa Margarita Sandstone in a well located north of Raisin City oil field (RC, fig. 5.57) (Texaco Seaboard 1-28 well, API number 01906054; open red circle, fig. 5.57). Finally, in the vicinity of Coalinga and Priest Valley (PV, fig. 5.57), the Santa Margarita Sandstone underlies the Reef Ridge Shale Member of the Monterey Formation but is partially temporally equivalent with the underlying McLure Shale Member of the Monterey Formation (Bishop and Davis, 1984). In the absence of more definitive age determinations, we use the same age for the Santa Margarita Sandstone in the central and northern San Joaquin Basin as for the southern basin—11 to 6.5 Ma.

Although our well database contains very few identifications of the Santa Margarita Sandstone west of the Bakersfield Arch, the importance of the unit cannot be underestimated because of the equivalency (see for example, Ryder and Thomson, 1989) between it and the western members of the Stevens sand system in the southwestern part of the basin, where stratigraphic relationships show basinward interfingering and replacement of the shelfal sandstone with the basinal sand (Webb, 1981; Clark and others, 1996). Although the correlation chart (fig. 5.1) lacks a western facies of Santa Margarita Sandstone in the column for the southern part of the basin, the Stevens sand essentially represents the Santa Margarita Sandstone in that region.

Chanac Formation: 9 to 6 Ma (fig. 5.58)

Confined to a narrow band in the subsurface of the southeastern San Joaquin Basin, the nonmarine Chanac Formation, the Cattani zone sand of Porter (1965) (the basal oil-productive sand at Mountain View oil field, MV, fig. 5.58), the Kernco and Martin zones of Miller (1940) (at Fruitvale field, F, fig. 5.58), and a pick labeled "Chanac/Transition" occur in 46 wells in our database. As mentioned above, the Chanac Formation overlies the Santa Margarita Sandstone in outcrop but its lower part grades into the Santa Margarita Sandstone in the subsurface, indicating partial age equivalency (Bartow and McDougall, 1984). The nonmarine Kern River Formation overlies the Chanac Formation, both conformably (Miller, 1999) and unconformably (Kodl and others, 1990), although Kodl and others (1990) indicate that the unconformity between the two units at Kern River oil field (KR, fig. 5.58) is masked within basal conglomeratic sequences.

Absolute age control on the Chanac Formation derives only from coupled magnetostratigraphic and paleontologic studies of Prothero and Wilson (1993) and Wilson and Prothero (1997). These studies indicate an age of about 10.5 Ma at the top of the Chanac Formation in the Tejon Hills (TH, fig. 5.58) area on the southeastern rim of the San Joaquin Basin. Published stratigraphic correlation charts, however, indicate a somewhat younger section with ages of about 11 to 6 Ma (Callaway, 1990), 11 to 9 Ma (Bartow and McDougall, 1984), and 9 to 6 Ma (Bishop and Davis, 1984). These upper ages generally agree with the basal age (8 Ma) of the overlying Kern River Formation. Because the Chanac Formation is probably somewhat younger than the Santa Margarita Formation (Bartow and McDougall, 1984), we assume deposition of the Chanac Formation occurred from about 9 to 6 Ma.

The hiatus of 1 m.y. duration shown on figure 5.1 between the Chanac Formation and the Etchegoin Formation derives from Bartow and McDougall (1984).

Kern River Formation: 8 to 6 Ma (fig. 5.59)

Though defined in only 3 wells in our database, the Kern River Formation is included on the stratigraphic column because it contains the largest volume of oil in the southeastern San Joaquin Basin (~2,100 MMBO; table 5.2). The distribution map also includes a well pick of the China Grade of Kodl and others (1990), an oil sand at Kern River field (KR, fig. 5.59). The lower part of the nonmarine Kern River Formation grades westward into the Etchegoin Formation, whereas the upper Kern River Formation merges basinward with the San Joaquin and Tulare Formations (Foss and Blaisdell, 1968; Bartow and Pittman, 1983; Bartow and McDougall, 1984; Graham and others, 1988). Close to the paleoshoreline in the Kern River oil field, the Kern River Formation unconformably overlies the nonmarine Chanac Formation (Kodl and others, 1990), although in other areas the two formations may exhibit a conformable relationship (Miller, 1999). Based on stratigraphic relationships with the Etchegoin Formation (Graham and others, 1988; Kodl and others, 1990), on the presence of an early Hemphillian Stage (9 to 4.75 Ma) fossil near its base (Bartow and Pittman, 1983), and on the presence of a volcanic tuff dated at 8.2 Ma in correlative strata of the northern San Joaquin Basin (Bartow and Pittman, 1983), the basal age of the Kern River Formation is about 8 Ma.

Age estimates for the upper Kern River Formation vary by nearly an order of magnitude. Graham and others (1988) concluded that the Kern River Formation predates the Corcoran Clay Member of the Tulare Formation, a widespread, Quaternary lake-bed deposit with a basal age of about 725,000 years (Lettis, 1988). Radiometric dating of a volcanic ash layer near the top of the Kern River Formation at Kern River field appears to agree with this constraint; McGuire (1989) correlates this ash with the Bishop Tuff erupted from Long Valley Caldera (LV, fig. 5.59), which is dated at about 0.62 ± 0.02 Ma (Sarna-Wojcicki and others, 1984). In contrast, Miller (1999) used ^{40}Ar/^{39}Ar analysis of sanidine crystals from the same ash bed in the Kern River Formation and obtained an age of 6.12 ± 0.05 Ma, thereby questioning McGuire's (1989) correlation of the ash bed with the Bishop Tuff. Recent evaluation of this discrepancy by Golob and others (2005) supports Miller's (1999) result—the ash in the Kern River Formation exhibits closer statistical similarity with a 6.0 ± 0.2 Ma old tephra erupted from the Volcano Hills and Silver Creek Range of western Nevada than the much younger tuffs.

The implications of this revised age are significant; if deposition of the Kern River Formation occurred between 8 and 6 Ma, instead of over a much longer period between 8 and 0.6 Ma, the single-most important reservoir rock in terms of volume of produced oil was completely deposited by the time oil generation began in the Tejon depocenter about 4.6 Ma (see Peters, Magoon, Lampe, and others, this volume, chapter 12, for more on the timing of petroleum generation). The revised age also implies temporal equivalence of the Kern River Formation with other important oil-bearing reservoir rocks such as the Chanac Formation, Santa Margarita Sandstone, and Fruitvale shale. However, the gradational relationship between the Kern River Formation and seemingly younger units such as the Etchegoin, San Joaquin, and Tulare Formations must be reexamined.

On the basis of the analyses of Miller (1999) and Golob and others (2005), we assume deposition of the Kern River Formation occurred between 8 and 6 Ma.

Reef Ridge Shale Member of the Monterey Formation: 6.5 to 5.5 Ma (fig. 5.60)

The Reef Ridge Shale Member of the Monterey Formation, identified in 248 wells in our database, occurs in the subsurface of the western part of the central San Joaquin Basin and throughout the western and middle portion of the southern part of the basin. The distribution map includes identifications of the Belridge Diatomite Member of the Monterey Formation, an equivalent of the Reef Ridge Shale Member at South Belridge oil field (SB, fig. 5.60) and Chico Martinez Creek (CMC, fig. 5.60) (Siegfus, 1939; Foss and Blaisdell, 1968; Schwartz, 1988), as well as identifications of the Sublakeview sand of Callaway (1962), the Olig sand of Adkison (1973), and the Potter sand of Callaway (1962) (hereafter referred to as Olig sand and Potter sand).

Accurate classification of the Olig and Potter sands illustrates the difficulty in defining the top of the Reef Ridge Shale. Deposited during latest Miocene and (or) earliest Pliocene time from sources in the Gabilan Range (Ryder and Thomson, 1989), the sand bodies lie between the Reef Ridge Shale (below) and Etchegoin Formation (above). Several studies assume that the two sands are coeval and constitute the youngest members of the Reef Ridge Shale on the basin's southwestern margin (Webb, 1981; Schwartz, 1988; Reid, 1995). However, an unconformity overlying the Potter sand at Midway-Sunset field (MS, fig. 5.60) suggests inclusion of that unit with the Reef Ridge Shale (Callaway, 1962), whereas the deposition of the Olig sand on a regional unconformity truncating Miocene-age shale at McKittrick oil field (M, fig. 5.60) (Harding, 1976; Farley, 1990) argues for its inclusion with the Etchegoin Formation. Although an unconformity does not appear at the base of the Olig sand in the Occidental 526-30R well (API number 02941949; open red circle, fig. 5.60), Adkison (1973) includes the Olig sand with the Etchegoin Formation but admits the difficulty in determining the boundary between the Reef Ridge Shale and Etchegoin Formation. Callaway's (1990) comprehensive study of the stratigraphic sequences of the San Joaquin Basin separates the two units by a sea level transgression at 6 Ma, with Potter sand below the sequence boundary and Olig sand above, but both sands lie within the Reef Ridge Shale. Finally, Ryder and Thomson (1989) include the Potter sand not with the Reef Ridge Shale or Etchegoin Formation but instead with the Santa Margarita Sandstone on the basis of lithologic and stratigraphic similarity. For the purposes of this study, we include the well picks for the Olig and Potter sands with the Reef Ridge Shale.

Foraminifers of general Delmontian age (8 to 5 Ma) characterize the middle to lower Reef Ridge Shale at its type section (RR, fig. 5.60) (Woodring and others, 1940; Foss and Blaisdell, 1968). Miller (1999) integrates diatom biostratigraphy and borehole density logs to obtain lower and upper ages of 6.2 and 5.4 Ma, respectively, for the Reef Ridge Shale at Lost Hills oil field (LH, fig. 5.60), where the basal contact corresponds to the transition from widespread biosiliceous to siliciclastic depositional facies in the basin. Similarly, Gruenenfelder (1987) equates the base of the Reef Ridge Shale in the southern San Joaquin Basin with the "N" electric-log marker that signals the transition from dominantly silica to dominantly clay compositions. The biostratigraphic age of this marker is 6.5 Ma (Clark and others, 1996). Diatom floras representative of the earliest part of the *Thalassiosira oestrupii* zone characterize the Belridge Diatomite at North Belridge oil field (NB, fig. 5.60) (Graham and Williams, 1985); the base of this zone corresponds to about 5.5 Ma in a recent chronostratigraphic framework for the Monterey Formation (Barron and Isaacs, 2001). Finally, in the Bakersfield Arch area (broad gray shading, BA, fig. 5.60), Harrison and Graham (1999) indicate deposition of the Reef Ridge Shale between about 6.0 and 5.1 Ma. This younger section of Reef Ridge Shale documents the delayed transition from biosiliceous to siliciclastic deposition in the center of the southern San Joaquin Basin (Graham and Williams, 1985).

The Reef Ridge Shale is difficult to date accurately in the southwestern part of the basin because it appears undifferentiated from the overlying Etchegoin Formation. A detailed study of Elk Hills field (EH, fig. 5.60), Buena Vista field (BV, fig. 5.60) and the southern Temblor Range (TR, fig. 5.60) reports that the two units cannot be distinguished either on electric logs or within microfossil assemblages (Imperato, 1995). Farther east at South Coles Levee oil field (SCL, fig. 5.60), Clark assigns an age of 6 Ma to the unconformity at the base of both the Reef Ridge Shale and Etchegoin Formation, reflecting the undifferentiated character between the two units.

With the exception of the younger section of Reef Ridge Shale in the Bakersfield Arch area, most age constraints indicate that this uppermost member of the Monterey Formation was deposited between about 6.5 and 5.5 Ma.

Monterey Formation: 16 to 5.5 Ma (south) and 12 to 5.5 Ma (central) (fig. 5.61)

The distribution map for the Monterey Formation illustrates its widespread distribution in the subsurface of the southern and central San Joaquin Basin. The well database contains 860 wells containing more than 1,300 identifications of the Monterey Formation and its members, including the Devilwater Shale and Gould Shale, McDonald Shale, Stevens sand, Fruitvale shale, McLure Shale, Antelope shale, and Reef Ridge Shale, as well as the N-electric log marker and a well-pick labeled the “Monterey chert.” The age of the Monterey Formation based on the age of its members ranges from the age at the base of the Devilwater Shale to the age at the top of the Reef Ridge Shale in the southern San Joaquin Basin (16 to 5.5 Ma), and from the age at the base of the McLure Shale to the age at the top of the Reef Ridge Shale in the central basin (12 to 5.5 Ma). Diatom biostratigraphy in the Chevron Vulcan 48 well in Lost Hills oil field (LH, fig. 5.61) supports this upper age; the last occurrence of *Thalassiosira miocenica* and the first occurrence of *Thalassiosira hyalinopsis,* both occurring just below the Miocene-Pliocene boundary (5.3 Ma), are found above the opal CT phase in the well (Dumont, 1989).

Absolute age dating of the Monterey Formation presents varied problems, as discussed by Graham and Williams (1985) and Omarzai (1992). Numerous studies seek to remedy these challenges with biostratigraphy, magnetostratigraphy, and radiometric techniques at exposed coastal and inland sections of the Monterey Formation. Resulting ages vary widely, however, encompassing 15 to 11 Ma for a complete section at Shell Beach (SB, fig. 5.61) in Pismo Basin (Omarzai, 1992), 18 to 12 Ma for a complete section at Horse Canyon (HC, fig. 5.61) in Salinas Basin (Omarzai and others, 1997), 15 to 8 Ma at the type area in Monterey County (M, fig. 5.61) (Obradovich and Naeser, 1981), 16 to 4 Ma for a complete section at Palos Verdes Hills (located to the southwest of the map area in fig. 5.61) (Obradovich and Naeser, 1981), 22 to 14 Ma in the Cuyama Valley (CV, fig. 5.61) (Obradovich and Naeser, 1981), 18 to 7.5 Ma for a section spanning all but the upper 400 feet of the formation at Naples Beach (located to the southwest of the map area in fig. 5.61) (DePaolo and Finger, 1991) and 16 to 18 Ma for the lower Monterey Formation at Graves Creek (GC, fig. 5.61) (DePaolo and Finger, 1991). The age of the Monterey Formation thus varies widely throughout central and southern California, indicating a variety of depositional environments and controls.

For the purposes of this study, we use an age of 16 to 5.5 Ma for the Monterey Formation in the southern San Joaquin Basin and 12 to 5.5 Ma for the Monterey Formation in the central part of the basin.

[End Monterey Formation and equivalents]

Pliocene

Etchegoin Formation: 5.5 to 4.5 Ma (fig. 5.62)

Identified in 371 wells in our database, the Etchegoin Formation is broadly distributed across the southern region of the San Joaquin Basin between the San Andreas Fault and the Bakersfield Arch (broad gray shading, BA, fig. 5.62). Limited deposition of this marine unit in the central San Joaquin Basin reflects the recession of the marine basin in late Miocene-early Pliocene times. Identifications of the Etchegoin Formation in our database are variously labeled as “base Etchegoin,” “Etchegoin D sand,” “Etchegoin E7 sand,” “Etchegoin G sand,” “Etchegoin G2 sand,” “Etchegoin H sand,” “Etchegoin W2 sand,” “Etchegoin W3 sand,” “Etchegoin-Jacalitos,” and “Etchegoin Main.” Correlative sands confined principally to the southwest margin of the basin include the Calitroleum, Gusher, and Wilhelm sands of Woodward (1945) and the Mulinia sand zone and Submulinia sand of Berryman (1973). Also included in this compilation are the Fairhaven sand of Miller (1940) (restricted to Fruitvale oil field, F, fig. 5.62), the Macoma shale of Hoots and others (1954) (a transgressive unit that overlies the Reef Ridge Shale Member of the Monterey Formation in the Bakersfield Arch area), the basal Lerdo zone of Betts (1955) (at Rosedale Ranch field, RR, fig. 5.62), and the basal Randolph sand of Mitchell and Chamberlain (1983) (at Semitropic field, S, fig. 5.62).

The Etchegoin Formation is well dated with radiometric techniques. $^{87}Sr/^{86}Sr$ analyses of fossil shells from outcrops west of the Kettleman Hills (KH, fig. 5.62) and Coalinga oil field (C, fig. 5.62) indicate an age of about 7 Ma for the base of the Jacalitos Formation (Loomis, 1990), a unit that is equivalent to the lower Etchegoin Formation in the subsurface (Foss and Blaisdell, 1968; Bloch, 1991). This age generally agrees with the 7.0 ± 1.2 Ma date reported for the Etchegoin Formation at Kettleman Hills by Obradovich and others (1978) based on fission-track analyses of detrital zircon, although the stratigraphic position of the sample is unstated and Sarna-Wojcicki and others (1991) suggest that the sample is contaminated with detrital zircons from older volcanic layers. The age of the base of the Etchegoin Formation in the southwestern part of the basin may be somewhat younger than in these central regions; Loomis (1990) reports a basal age of 5.5 Ma at Lost Hills (LH, fig. 5.62), South Belridge (SB, fig. 5.62), and Cymric (Cy, fig. 5.62) oil fields from analyses of diatom assemblages. A contradictory age constraint at Lost Hills field is cited by Graham and Williams (1985), who refer the basal sandy diatomite zones of the Etchegoin Formation to the *Thalassiosira antiqua* diatom zone, or 7.5 to 8.5 Ma (Barron and Isaacs, 2001). However, based on lithologic similarity, Graham and Williams (1985) suggest that these diatomites are better classified with the underlying Monterey Formation. Finally, Clark (1996) cites an age of 6 Ma for the unconformity at the base of the Etchegoin Formation in the Coles Levee area (CL, fig. 5.62), but the distinction between the Etchegoin Formation and the Reef Ridge Shale Member of the Monterey Formation in the south-central basin is unclear (discussed above).

Upper age constraints for the Etchegoin Formation derive from geochronologic analysis at Kettleman Hills of a tuff located at the top of the formation. On the basis of chemical similarity with the Lawlor Tuff of northern California, potassium-argon dating of this tuff by Sarna-Wojcicki and others (1979) indicates an age of 4.5 ± 0.5 Ma. We thus use an age of 5.5 (base) to 4.5 (top) Ma for the Etchegoin Formation in the southern San Joaquin Basin, but note that it is probably older in the central basin.

San Joaquin Formation: 4.5 to 2.5 Ma (fig. 5.63)

The subsurface distribution of the San Joaquin Basin as defined by 280 wells in our database is similar to that of the underlying Etchegoin Formation, except that it occupies a more westerly location due to the westward retreat of the marine basin in the early Pliocene. Nearly all of the wells located northeast of Semitropic oil field (S, fig. 5.63) contain identifications of the Mya sand zone of Berryman (1973; hereafter referred to as Mya sand), a horizon located near the top of the San Joaquin Formation (Bloch, 1991) that is named for the occurrence of the *Mya* molluscan assemblage. The Mya sand also corresponds to a widespread, high-amplitude seismic reflector, which Miller (1999) mapped throughout the south-central San Joaquin Basin and correlated to a major change in depositional environments. The distribution map also includes picks for the Scalez sand zone of Berryman (1973), a seismic, fossil, and electric log marker located near the base of the San Joaquin Formation on the basin's western margin (Maher and others, 1972).

Potassium-argon dating of volcanic layers within the Etchegoin and San Joaquin Formations at Kettleman Hills (KH, fig. 5.63) bracket the latter unit's depositional age. As discussed above, the chemistry of a tuff located in the uppermost Etchegoin Formation is statistically similar with the Lawlor Tuff, which erupted from the Sonoma volcanic field at 4.5 ± 0.5 Ma (Sarna-Wojcicki and others, 1979). This date is identical to a fission track date of 4.5 ± 0.5 Ma and nearly identical to a potassium-argon date of 4.5± 0.8 Ma reported for the San Joaquin Formation by Obradovich and others (1978), although the stratigraphic position of the samples are unstated. Sarna-Wojcicki and others (1991) establish equivalency between a tephra layer in the middle part of the San Joaquin Formation and the Cascade-derived Nomlaki Tuff Member of the Tehama and Tuscan Formations, which erupted 3.4 ± 0.4 Ma. Finally, the Ishi Tuff Member of the Tuscan Formation, dated at 2.5 Ma, also appears to occur near the top of the San Joaquin Formation at Kettleman Hills, just beneath the contact with the overlying Tulare Formation (Sarna-Wojcicki and others, 1991).

In summary, deposition of the San Joaquin Formation occurred between 4.5 and 2.5 Ma.

Tulare Formation: 2.5 to 0.6 Ma (fig. 5.64)

Identified in 86 wells, the Tulare Formation is confined in the subsurface of the San Joaquin Basin principally to its southwestern margin, although scattered identifications appear in the south-central part of the basin (fig. 5.64). Identifications of this formation and its members are variously labeled as "Tulare tar," "upper Tulare," "second Tulare," "lower Tulare," "base Tulare," and "Amnicola;" this latter unit is the Amnicola sand of Foss and Blaisdell (1968), a gastropod-bearing unit that occurs near the base of the Tulare Formation in outcrop at Kettleman North Dome (KND, fig. 5.64) (Woodring and others, 1940) and in surface and subsurface sections near Cymric (C, fig. 5.64) and McKittrick (M, fig. 5.64) oil fields (Farley, 1990).

A variety of dating methods have been applied to different sections of the Tulare Formation. We assign an age of 2.5 to 0.6 Ma based on the following evidence. The base of the Tulare Formation is time transgressive in the Kettleman area—a tuff correlative with the 3.4 m.y. old Nomlaki Tuff Member of the Tehama and Tuscan Formations occurs in the Tulare Formation at Kettleman Middle Dome (KMD, fig. 5.64) but occurs in the underlying San Joaquin Formation at Kettleman North Dome about 10 miles to the north (Miller, 1999). At the Kettleman North Dome location, Sarna-Wojcicki (1991) dated the Ishi Tuff, a member of the Tuscan Formation, immediately beneath the base of the Tulare Formation at 2.4 to 2.6 Ma. Further, Obradovich and others (1978) report a fission-track age of 2.2 ± 0.3 Ma in zircon from an unspecified stratigraphic position in the Tulare Formation in the Kettleman area. Miller (1999) ascribes this sample to a tephra located near the base of the Amnicola sand of Foss and Blaisdell (1968) in the lower Tulare Formation. For simplicity we assign an age of 2.5 Ma to the base of the Tulare Formation.

Incidentally, paleontological evidence from an exposed section of the Tulare Formation at Elk Hills (EH, fig. 5.64) is consistent with these ages; although the stratigraphic position of the samples are unspecified, limestone members of the formation are dated at 2.4 to 1.9 Ma based on the presence of vertebrate fossils throughout the section (Repenning, unpub. report reprinted in Miller, 1999).

Age control for the upper Tulare Formation derives from dating of the Corcoran Clay, an upper lacustrine member that accumulated between 740,000 and 615,000 years ago (Lettis, 1988). Paleomagnetic measurements of samples from the Tulare Formation at Kettleman Hills, Elk Hills, Cymric oil field, and Midway-Sunset oil field (MS, fig. 5.64) provide consistent dates—samples appear to lie entirely within the Matuyama chron (2.6 to 0.8 Ma) (White, 1987). We thus use an age for the Tulare Formation of 2.5 to 0.6 Ma.

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Figures 5.1–5.64

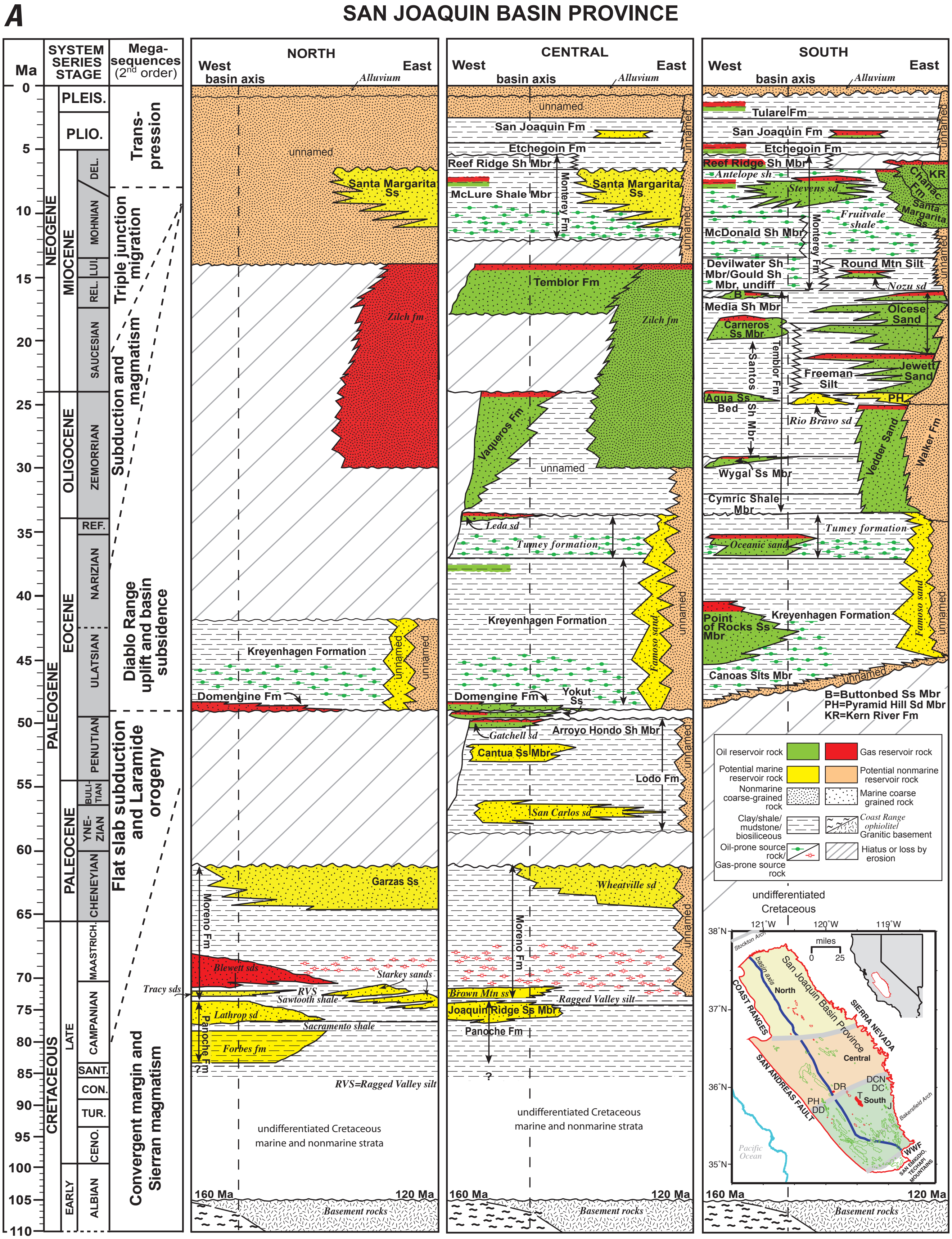
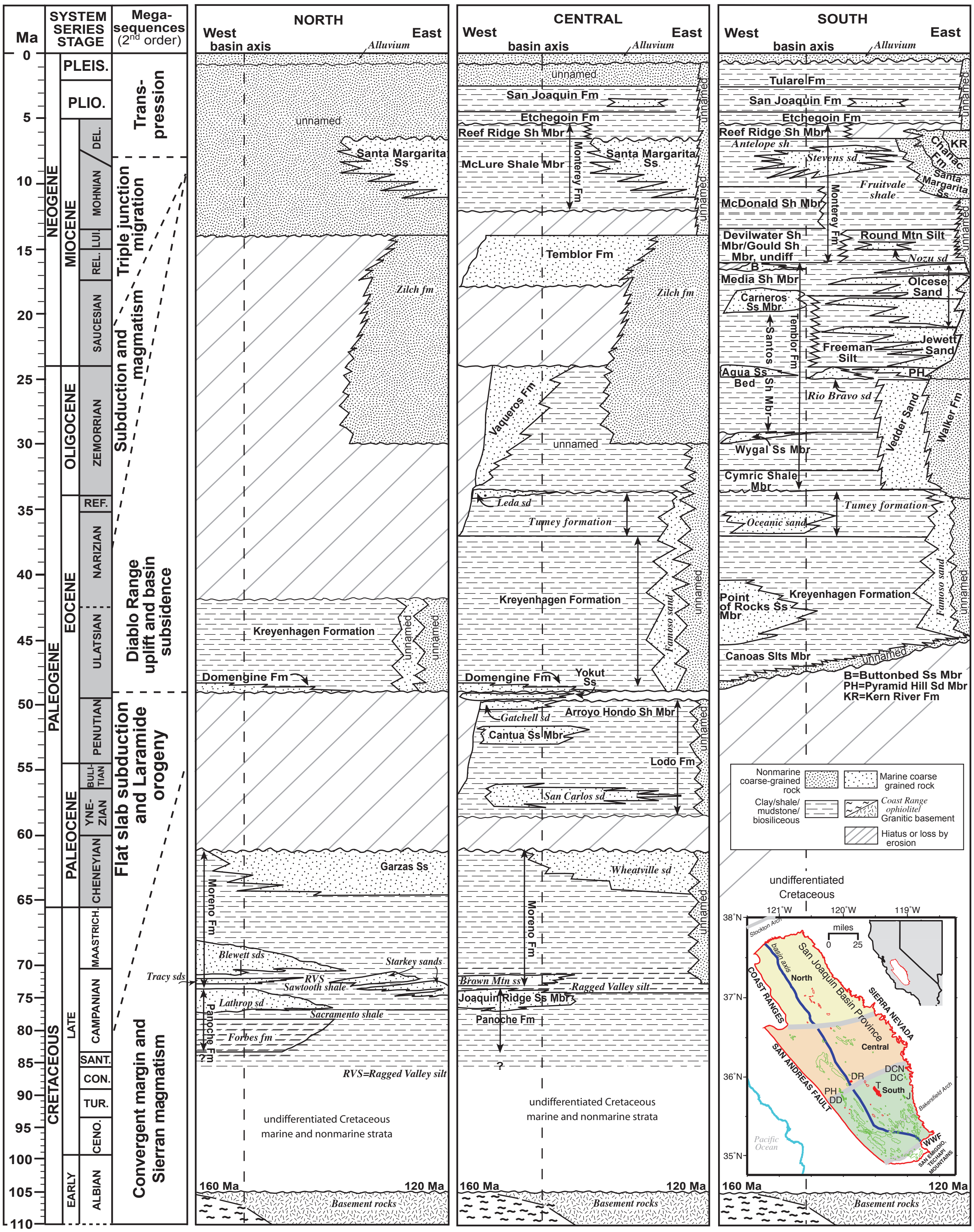

A
SAN JOAQUIN BASIN PROVINCE
Ma
SYSTEM SERIES STAGE
Mega-sequences (2nd order)
NORTH
CENTRAL
SOUTH
West
East
basin axis
Alluvium
Trans-pression
Triple junction migration
Subduction and magmatism
Diablo Range uplift and basin subsidence
Flat slab subduction and Laramide orogeny
Convergent margin and Sierran magmatism
NEOGENE
PALEOGENE
CRETACEOUS
PLEIS.
PLIO.
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
LATE
EARLY
DEL.
MOHNIAN
LUI.
REL.
SAUCESIAN
ZEMORRIAN
REF.
NARIZIAN
ULATSIAN
PENUTIAN
BULI-TIAN
YNE-ZIAN
CHENEYIAN
MAASTRICH.
CAMPANIAN
SANT.
CON.
TUR.
CENO.
ALBIAN
unnamed
Santa Margarita Ss
Zilch fm
Kreyenhagen Formation
Domengine Fm
Garzas Ss
Moreno Fm
Blewett sds
Starkey sands
Tracy sds
RVS
Sawtooth shale
Lathrop sd
Sacramento shale
Forbes fm
Panoche Fm
RVS=Ragged Valley silt
undifferentiated Cretaceous marine and nonmarine strata
San Joaquin Fm
Etchegoin Fm
Reef Ridge Sh Mbr
McLure Shale Mbr
Monterey Fm
Temblor Fm
Vaqueros Fm
Leda sd
Tumey formation
Famoso sand
Yokut Ss
Gatchell sd
Arroyo Hondo Sh Mbr
Cantua Ss Mbr
Lodo Fm
San Carlos sd
Wheatville sd
Brown Mtn ss
Ragged Valley silt
Joaquin Ridge Ss Mbr
Panoche Fm
Tulare Fm
Antelope sh
Stevens sd
KR
Chanac Fm
Santa Margarita Ss
Fruitvale shale
McDonald Sh Mbr
Devilwater Sh Mbr/Gould Sh Mbr, undiff
Round Mtn Silt
Nozu sd
Media Sh Mbr
Olcese Sand
Carneros Ss Mbr
Santos Sh Mbr
Freeman Silt
Jewett Sand
Agua Ss Bed
PH
Rio Bravo sd
Vedder Sand
Walker Fm
Wygal Ss Mbr
Cymric Shale Mbr
Oceanic sand
Point of Rocks Ss Mbr
Canoas Slts Mbr
B=Buttonbed Ss Mbr
PH=Pyramid Hill Sd Mbr
KR=Kern River Fm
Oil reservoir rock
Gas reservoir rock
Potential marine reservoir rock
Potential nonmarine reservoir rock
Nonmarine coarse-grained rock
Marine coarse grained rock
Clay/shale/ mudstone/ biosiliceous
Coast Range ophiolite/ Granitic basement
Oil-prone source rock/ Gas-prone source rock
Hiatus or loss by erosion
undifferentiated Cretaceous
160 Ma
120 Ma
Basement rocks
Stockton Arch
basin axis
San Joaquin Basin Province
North
Central
South
COAST RANGES
SIERRA NEVADA
SAN ANDREAS FAULT
Bakersfield Arch
Pacific Ocean
WWF
SAN EMIGDIO, TECHACHAPI MOUNTAINS
miles
0 25
121°W
120°W
119°W
38°N
37°N
36°N
35°N

Figure 5.1. Stratigraphic columns for the northern, central, and southern San Joaquin Basin—*(A)* with shading and source rock symbols and *(B)* with shading and source rock symbols removed. The subregions are defined in the text and illustrated graphically in the index map at lower right. Definition of megasequences are summarized from Graham and Johnson (2004). Note that the linear scale of the time axis between 110 and 70 Ma is half that from 70 Ma to present. Dashed line from 80 to 55 Ma denotes time period of slab flattening associated with the Laramide orogeny (Keith, 1978); dashed line from 38 to 10 Ma denotes uplift of Diablo Range (Bartow, 1985); and dashed line from 21 to 10 Ma denotes time period of Mendocino Triple Junction migration at the latitude of the San Joaquin Basin Province (Graham and others, 1983). Names of formally described rock units follow usage given in the geologic names lexicon of the USGS national geologic map database, (http://ngmdb.usgs.gov/Geolex/geolex_home.html). Informally named units (italic text) follow usage given by a definitive citation; these citations appear in captions for figures 5.4 through 5.64 and in table 5.2. California provincial benthic foraminiferal zones appear in gray shading. Basement configuration is schematic. (**continued on next page**)

(**continued from previous page**) PLEIS., Pleistocene; PLIO., Pliocene; DEL., Delmontian, LUI., Luisian; REL., Relizian; REF., Refugian; MAAST., Maastrichtian; SANT., Santonian; CON., Coniacian; TUR., Turonian; CENO., Cenomanian. B, Buttonbed Sandstone Member of Temblor Formation; Fm, Formation; fm, formation; KR, Kern River Formation; Mbr, Member; PH, Pyramid Hill Sand Member of Jewett Sand; RVS, Ragged Valley silt; sd, sand; sds, sands; Ss, Sandstone; ss, sandstone; Sh, Shale; sh, shale; undiff., undifferentiated. Inset map: The geographic subdivisions of the basin as defined in the text. The subsurface trace of the White Wolf Fault (WWF) bounds the stratigraphic column on the south. Oil fields are outlined in green and gas fields are outlined in red. The basin axis and the trend of the Bakersfield Arch are mapped on the three-dimensional geologic model of the San Joaquin Basin Province (see Hosford Scheirer, this volume, chapter 7). The basin axis is mapped in that model on the top of the Temblor Formation in the central and southern regions and on the top of the Ragged Valley silt of Hoffman (1964) in the northern region. Oil and gas field abbreviations are: DD, Devils Den; PH, Pyramid Hills; DR, Dudley Ridge; T, Trico; J, Jasmin; DC, Deer Creek; and DCN, Deer Creek, North. These fields are filled with color for emphasis. ⟹

B

SAN JOAQUIN BASIN PROVINCE



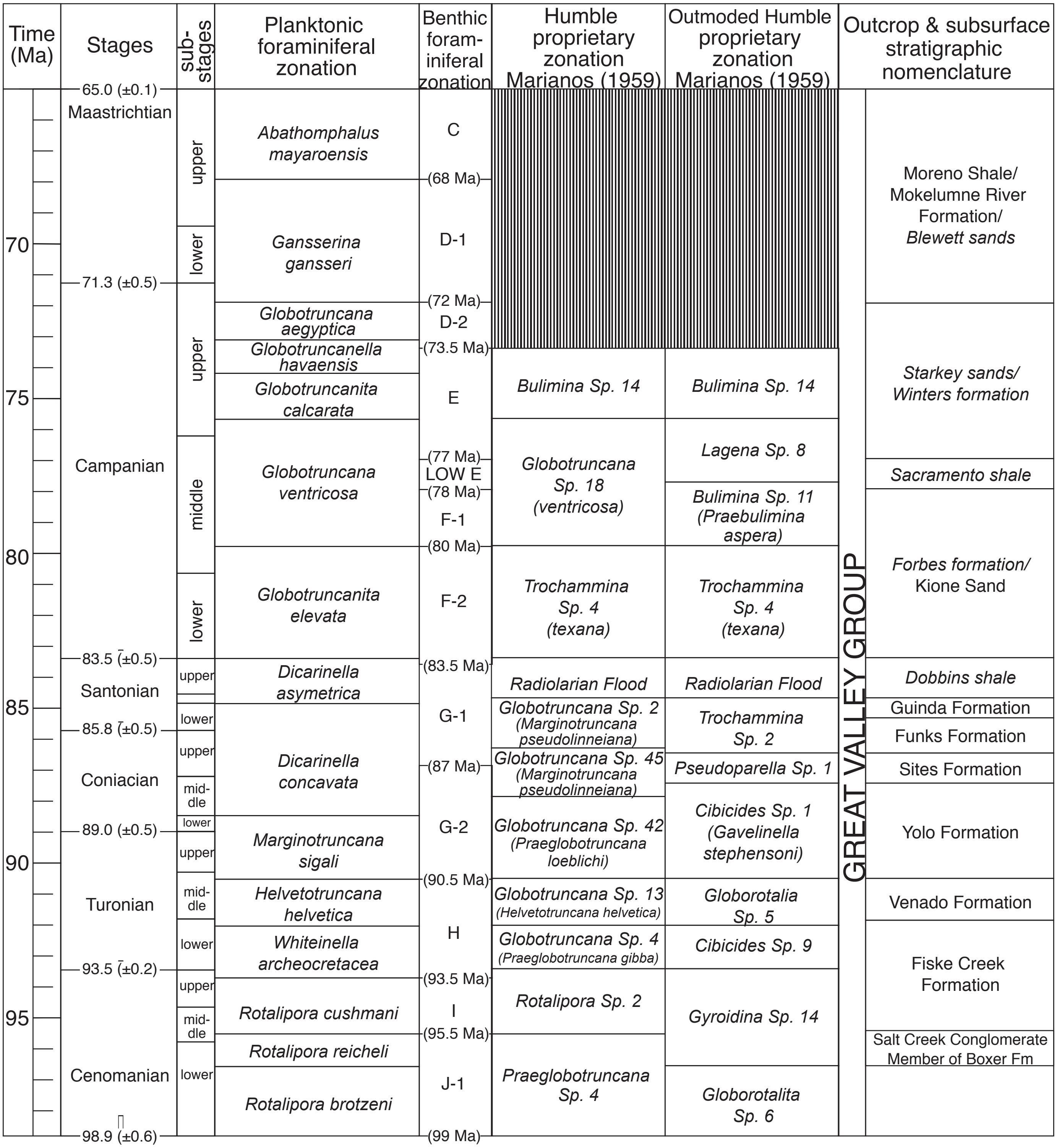
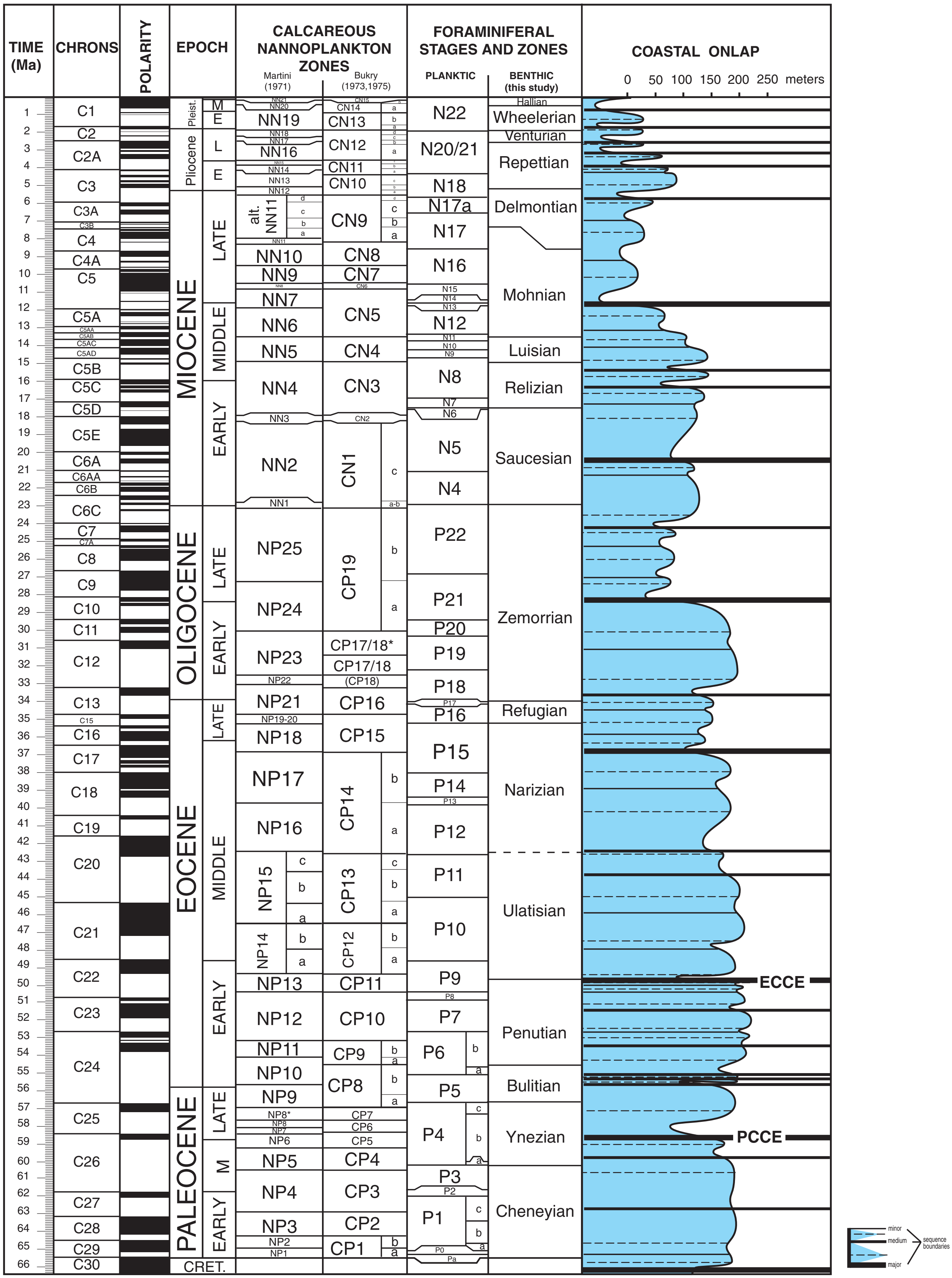


Figure 5.2. Late Cretaceous stratigraphic nomenclature of the Sacramento Basin and correlation to the geologic time scale of Gradstein and others (1994), the planktonic foraminiferal zones of Sliter (1989), and benthic foraminiferal zones of Goudkoff (1945), as modified by Almgren (1986) and Berry (1974). Stratigraphic nomenclature is from Kirby (1943). Italic lettering in stratigraphic nomenclature column denotes informal geologic name (references for these appear in text and table 5.2, except for Winters formation of Edmondson, 1962). Figure is modified from Williams (1997). Fm, Formation.

Figure 5.3. California Cenozoic biostratigraphic framework. Figure by McDougall (this volume, chapter 4); see caption for figure 4.2 for details on time scale, paleomagnetic chrons, calcareous nannofossil zones, planktonic foraminiferal zones, and coastal onlap fluctuations. Calcareous nannoplankton zones derive from Martini (1971) and Bukry (1973; 1975). ECCE, Eocene canyon cutting event; PCCE, Paleocene canyon cutting event. Cret., Cretaceous; Pleist., Pleistocene; E, Early; M, Middle. ⇒


TIME (Ma)
CHRONS
POLARITY
EPOCH
CALCAREOUS NANNOPLANKTON ZONES
Martini (1971)
Bukry (1973,1975)
FORAMINIFERAL STAGES AND ZONES
PLANKTIC
BENTHIC (this study)
COASTAL ONLAP
0 50 100 150 200 250 meters
Pleist.
Pliocene
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
CRET.
LATE
MIDDLE
EARLY
Hallian
Wheelerian
Venturian
Repettian
Delmontian
Mohnian
Luisian
Relizian
Saucesian
Zemorrian
Refugian
Narizian
Ulatisian
Penutian
Bulitian
Ynezian
Cheneyian
ECCE
PCCE
minor
medium
major
sequence boundaries

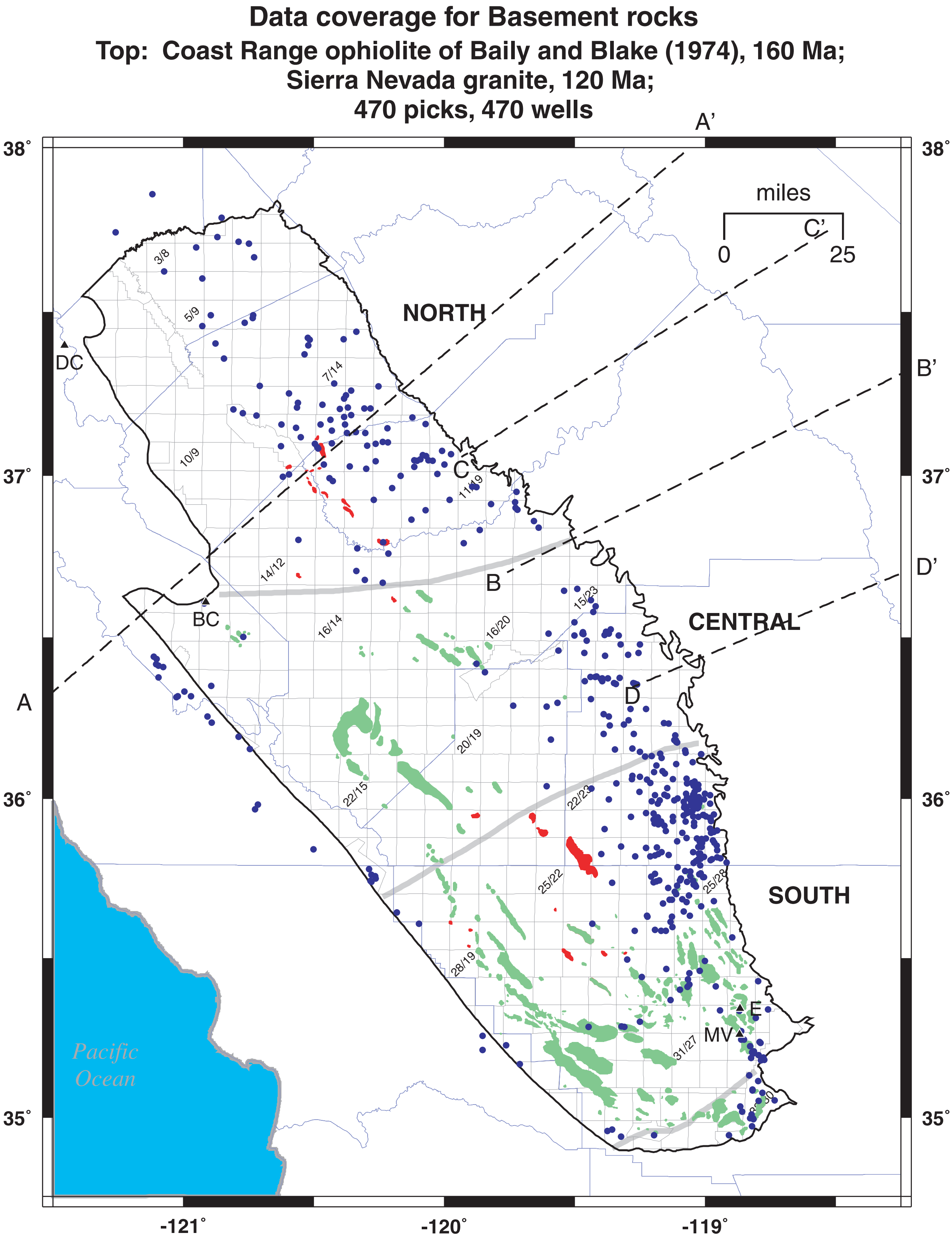

Data coverage for Basement rocks
Top: Coast Range ophiolite of Baily and Blake (1974), 160 Ma;
Sierra Nevada granite, 120 Ma;
470 picks, 470 wells
miles
0
25
NORTH
CENTRAL
SOUTH
A
A'
B
B'
C
C'
D
D'
DC
BC
E
MV
Pacific Ocean
38°
37°
36°
35°
-121°
-120°
-119°
3/8
5/9
7/14
10/9
11/19
14/12
15/23
16/14
16/20
20/19
22/15
22/23
25/22
25/28
28/19
31/27

Figure 5.4. Map of the geographic distribution of well locations in the well pick database for the San Joaquin Basin, California, that penetrate basement rocks (top of Coast Range ophiolite or Sierra Nevada granite). This and all subsequent figures illustrate well locations (filled blue circles), the San Joaquin Basin Province boundary (bold line), county boundaries (thin blue line), the boundaries between the north, central, and south subdivisions of the basin (thick gray line), township and range grid (thin gray line), geographic place-name locations (black triangles), and oil (green polygons) and gas (red polygons) fields in the basin. Select township-range labels provide location information, relative to the Mount Diablo base line (townships are south and ranges are east). See text for explanation of place-name abbreviations. Dashed lines labeled A-A′ and B-B′ mark transects along which ages for Sierran granite were obtained by Evernden and Kistler (1970); dashed lines labeled C-C′ and D-D′ denote similar analyses by Chen and Moore (1982). MV, Mountain View oil field; E, Edison oil field; BC, Bitterwater Canyon; DC, Del Puerto Canyon.

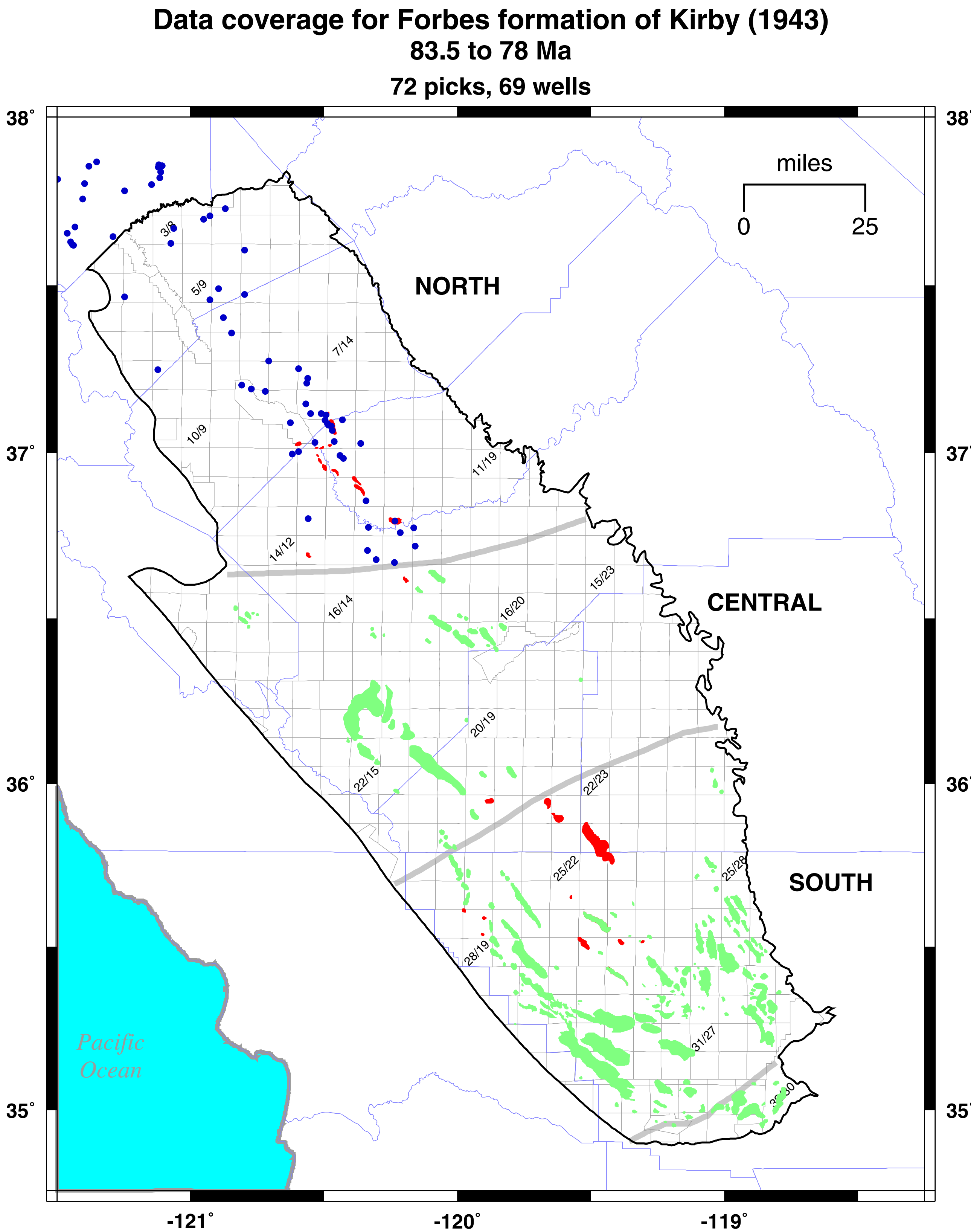


Figure 5.5. Same as figure 5.4, but for the Forbes formation of Kirby (1943).

Data coverage for Sacramento shale of Callaway (1964)

78 to 77 Ma

78 picks, 77 wells

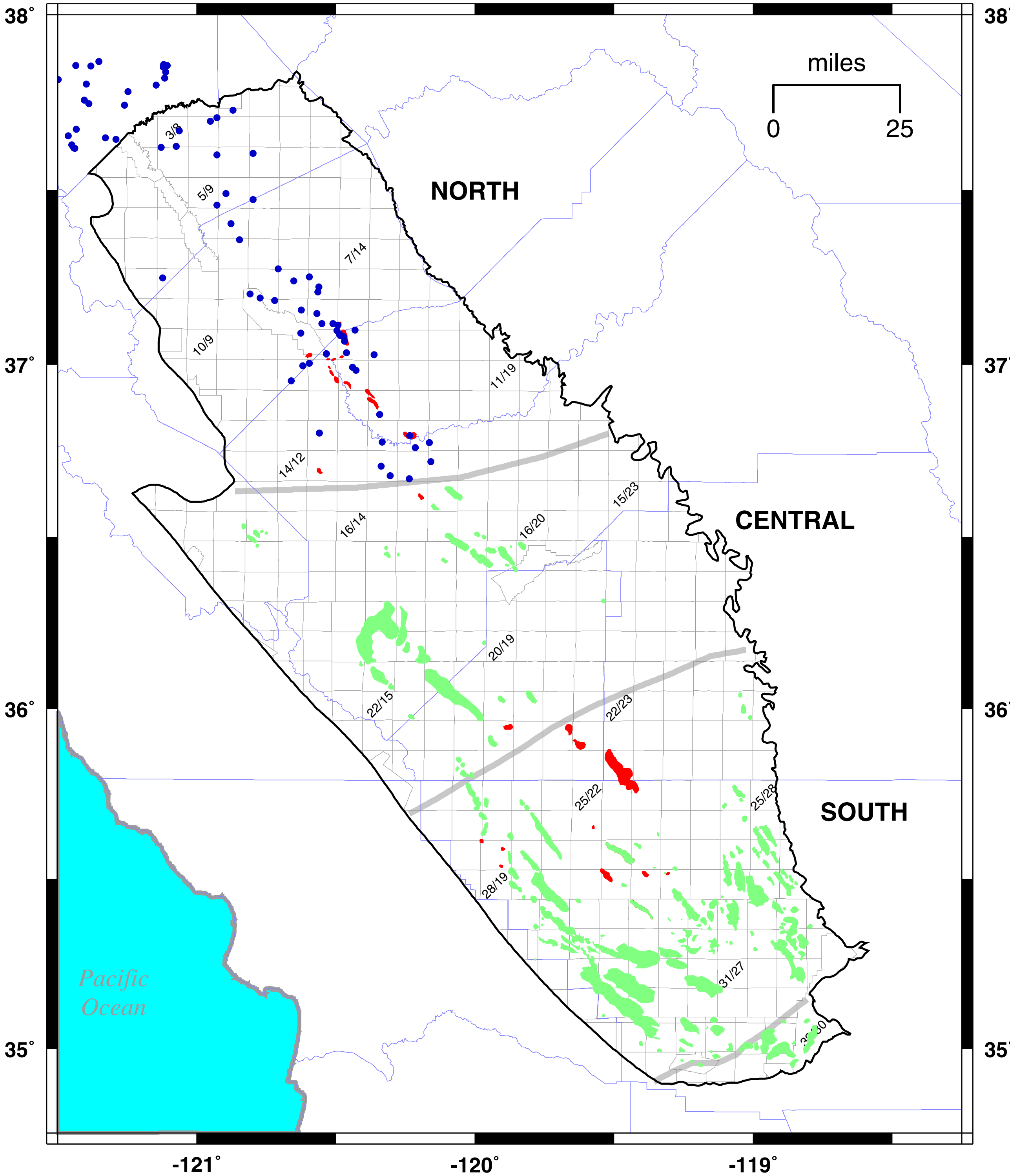


Figure 5.6. Same as figure 5.4, but for the Sacramento shale of Callaway (1964).

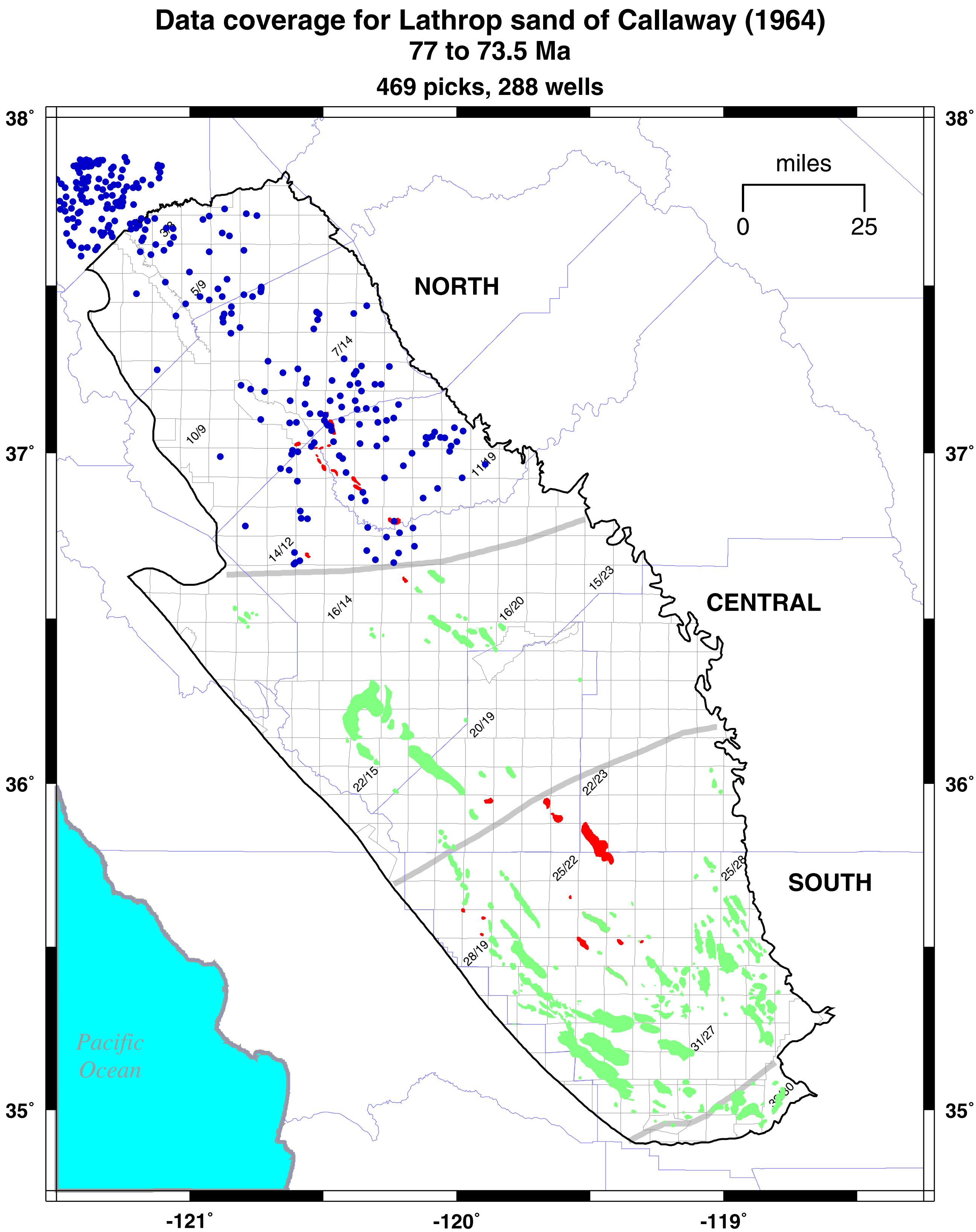


Figure 5.7. Same as figure 5.4, but for the Lathrop sand of Callaway (1964).

Data coverage for Joaquin Ridge Sandstone Member of Panoche Formation
77 to 73.5 Ma
14 picks, 14 wells

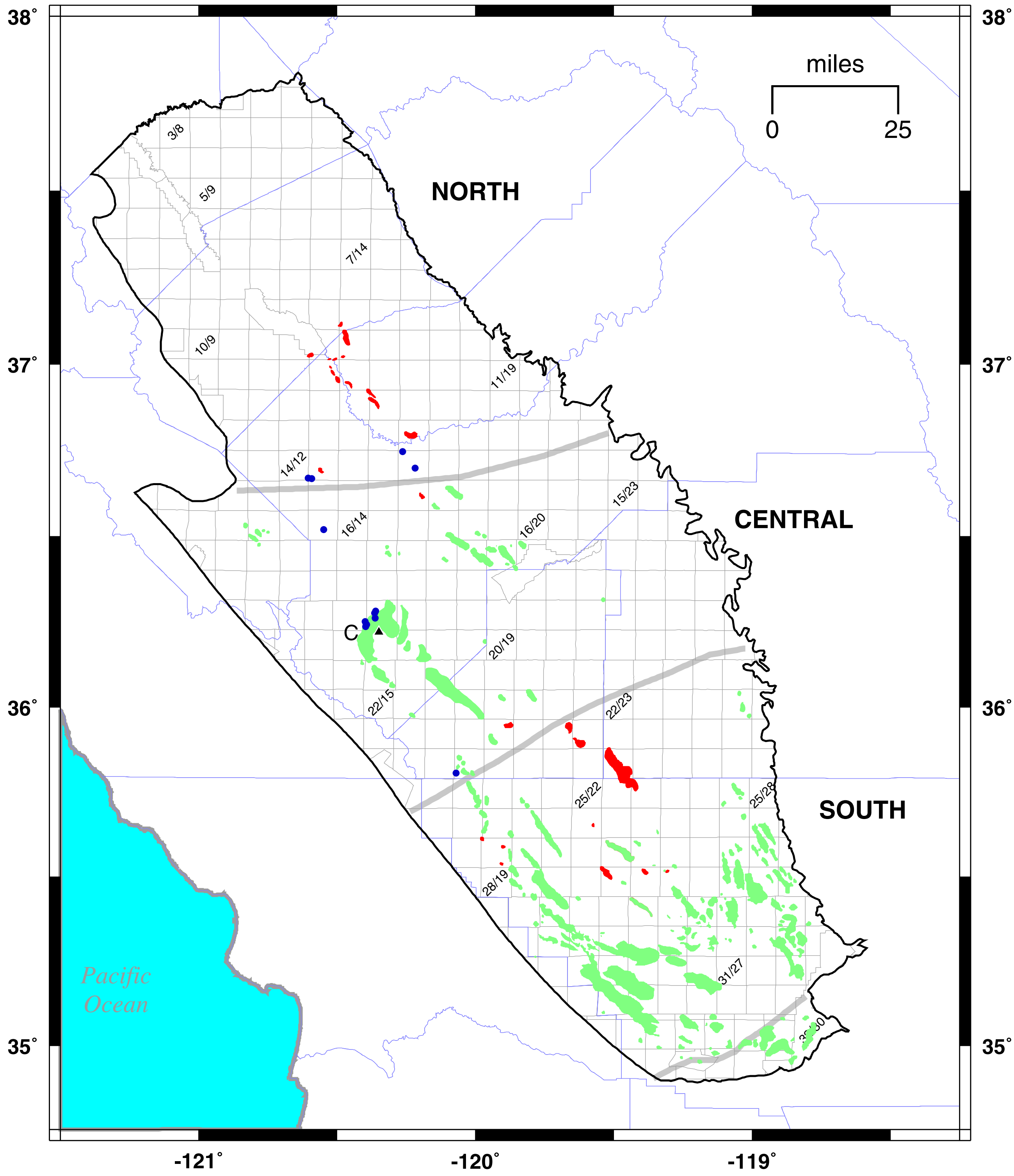


Figure 5.8. Same as figure 5.4, but for the Joaquin Ridge Sandstone Member of the Panoche Formation. This unit is time-correlative with the Lathrop sand in the northern San Joaquin Basin. C, Coalinga oil field.

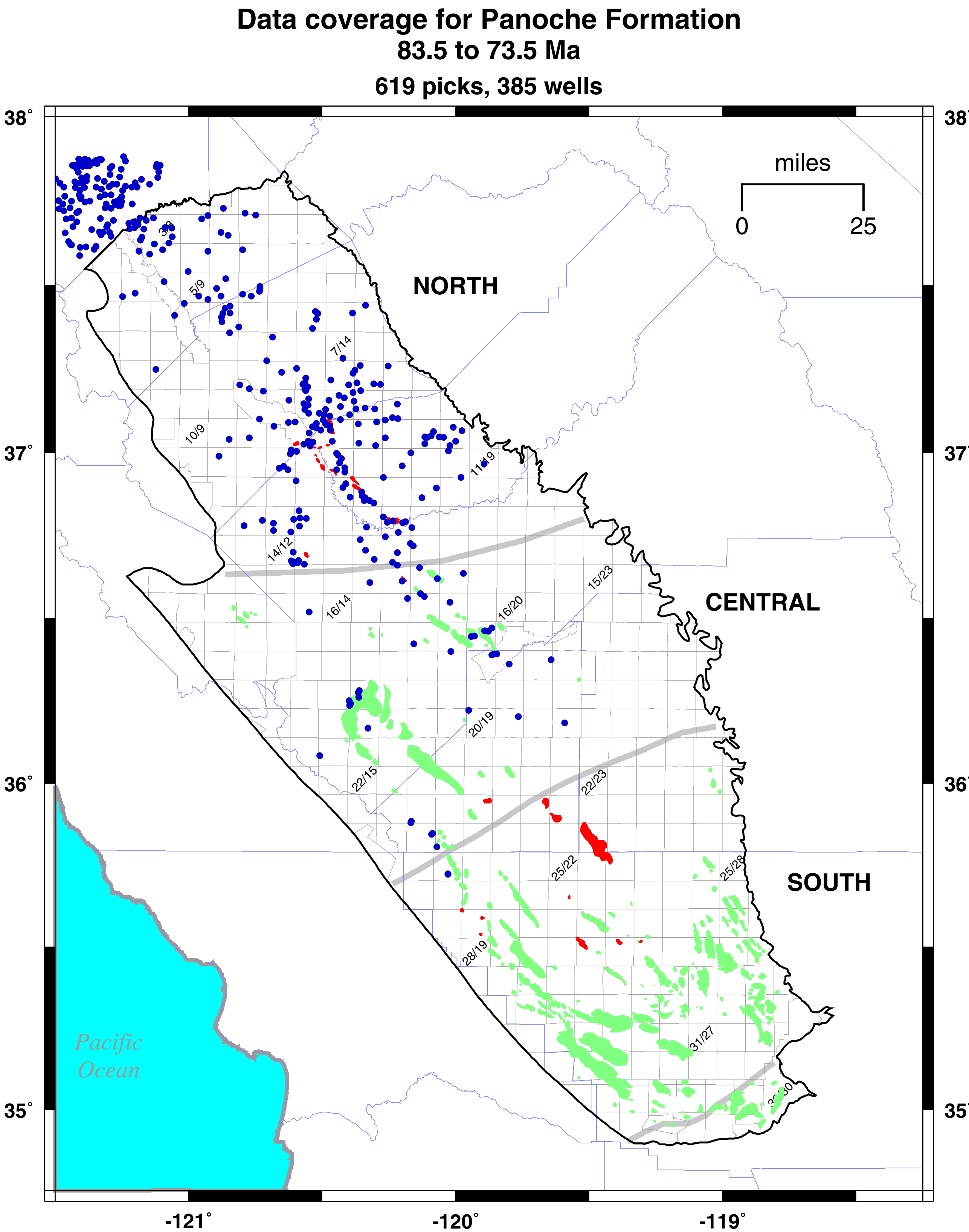


Figure 5.9. Same as figure 5.4, but for the Panoche Formation.

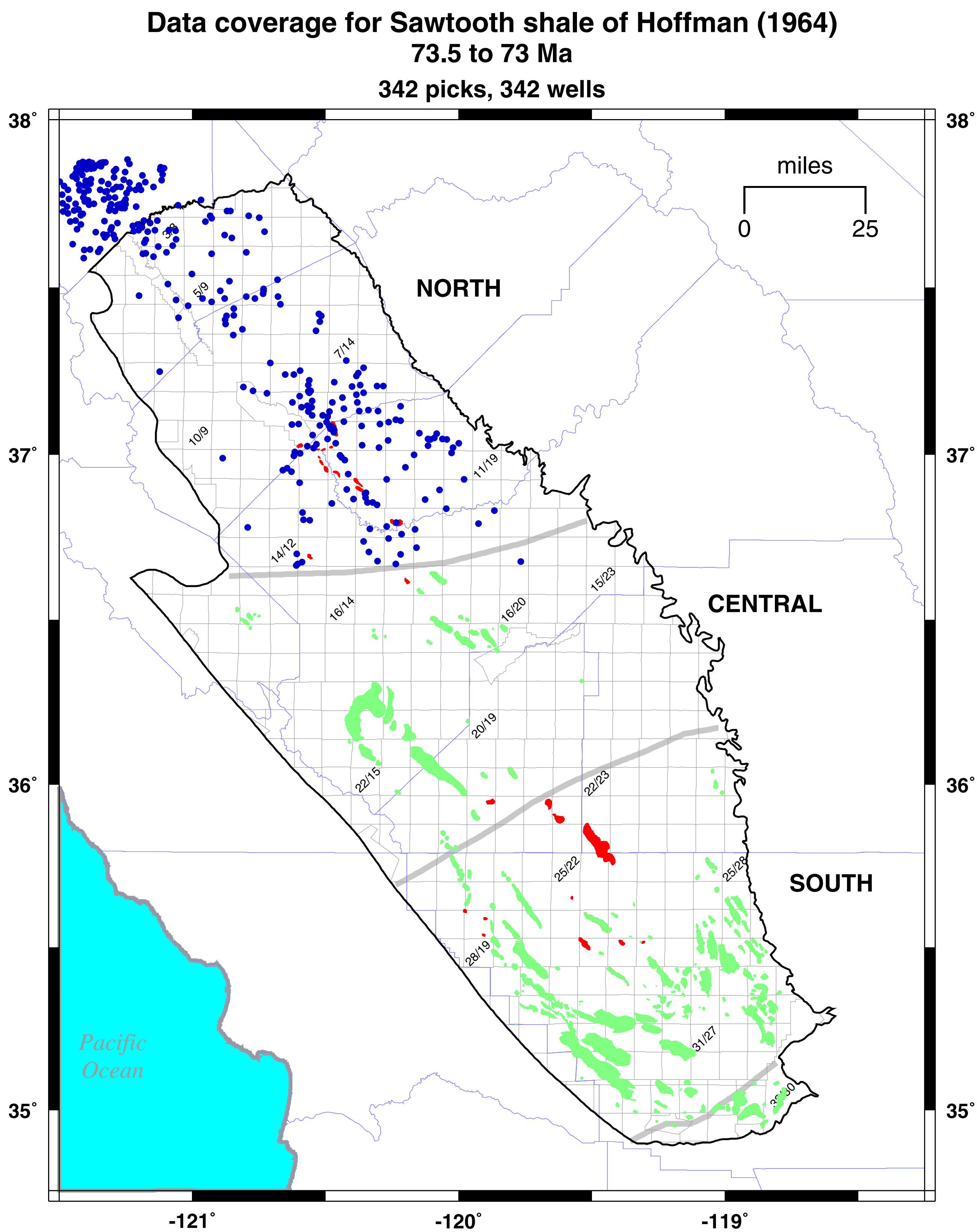


Figure 5.10. Same as figure 5.4, but for the Sawtooth shale of Hoffman (1964).

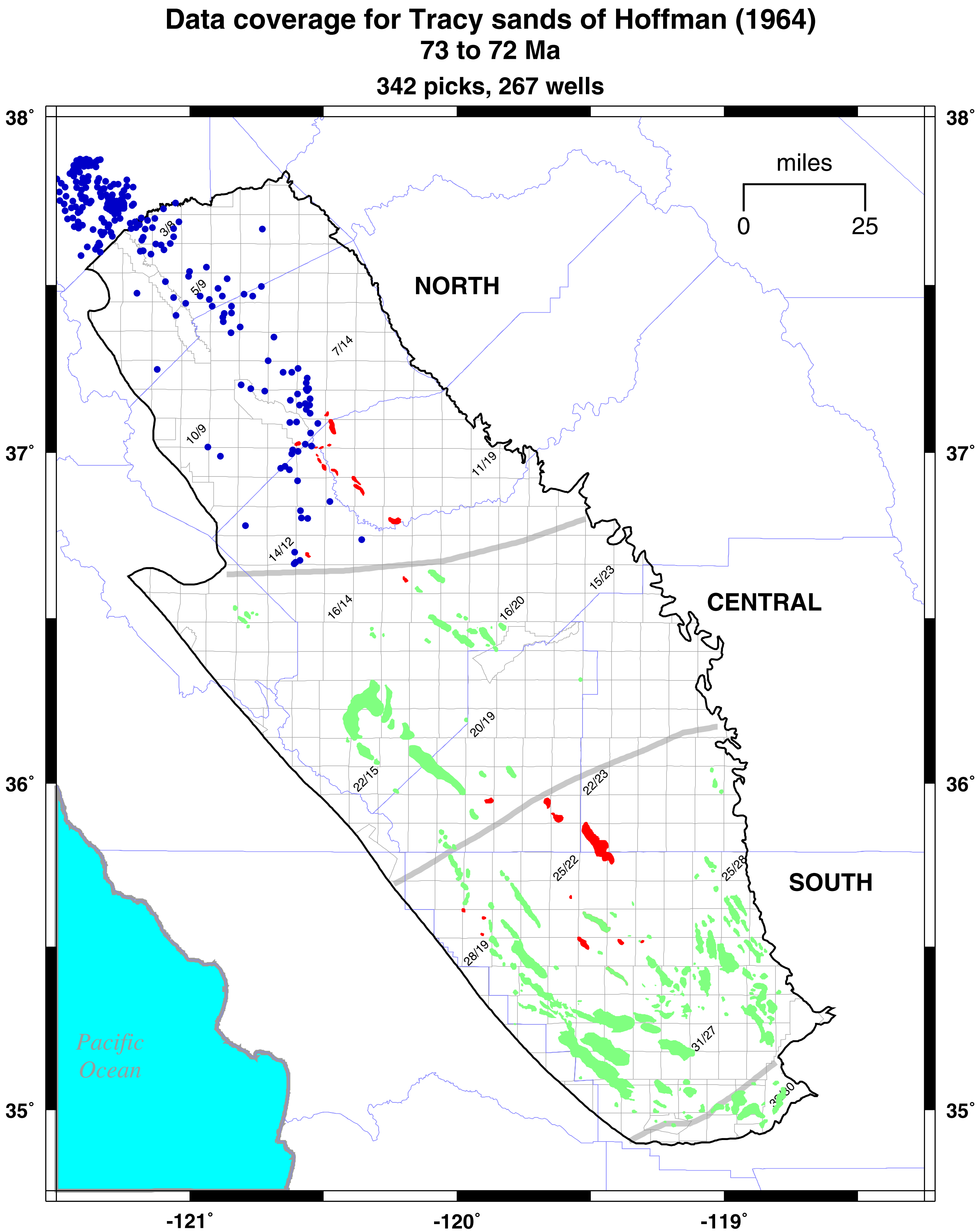


Figure 5.11. Same as figure 5.4, but for the Tracy sands of Hoffman (1964).

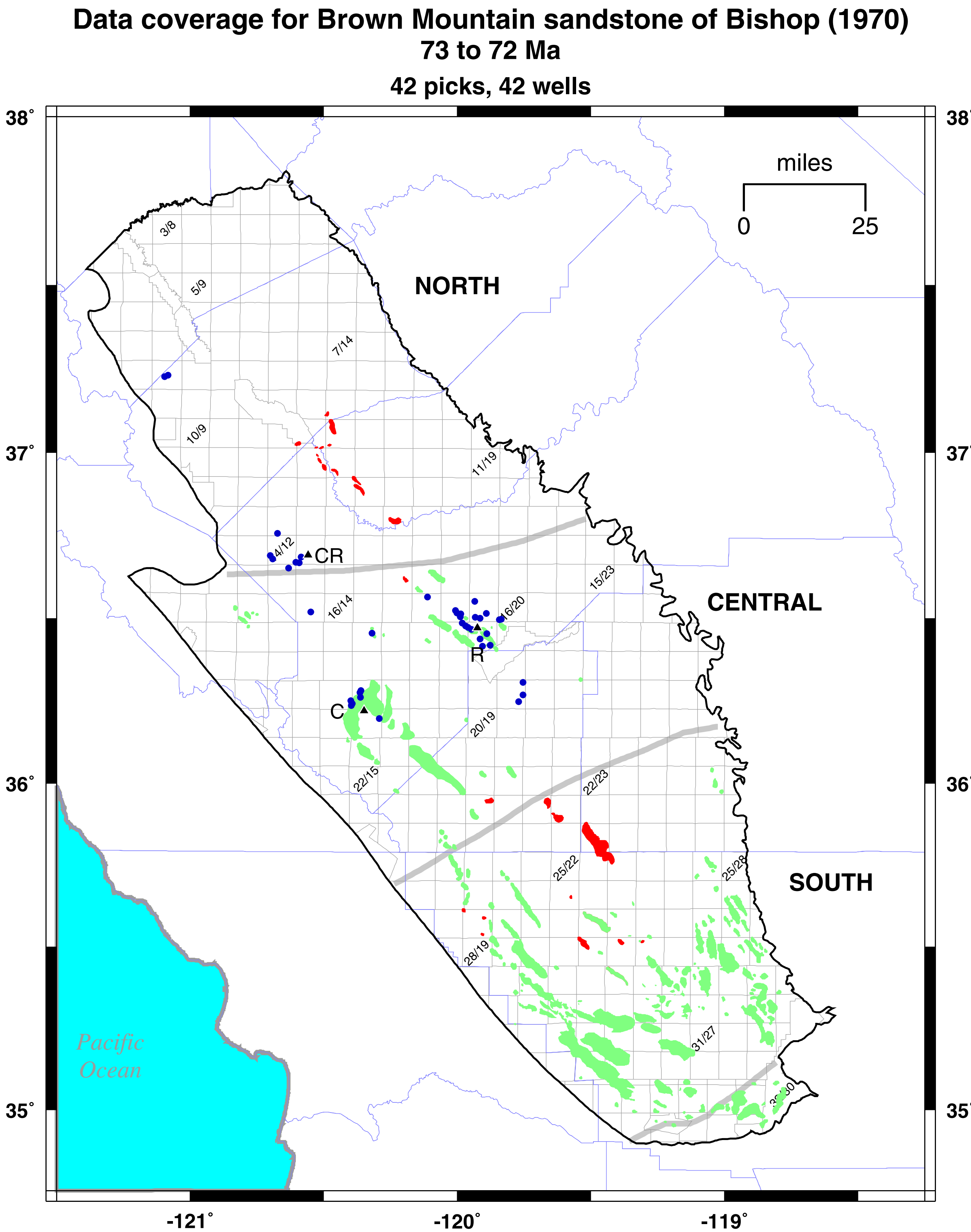


Figure 5.12. Same as figure 5.4, but for the Brown Mountain sandstone of Bishop (1970). This unit is time-correlative with the Tracy sands in the northern San Joaquin Basin. C, Coalinga oil field; R, Riverdale oil field; CR, Cheney Ranch oil field.

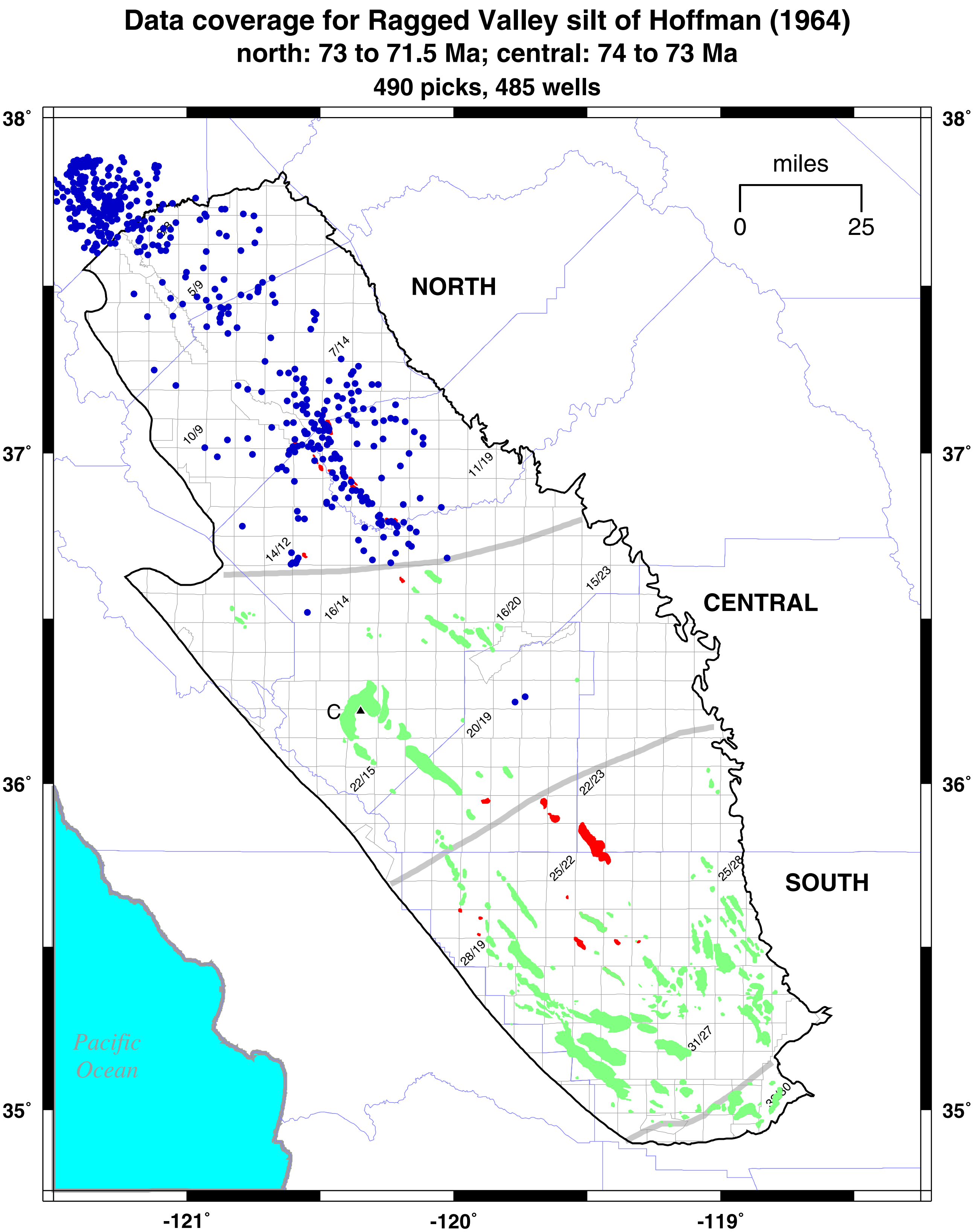


Figure 5.13. Same as figure 5.4, but for the Ragged Valley silt of Hoffman (1964). C, Coalinga oil field.

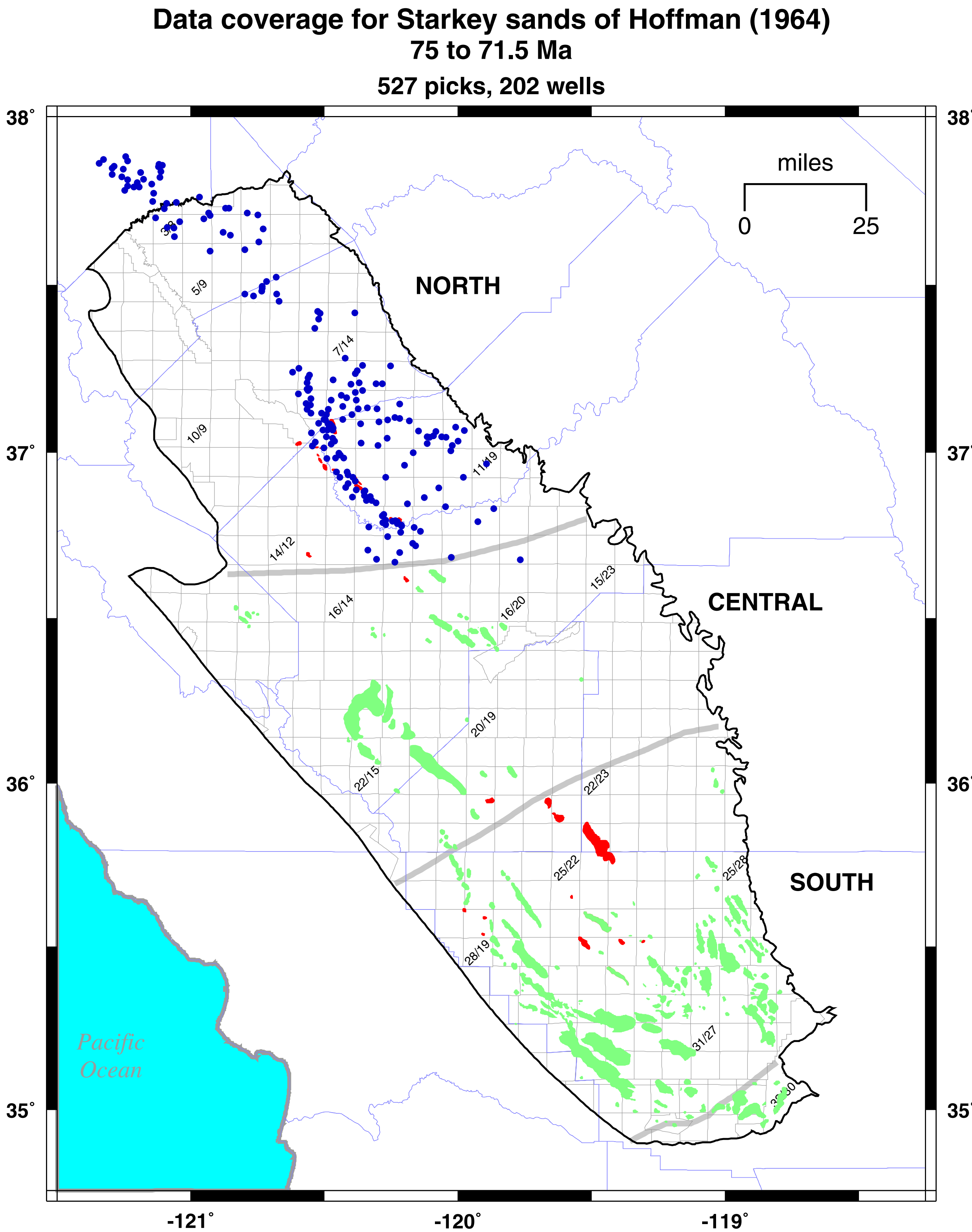


Figure 5.14. Same as figure 5.4, but for the Starkey sands of Hoffman (1964).

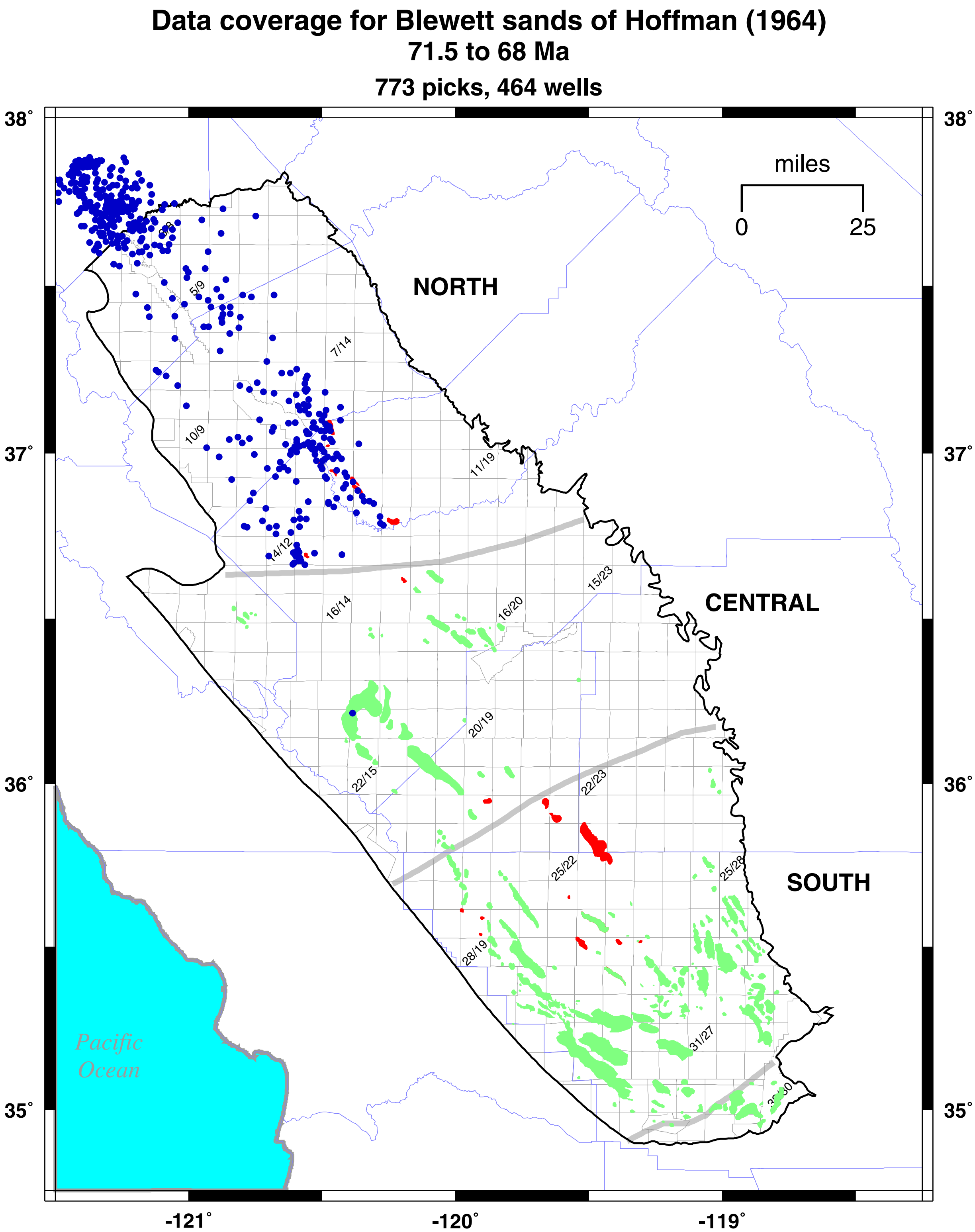


Figure 5.15. Same as figure 5.4, but for the Blewett sands of Hoffman (1964).

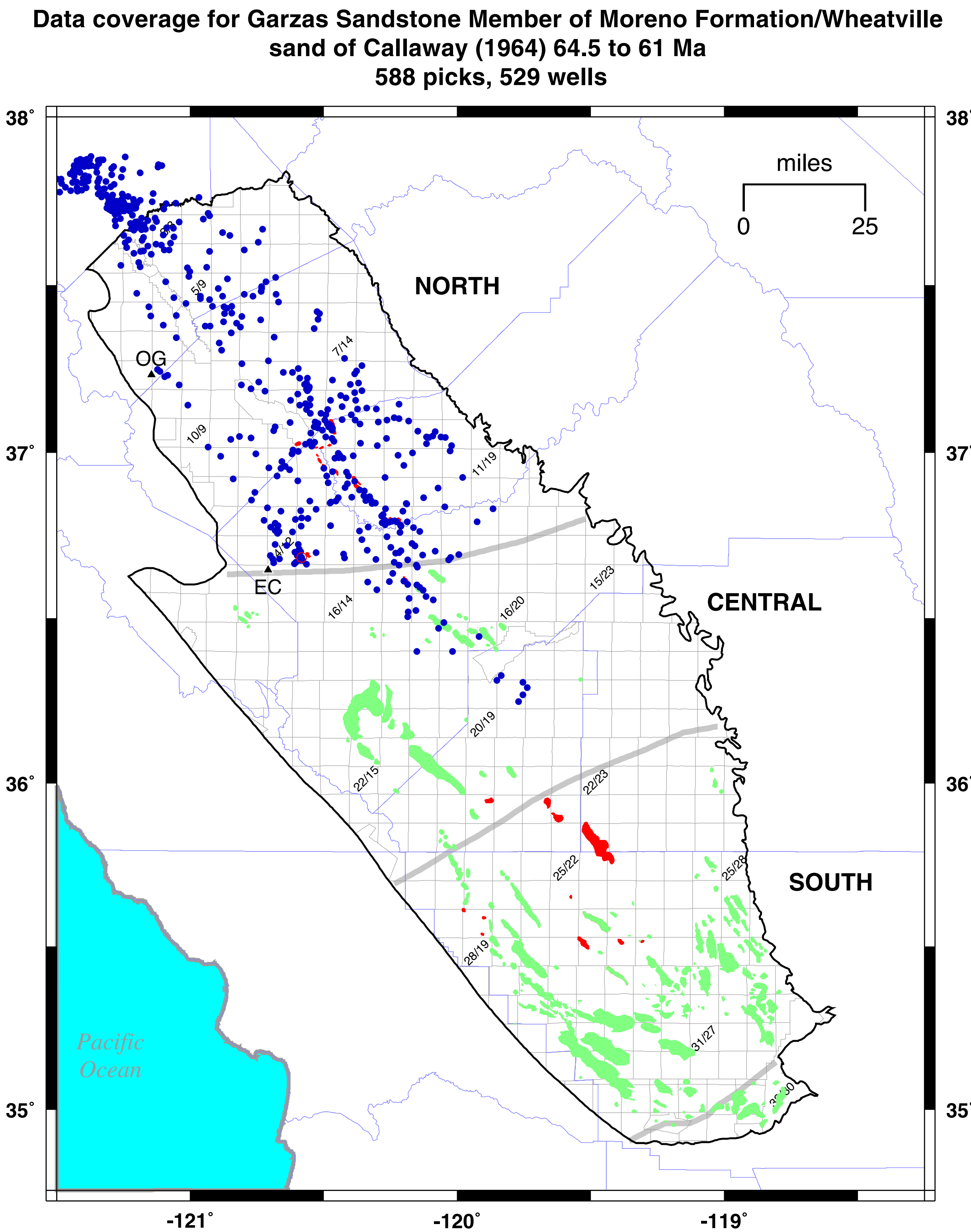


Figure 5.16. Same as figure 5.4, but for the Garzas Sandstone Member of the Moreno Formation and Wheatville sand of Callaway (1964). OG, Oat Gulch; EC, Escarpado Canyon. Open red circle denotes location of Cheney Ranch 1 well (API number 01900190).

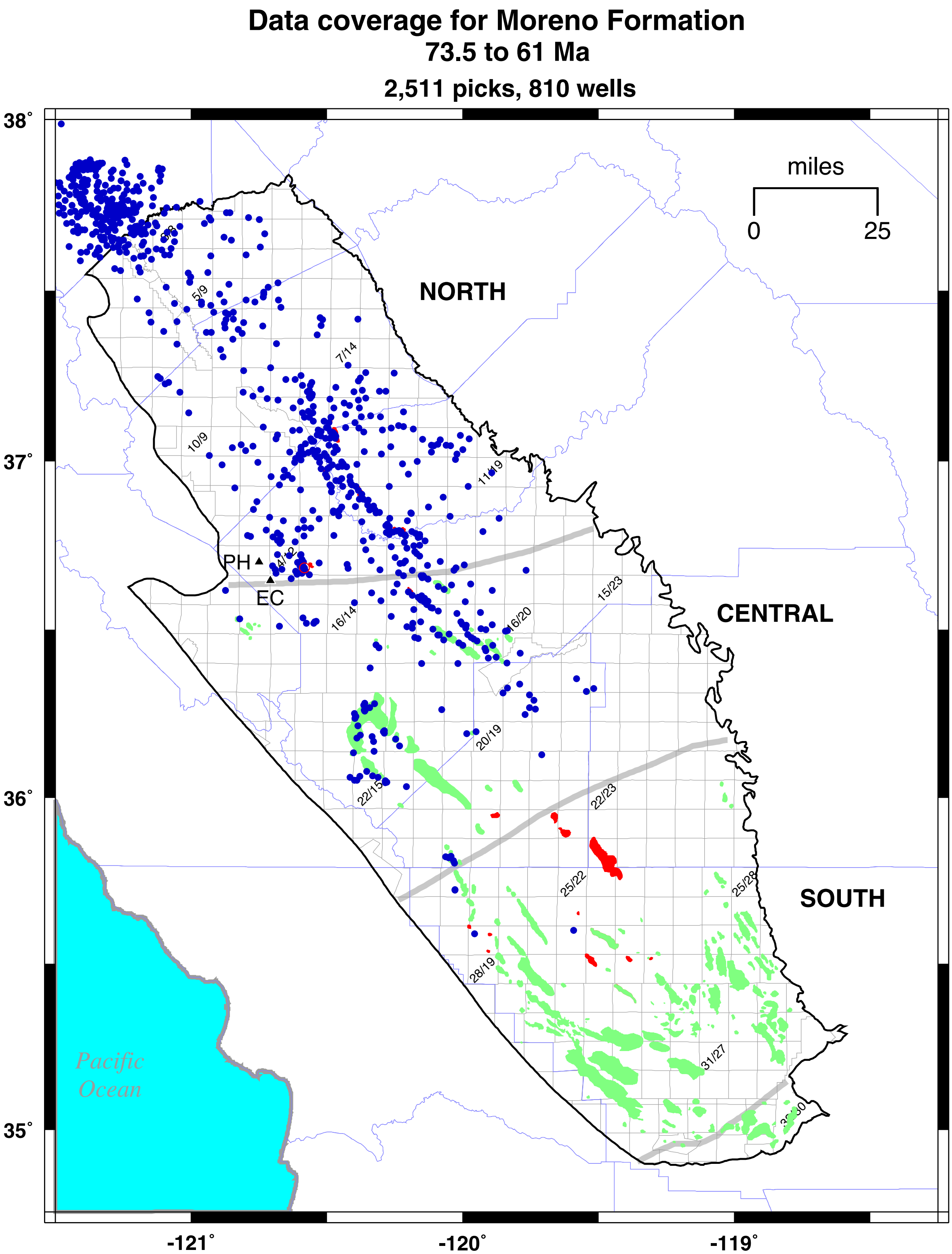


Figure 5.17. Same as figure 5.4, but for the Moreno Formation. EC, Escarpado Canyon; PH, Panoche Hills. Open red circle denotes location of Cheney Ranch 1 well (API number 01900190).

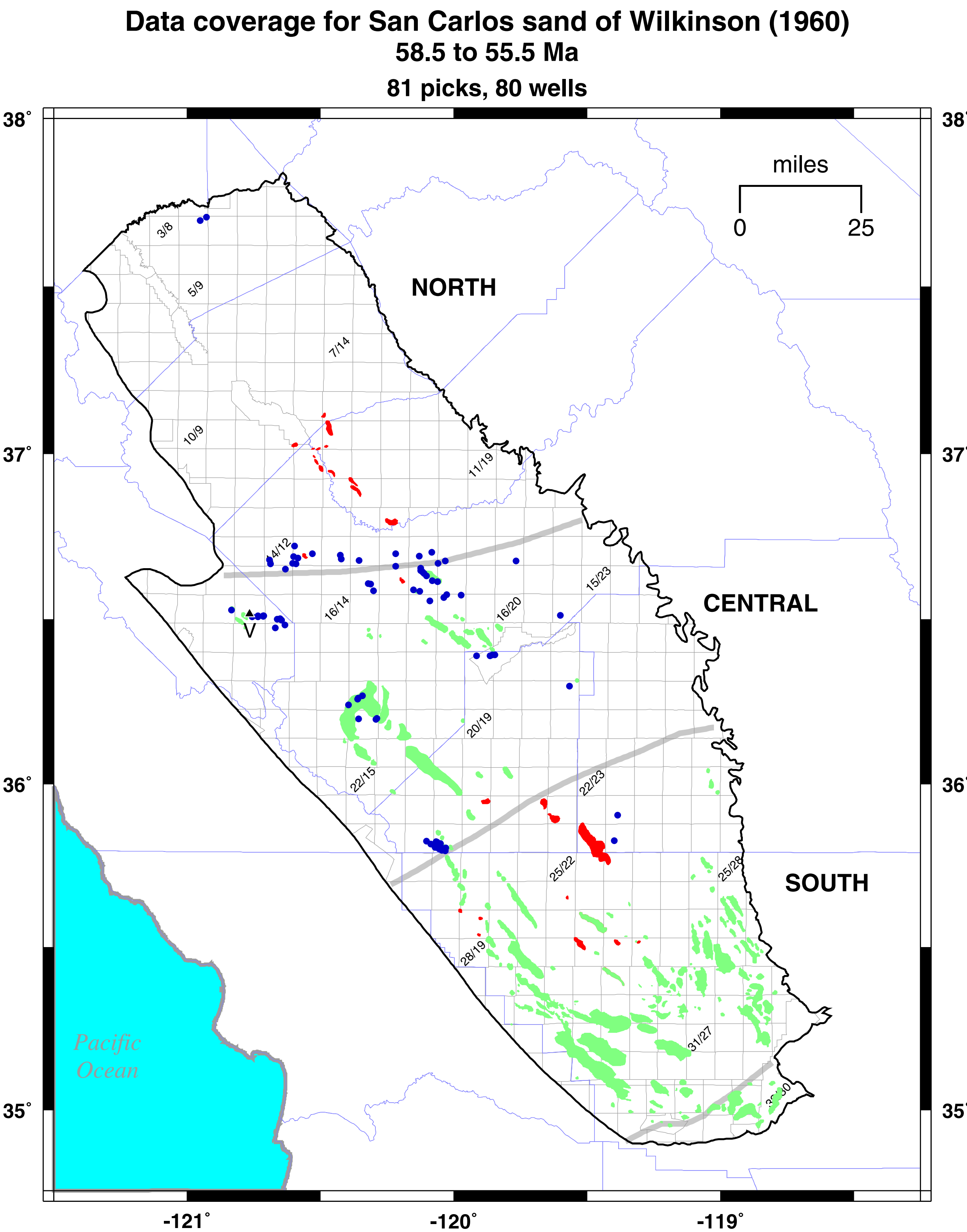


Figure 5.18. Same as figure 5.4, but for the San Carlos sand of Wilkinson (1960). V, Vallecitos oil field.

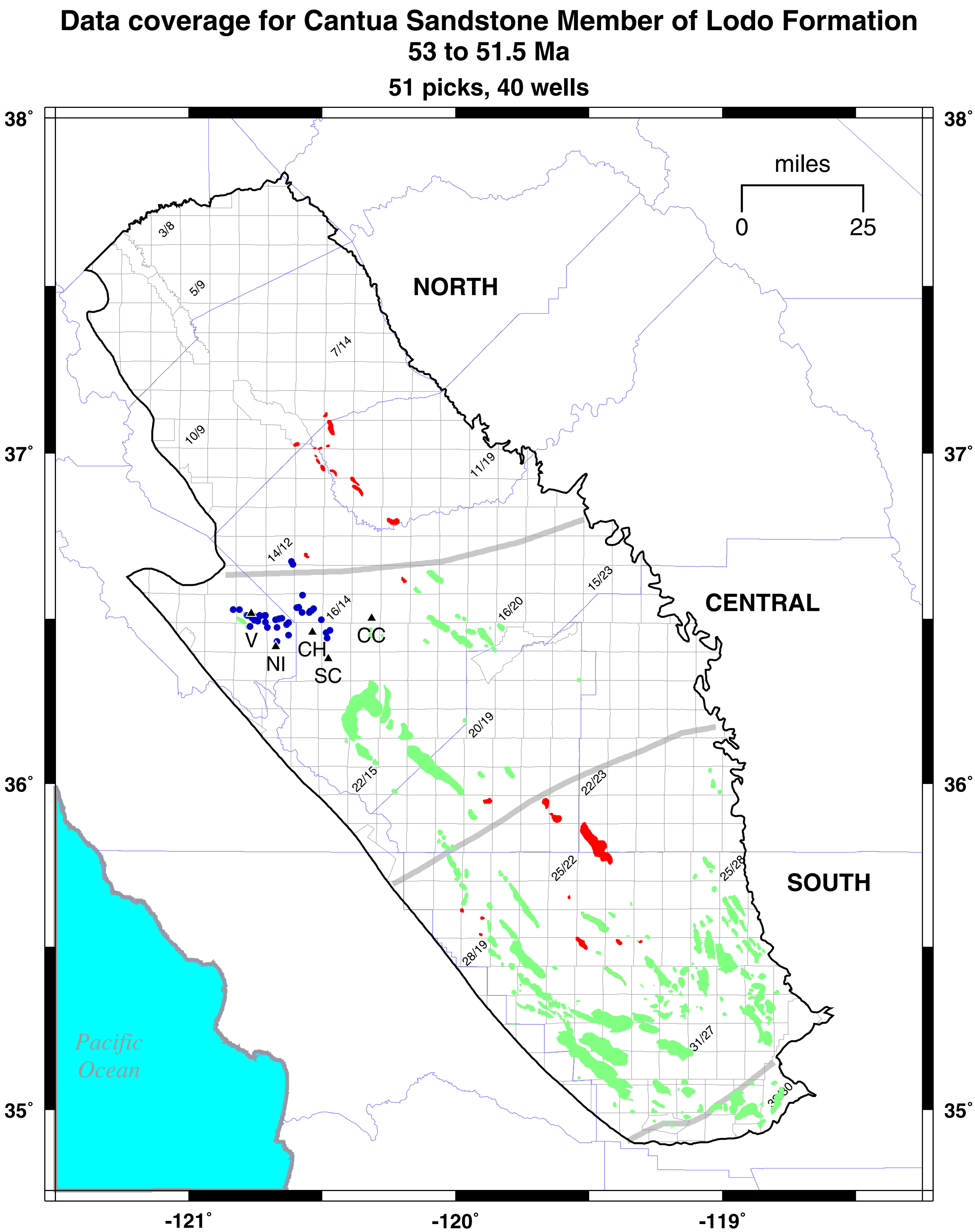


Figure 5.19. Same as figure 5.4, but for the Cantua Sandstone Member of the Lodo Formation. V, Vallecitos oil field; SC, Salt Creek; CC, Cantua Creek; CH, Ciervo Hills; NI, New Idria.

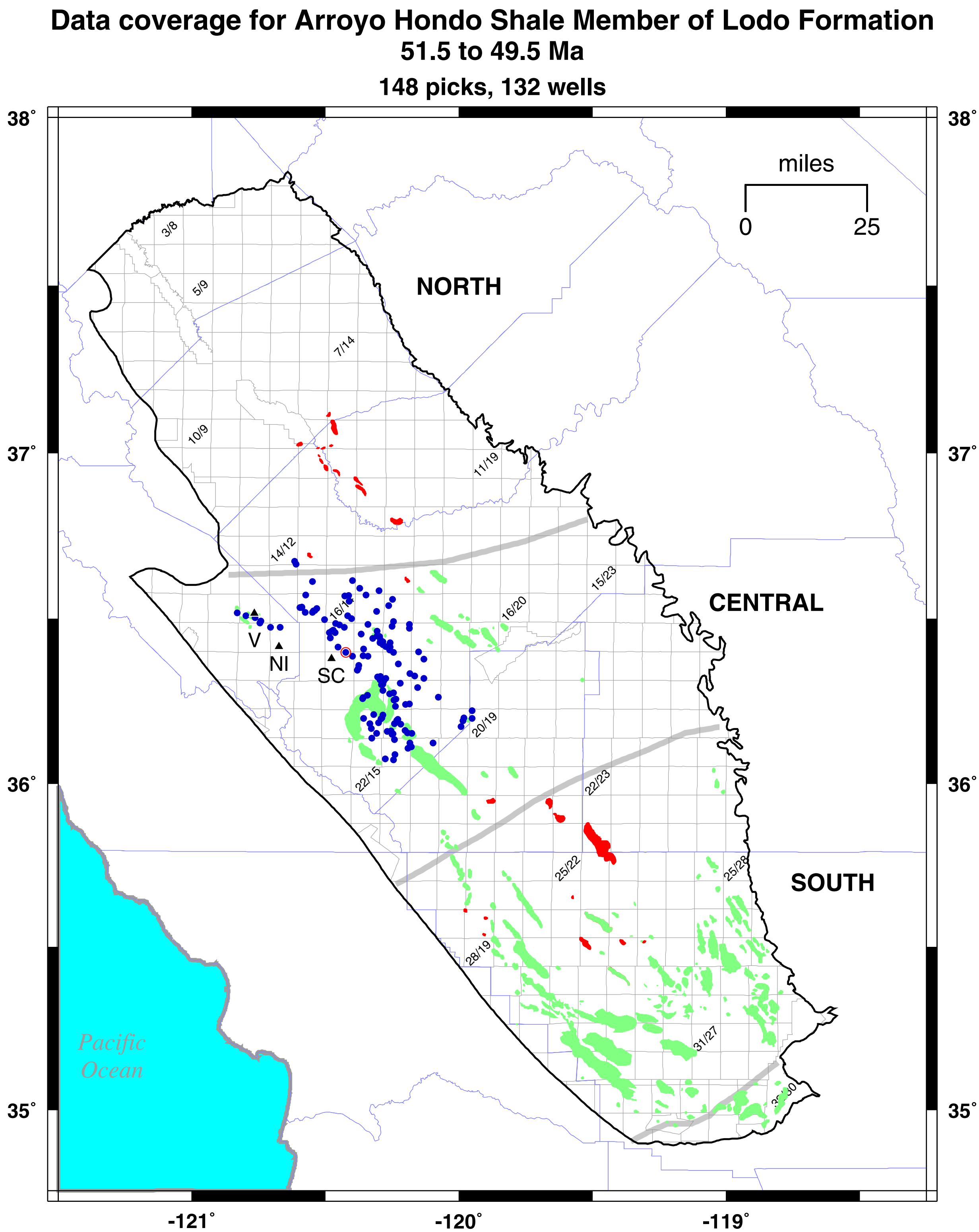


Figure 5.20. Same as figure 5.4, but for the Arroyo Hondo Shale Member of the Lodo Formation. SC, Salt Creek; NI, New Idria; V, Vallecitos oil field. Open red circle denotes location of Shell Core Hole 2 (API number 01906246).

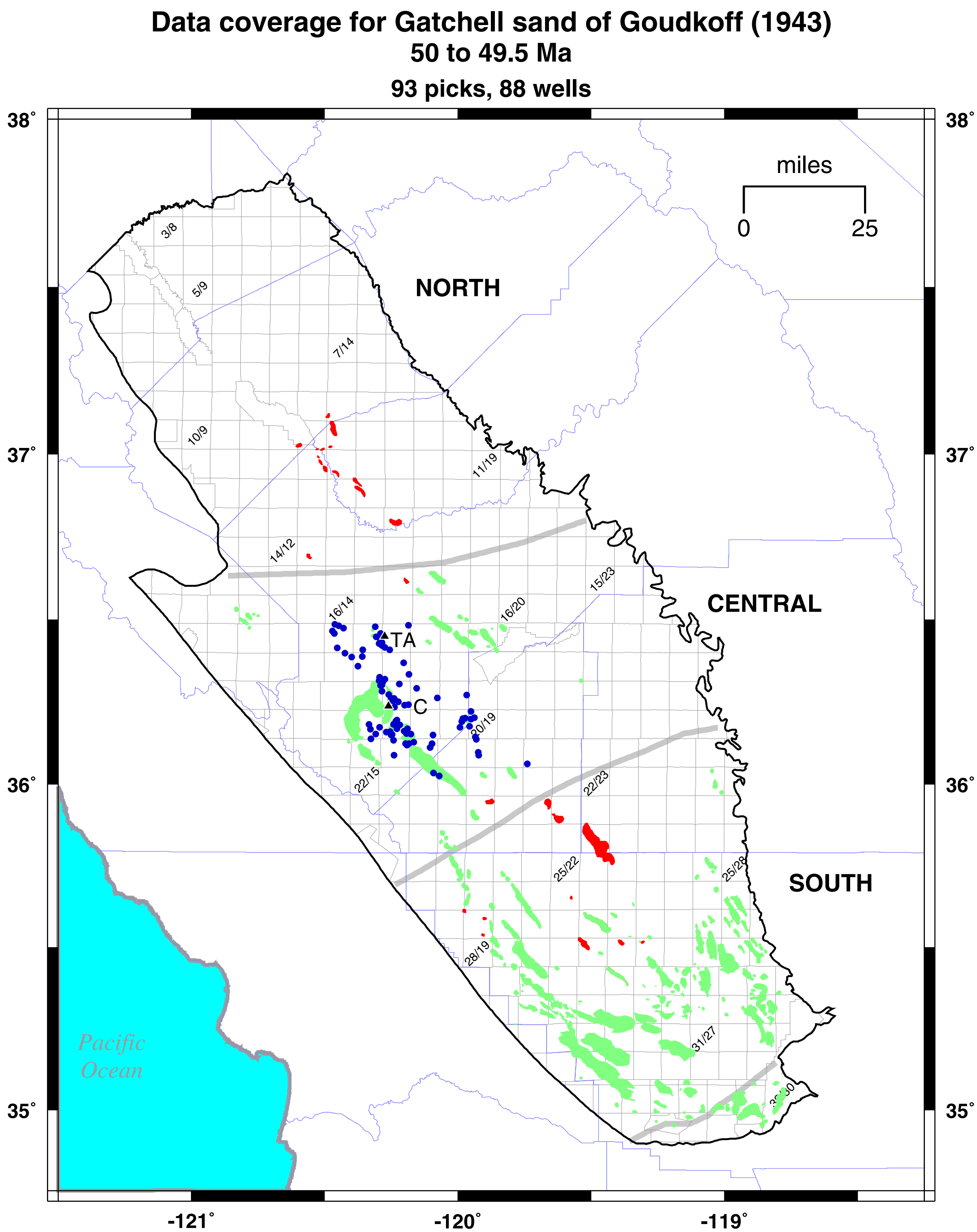


Figure 5.21. Same as figure 5.4, but for the Gatchell sand of Goudkoff (1943). C, Coalinga oil field; TA, Turk Anticline oil field.

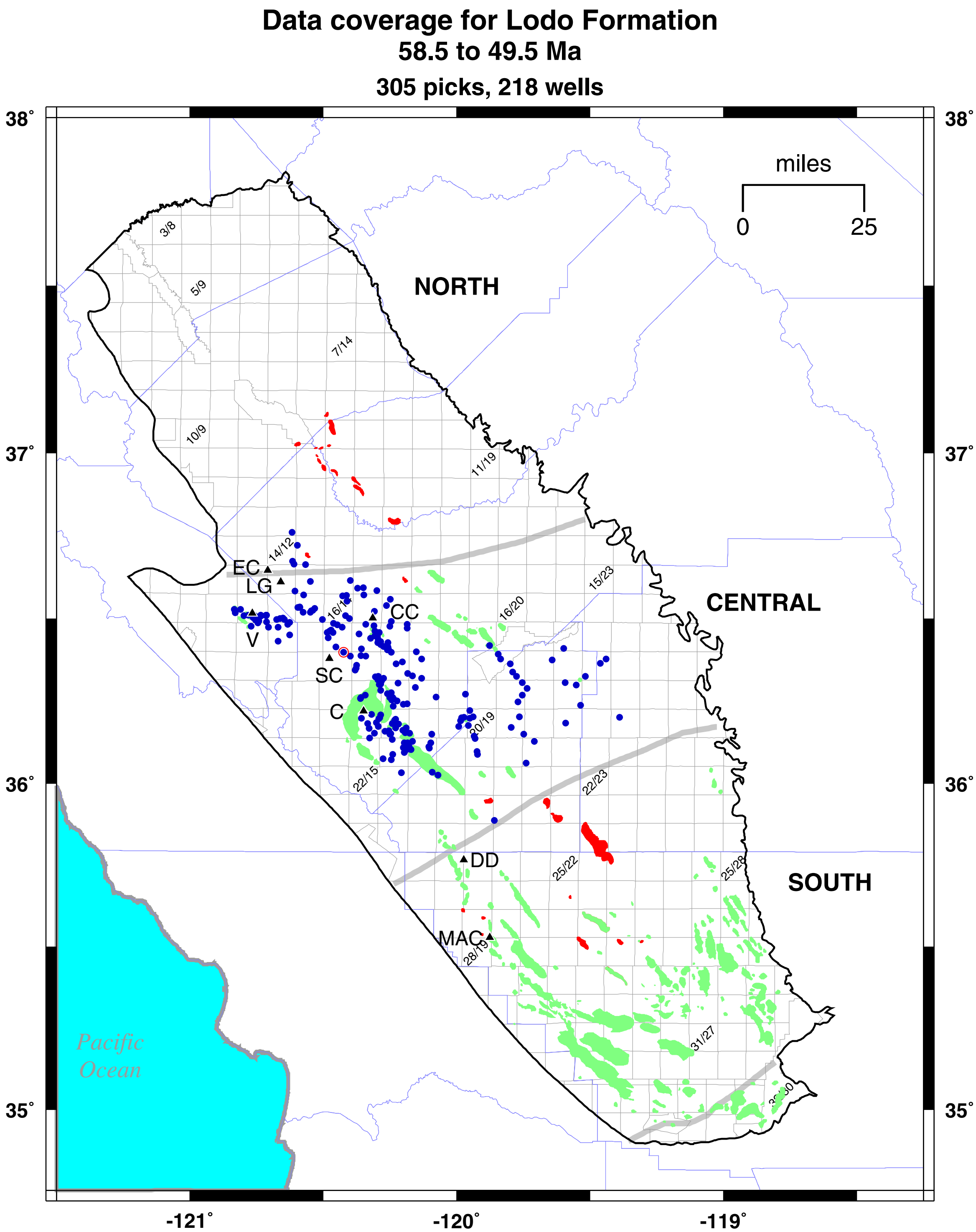


Figure 5.22. Same as figure 5.4, but for the Lodo Formation. EC, Escarpado Canyon; LG, Lodo Gulch; V, Vallecitos oil field; CC, Cantua Creek; C, Coalinga oil field; SC, Salt Creek; MAC, Media Agua Creek; DD, Devils Den. Open red circle denotes location of Shell Core Hole 2 (API number 01906246).

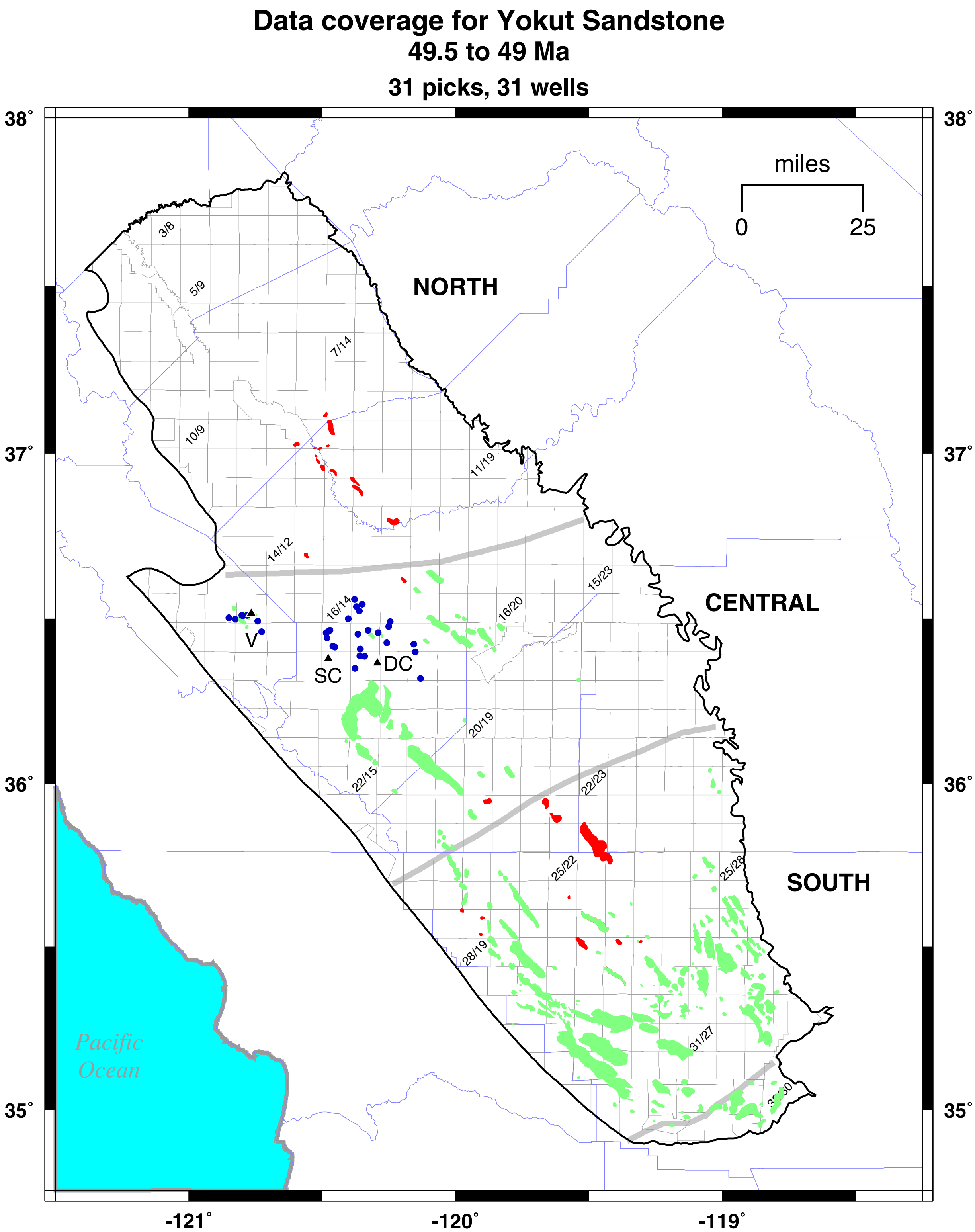


Figure 5.23. Same as figure 5.4, but for the Yokut Sandstone. V, Vallecitos oil field; DC, Domengine Creek; SC, Salt Creek.

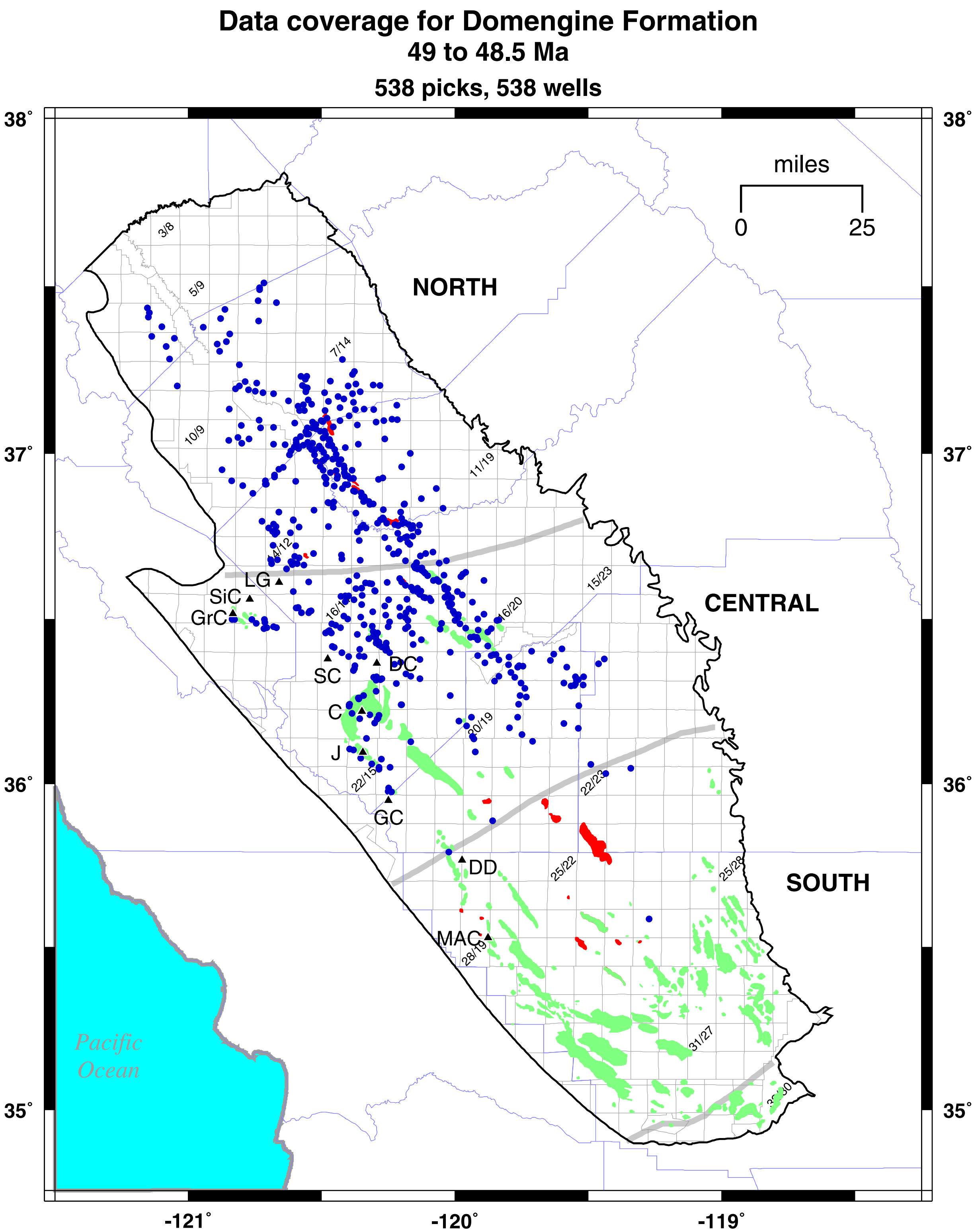


Figure 5.24. Same as figure 5.4, but for the Domengine Formation. J, Jacalitos oil field; GC, Garzas Creek; LG, Lodo Gulch; C, Coalinga oil field; SC, Salt Creek; SiC, Silver Creek; GrC, Griswold Canyon; DC, Domengine Creek; MAC, Media Agua Creek; DD, Devils Den.

Data coverage for Canoas Siltstone Member of Kreyenhagen Formation
48.5 to 45.5 Ma
38 picks, 38 wells

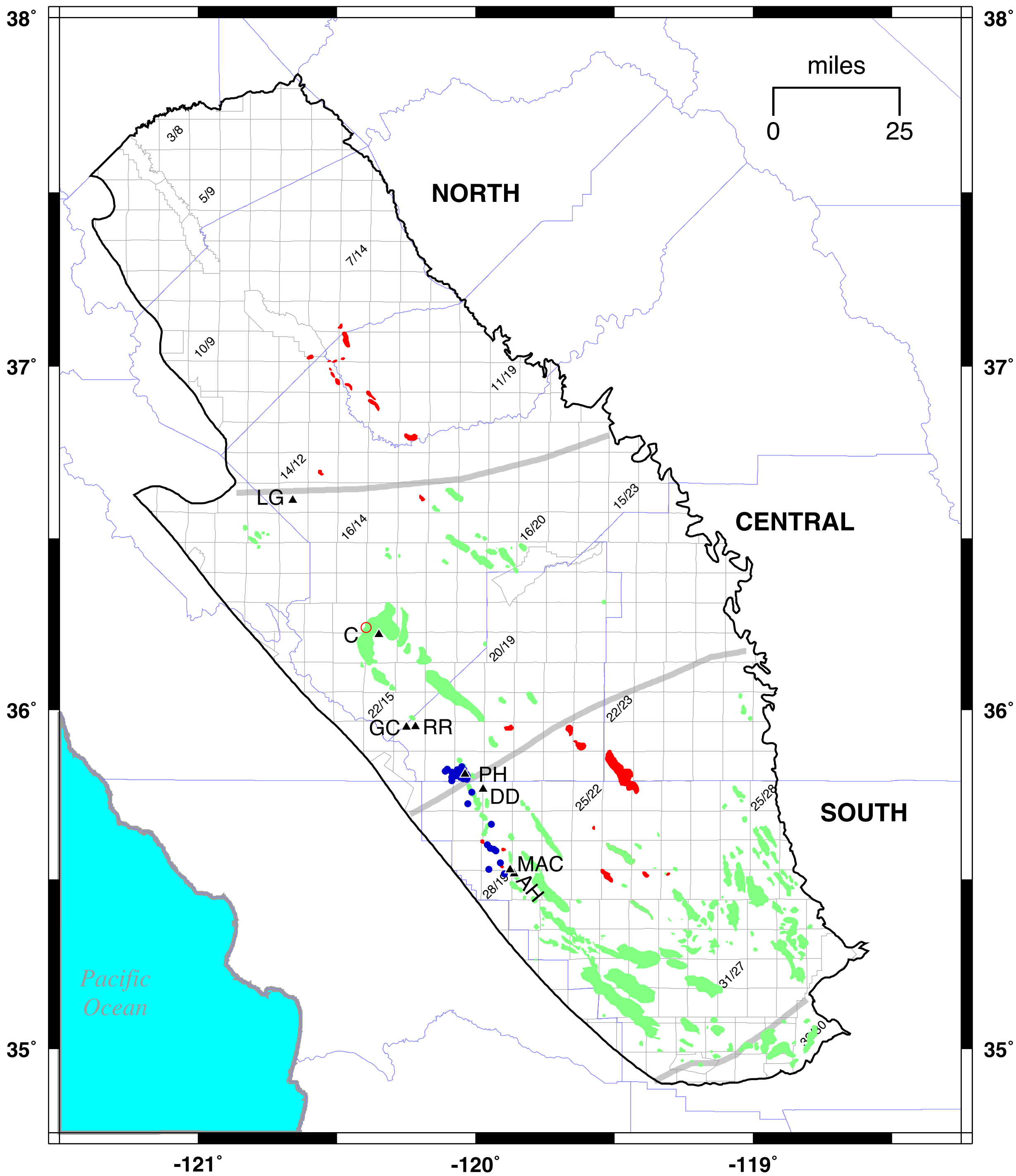


Figure 5.25. Same as figure 5.4, but for the Canoas Siltstone Member of the Kreyenhagen Formation. AH, Antelope Hills oil field; PH, Pyramid Hills oil field; RR, Reef Ridge; GC, Garzas Creek; DD, Devils Den; MAC, Media Agua Creek; LG, Lodo Gulch; C, Coalinga oil field. Open red circle denotes location of North Coalinga Oil Company 1 well (API number 01900437).

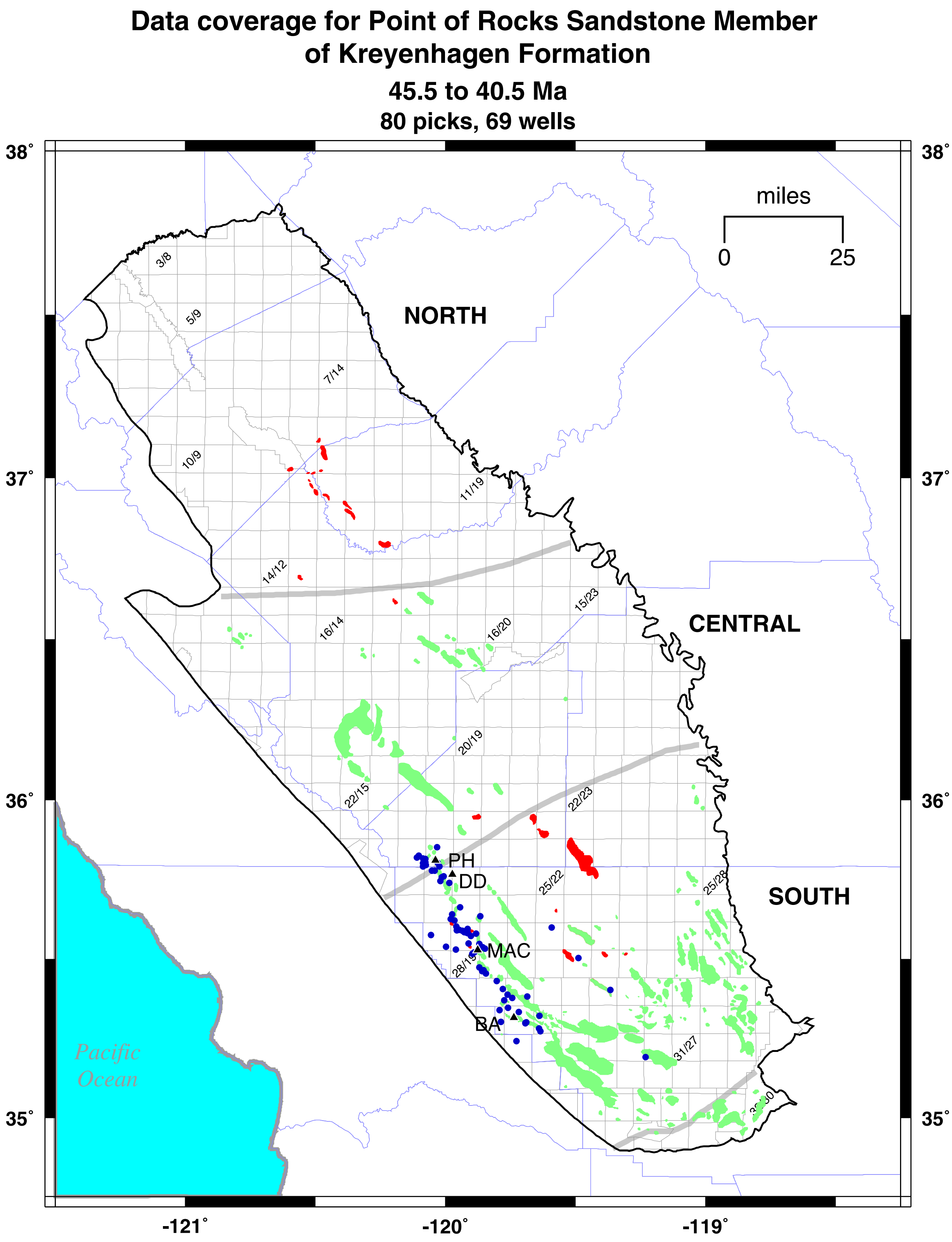


Figure 5.26. Same as figure 5.4, but for the Point of Rocks Sandstone Member of the Kreyenhagen Formation. BA, Belgian Anticline oil field; PH, Pyramid Hills oil field; DD, Devils Den; MAC, Media Agua Creek.

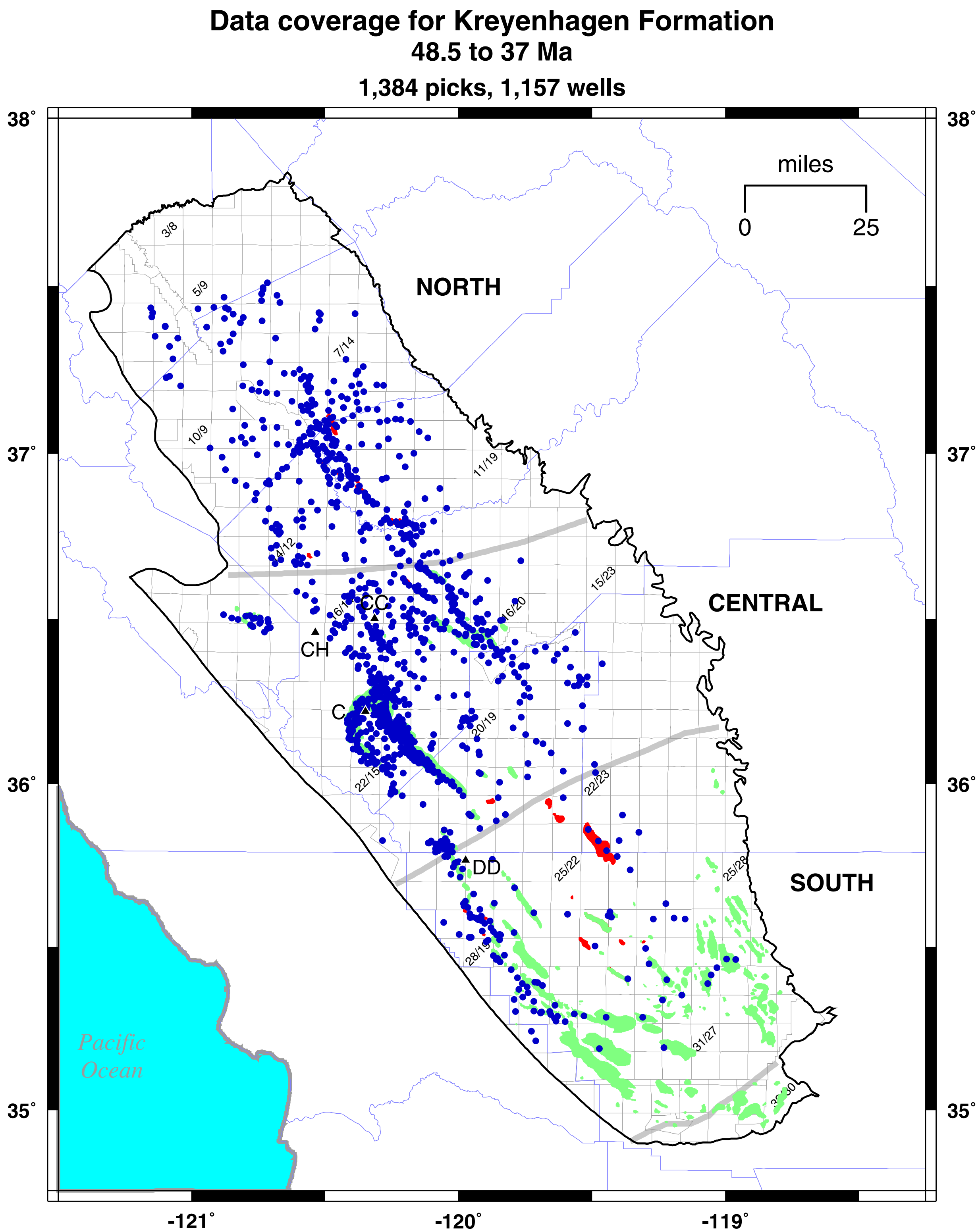


Figure 5.27. Same as figure 5.4, but for the Kreyenhagen Formation. DD, Devils Den; C, Coalinga oil field; CC, Cantua Creek; CH, Ciervo Hills.

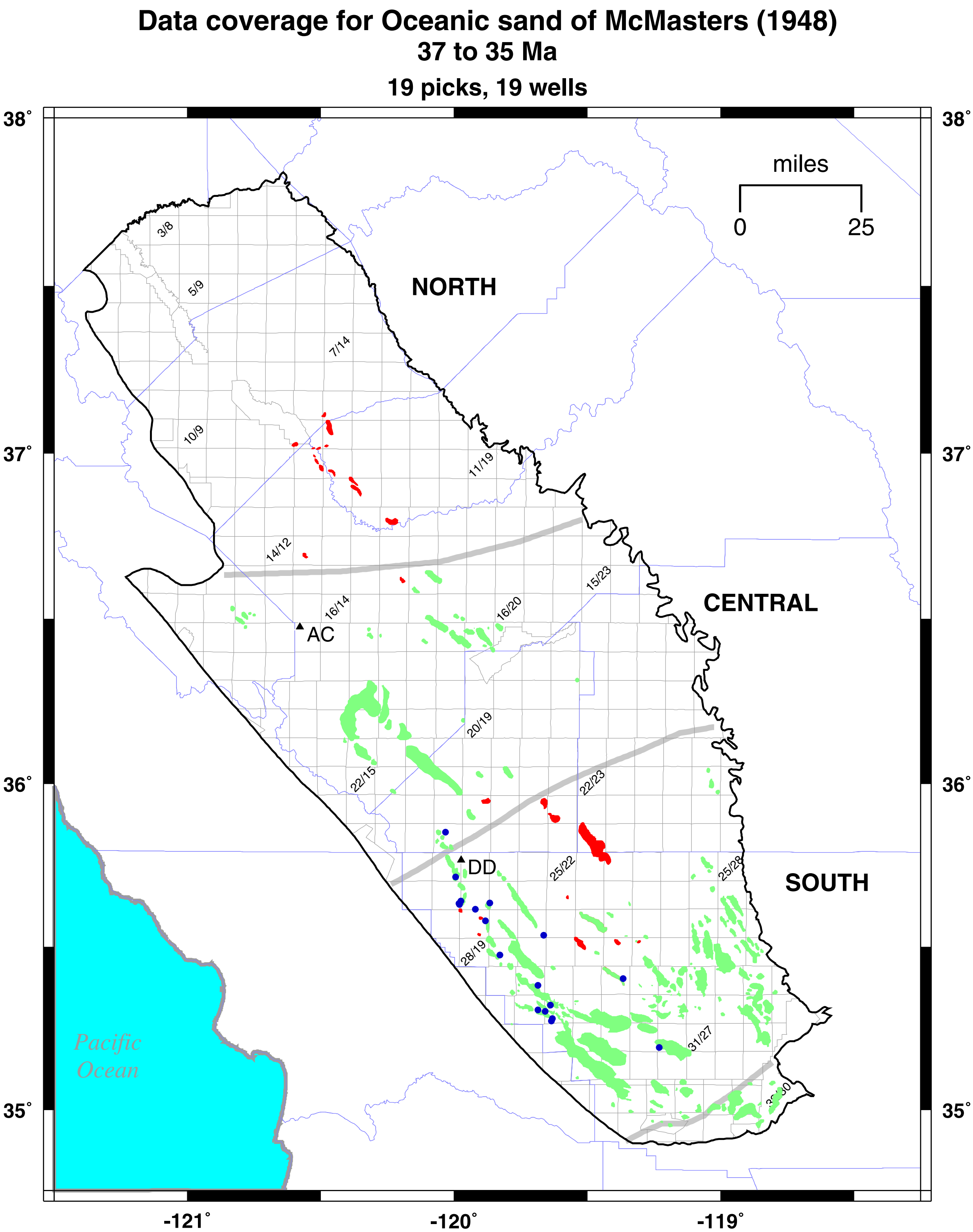


Figure 5.28. Same as figure 5.4, but for the Oceanic sand of McMasters (1948). This is the basal sand of the Tumey formation of Atwill (1935). AC, Arroyo Ciervo; DD, Devils Den.

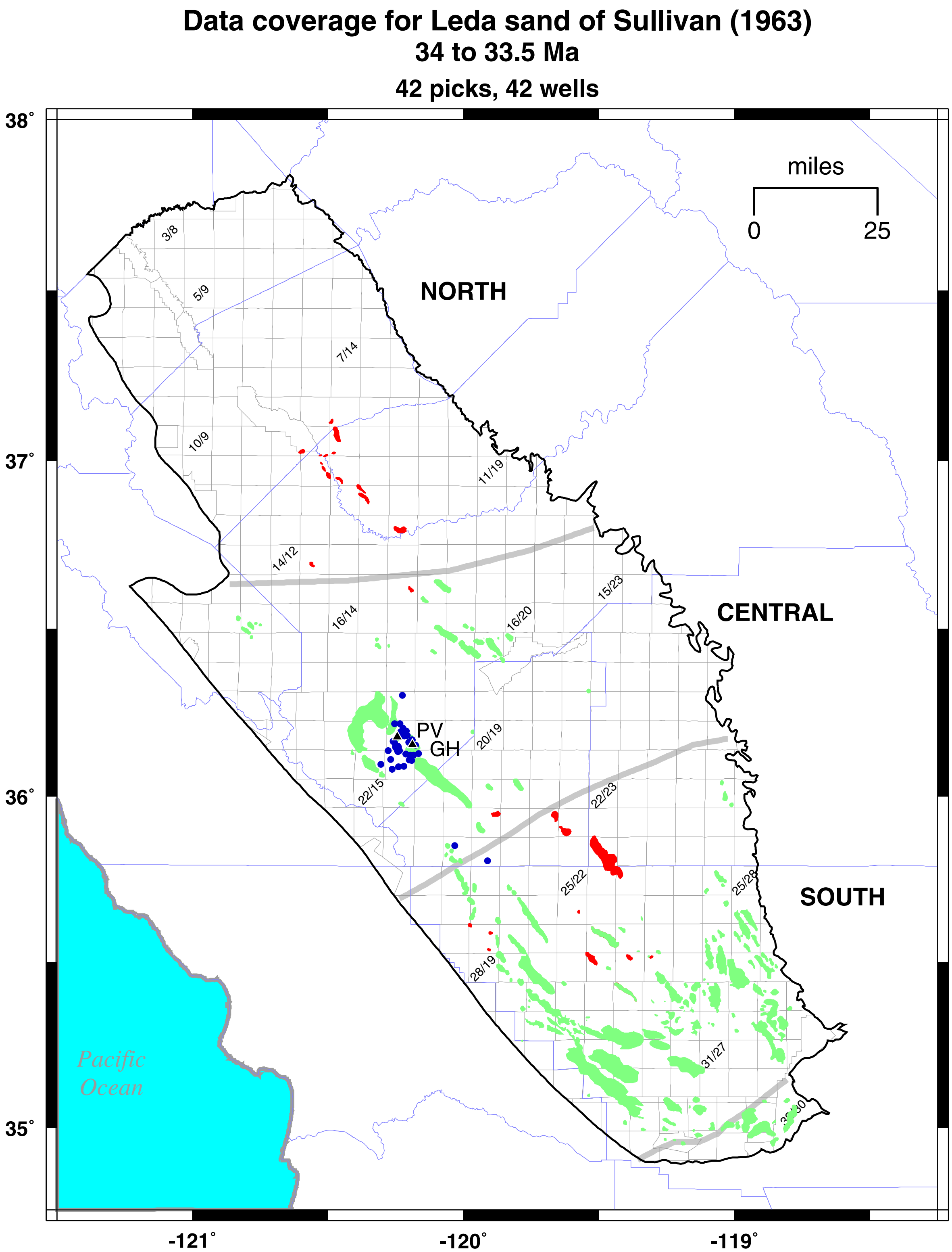


Figure 5.29. Same as figure 5.4, but for the Leda sand of Sullivan (1963). GH, Guijarral Hills oil field; PV, Pleasant Valley oil field.

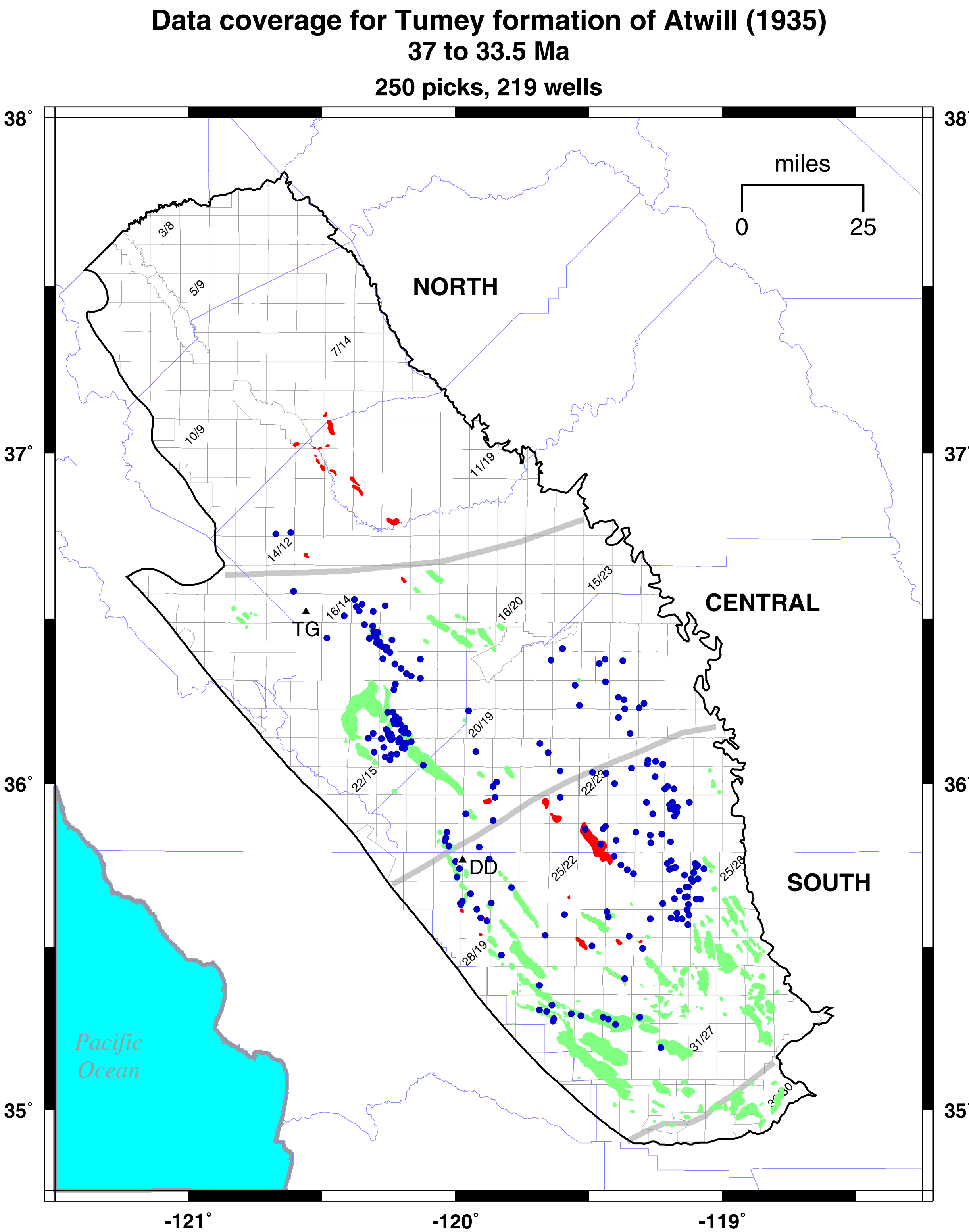


Figure 5.30. Same as figure 5.4, but for the Tumey formation of Atwill (1935). DD, Devils Den; TG, Tumey Gulch.

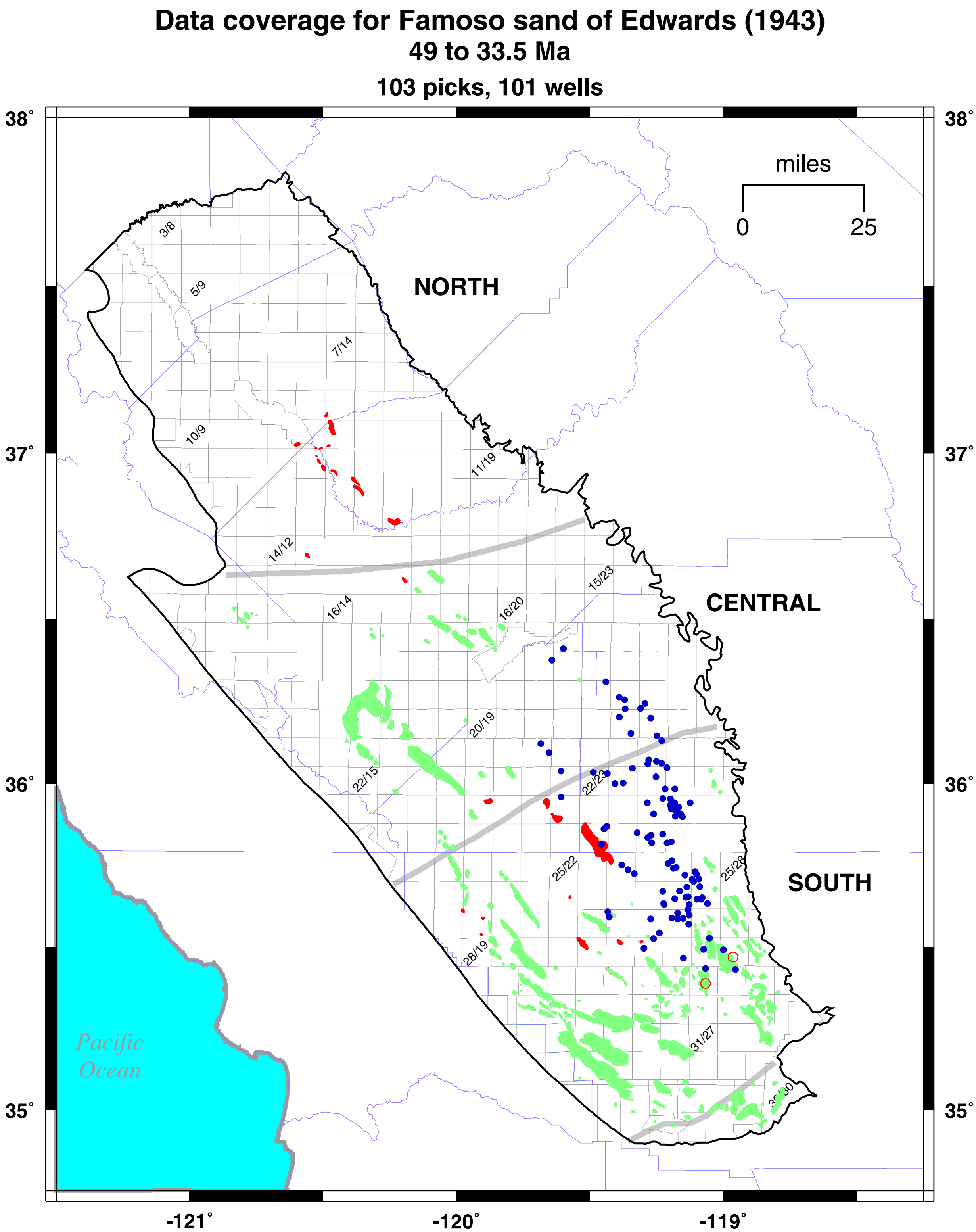


Figure 5.31. Same as figure 5.4, but for Famoso sand of Edwards (1943). Open red circles denote location of Gulf KCL-B 45 and Shell Fuhrman 1 wells (API numbers 02906949 and 02926316, respectively, from west to east).

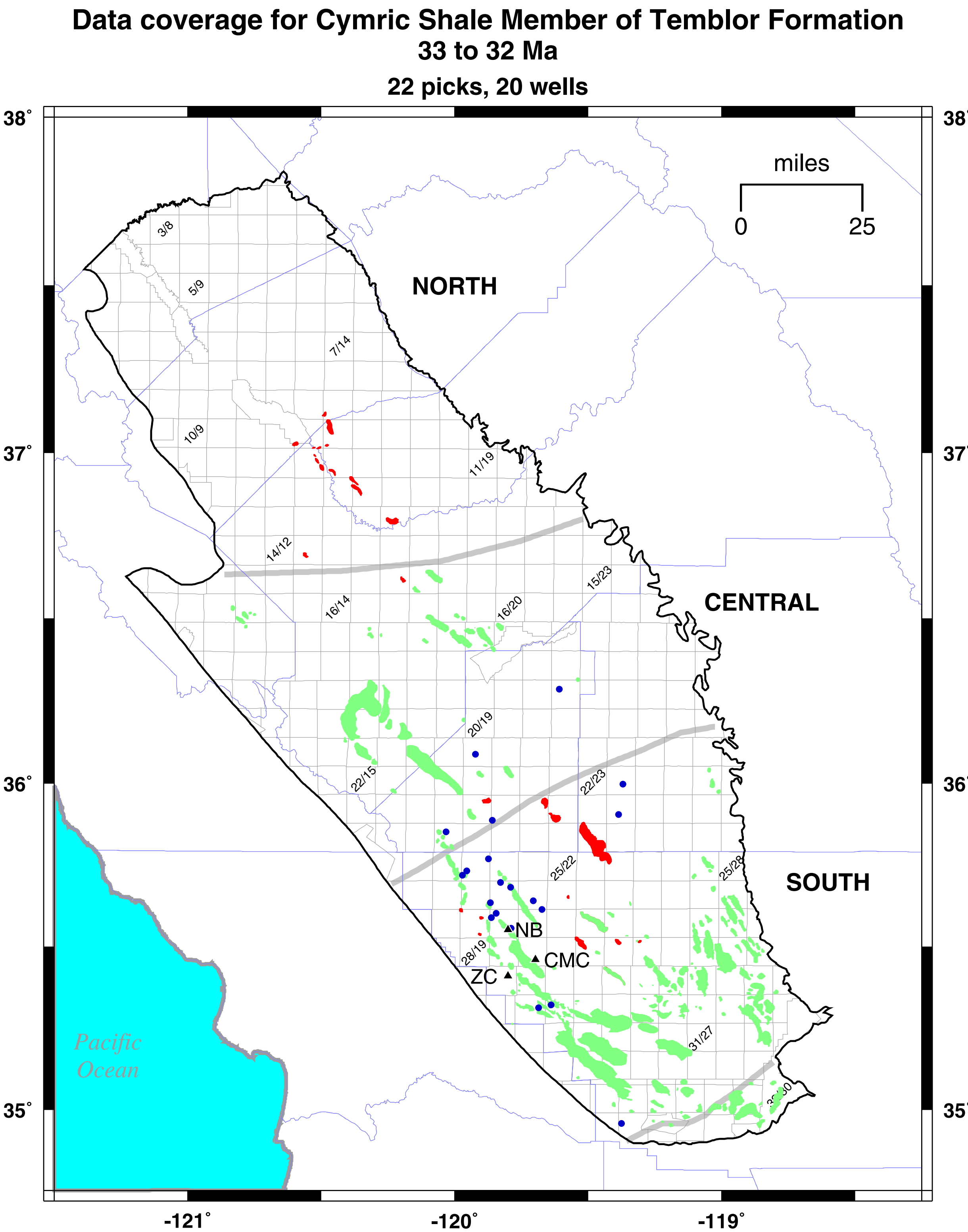


Figure 5.32. Same as figure 5.4, but for the Cymric Shale Member of the Temblor Formation. This unit is also called the Salt Creek shale of Foss and Blaisdell (1968). NB, North Belridge oil field; CMC, Chico Martinez Creek; ZC, Zemorra Creek.

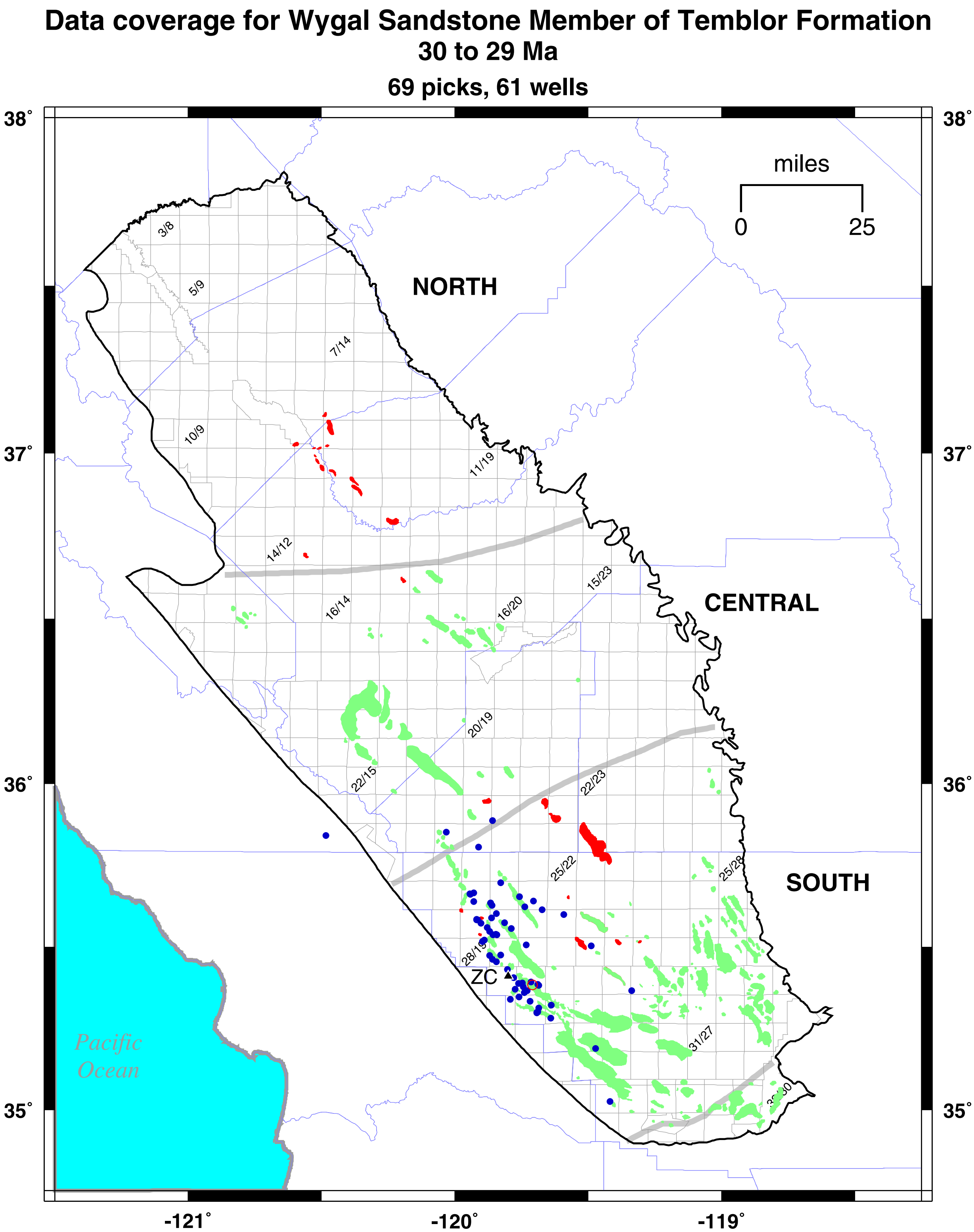


Figure 5.33. Same as figure 5.4, but for the Wygal Sandstone Member of the Temblor Formation. Open red circle denotes location of T.H. Purman Cymric 1 well (API number 02939376). ZC, Zemorra Creek.

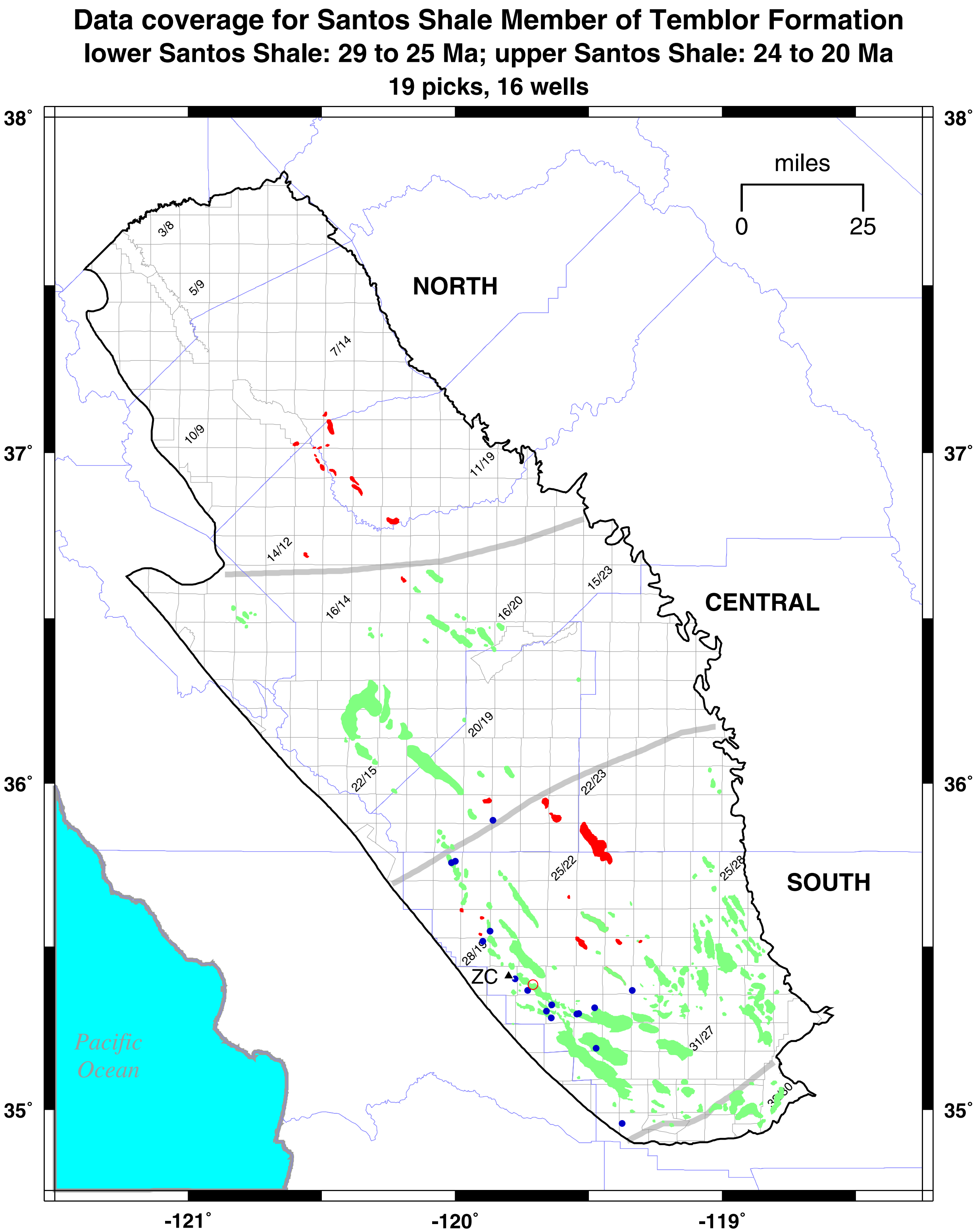


Figure 5.34. Same as figure 5.4, but for the upper and lower Santos Shale Member of the Temblor Formation. Open red circle denotes location of T.H. Purman Cymric 1 well (API number 02939376). ZC, Zemorra Creek.

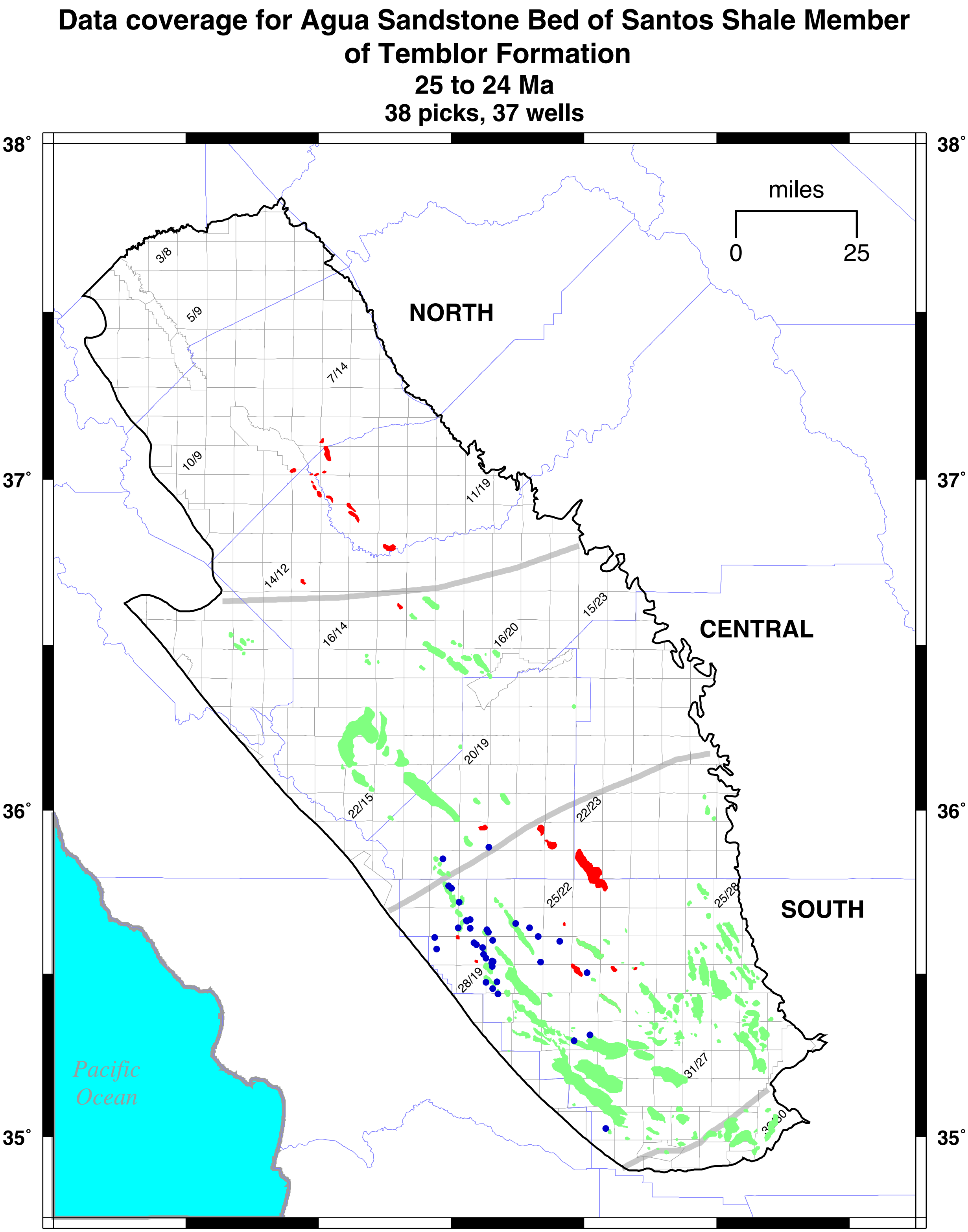


Figure 5.35. Same as figure 5.4, but for the Agua Sandstone Bed of the Santos Shale Member of the Temblor Formation.

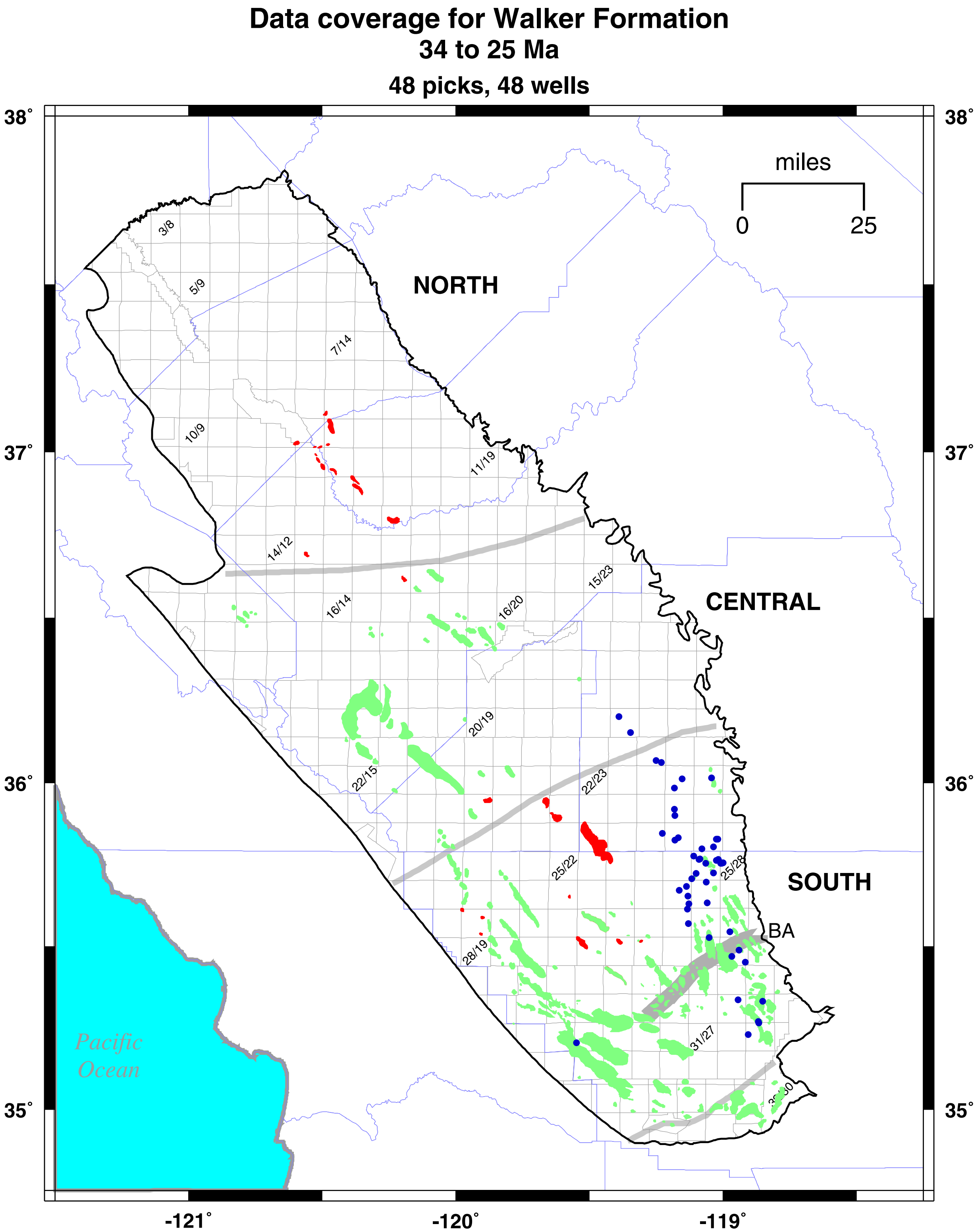


Figure 5.36. Same as figure 5.4, but for the Walker Formation. Note that the Walker Formation is 34 to 21.5 Ma old south of the Bakersfield Arch (BA), where the upper part is equivalent to the Jewett Sand and the lower Freeman Silt.

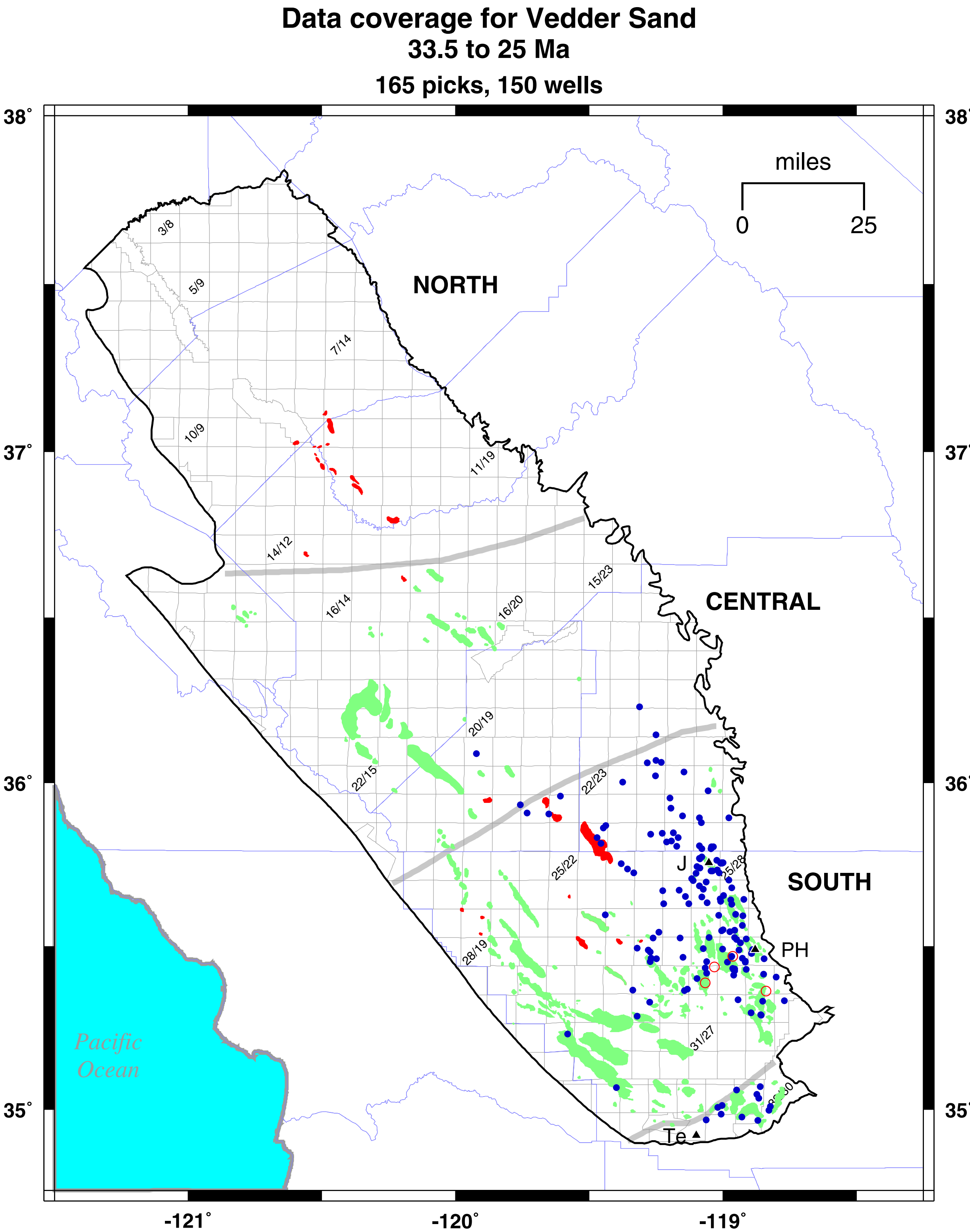


Figure 5.37. Same as figure 5.4, but for the Vedder Sand. Te, Tejon embayment; Jasmin oil field; PH, Pyramid Hill. Open red circles denote location of Gulf KCL-B 45, Chevron 33-1, Shell Fuhrman 1, and Chevron 24-35 wells (API numbers 02906949, 02930973, 02926316, and 02906398, respectively, from west to east).

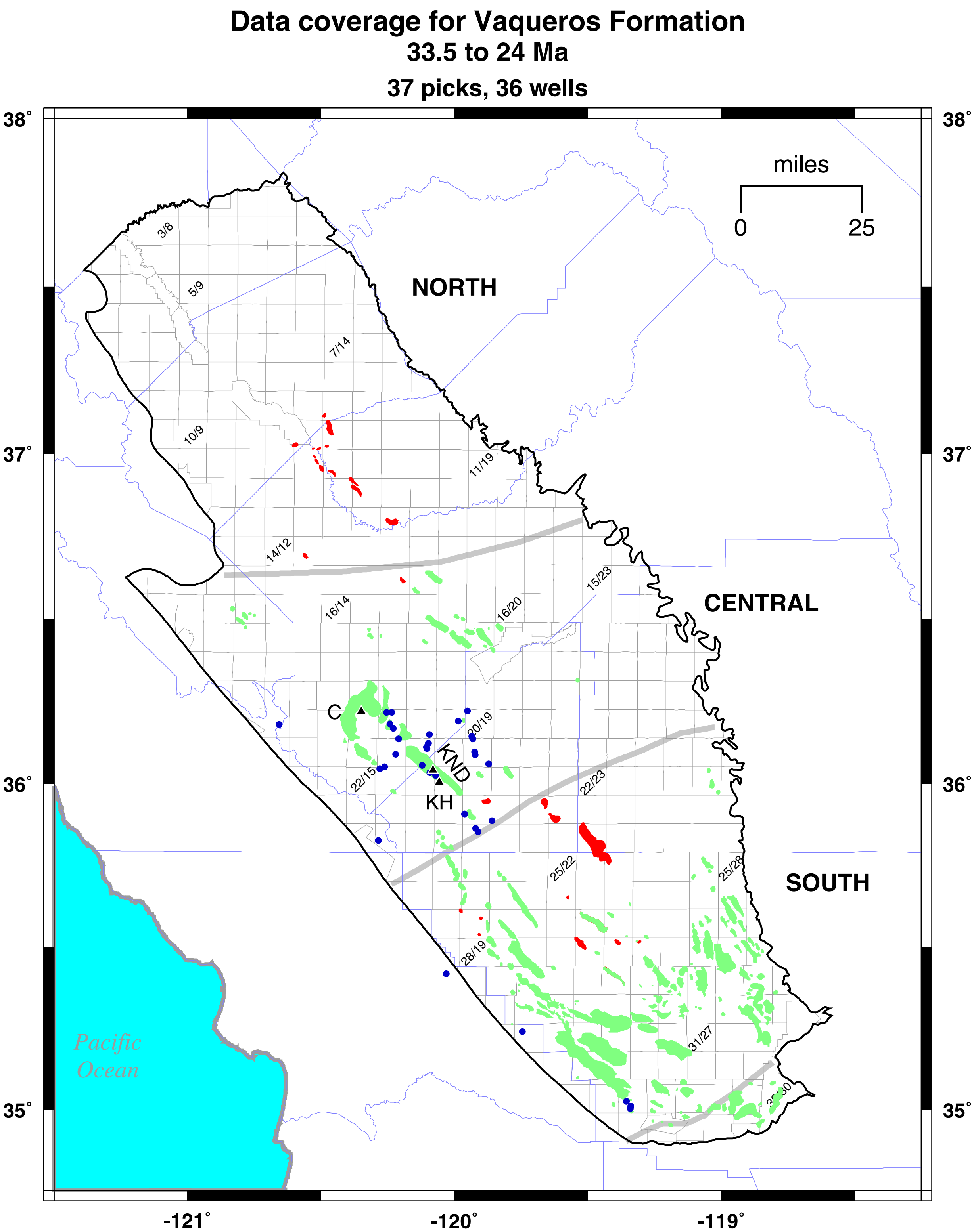


Figure 5.38. Same as figure 5.4, but for the Vaqueros Formation. KND, Kettleman North Dome oil field; C, Coalinga oil field; KH, Kettleman Hills.

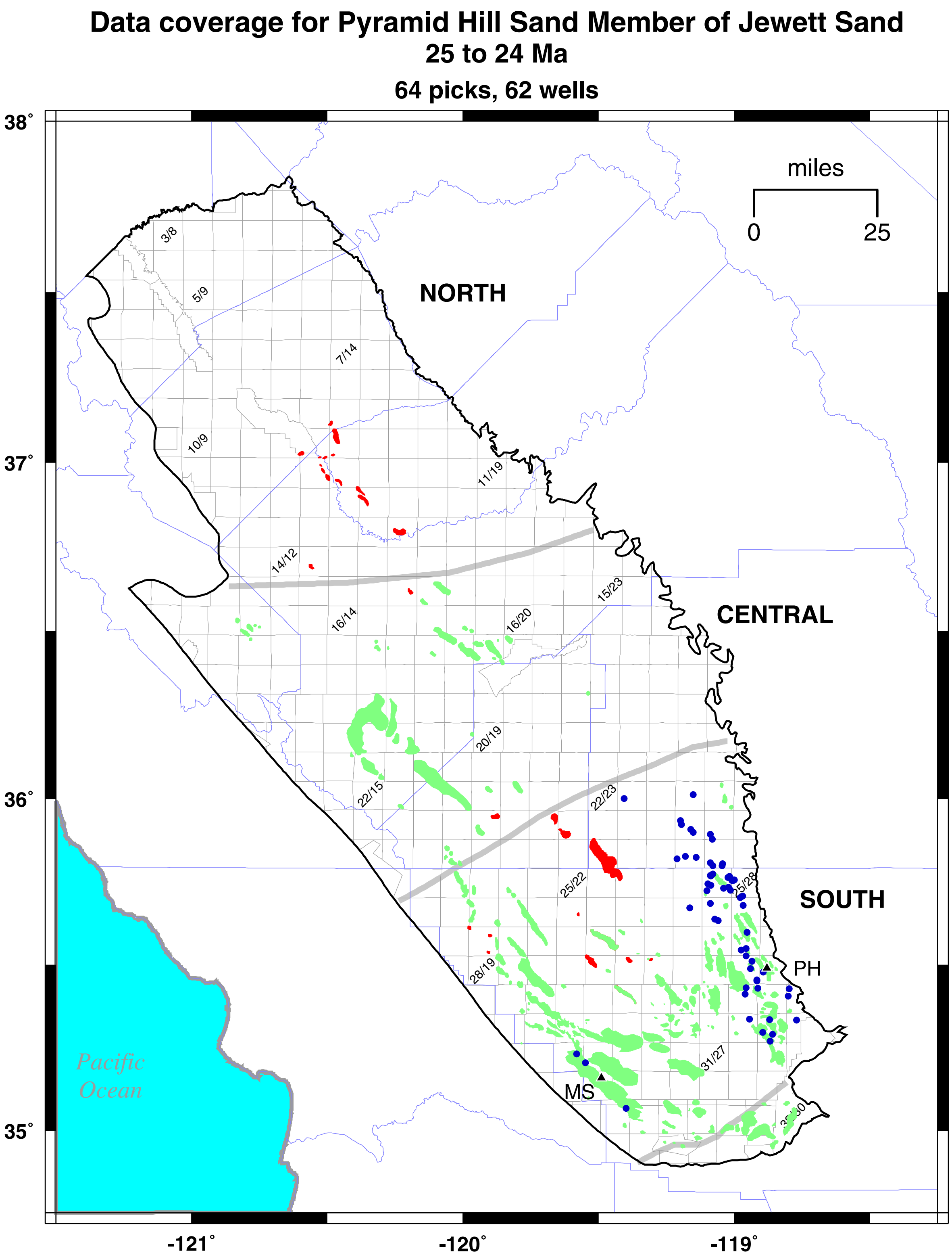


Figure 5.39. Same as figure 5.4, but for the Pyramid Hill Sand Member of the Jewett Sand. MS, Midway-Sunset oil field; PH, Pyramid Hill.

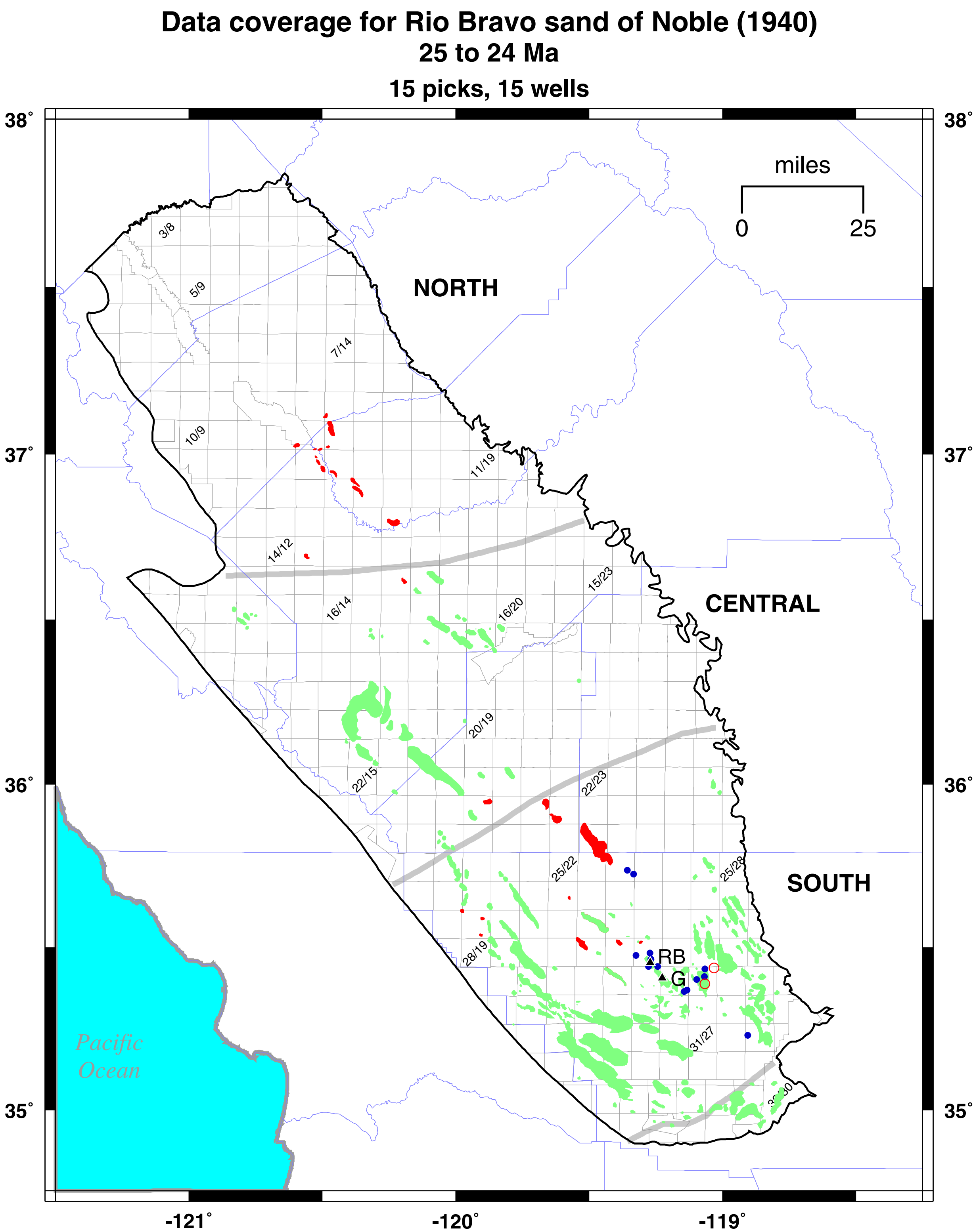


Figure 5.40. Same as figure 5.4, but for the Rio Bravo sand of Noble (1940). This unit correlates to the Pyramid Hill Sand. RB, Rio Bravo oil field; G, Greeley oil field. Open red circles denote location of Gulf KCL-B 45 and Chevron 33-1 wells (API numbers 02906949 and 02926316, respectively, from west to east).

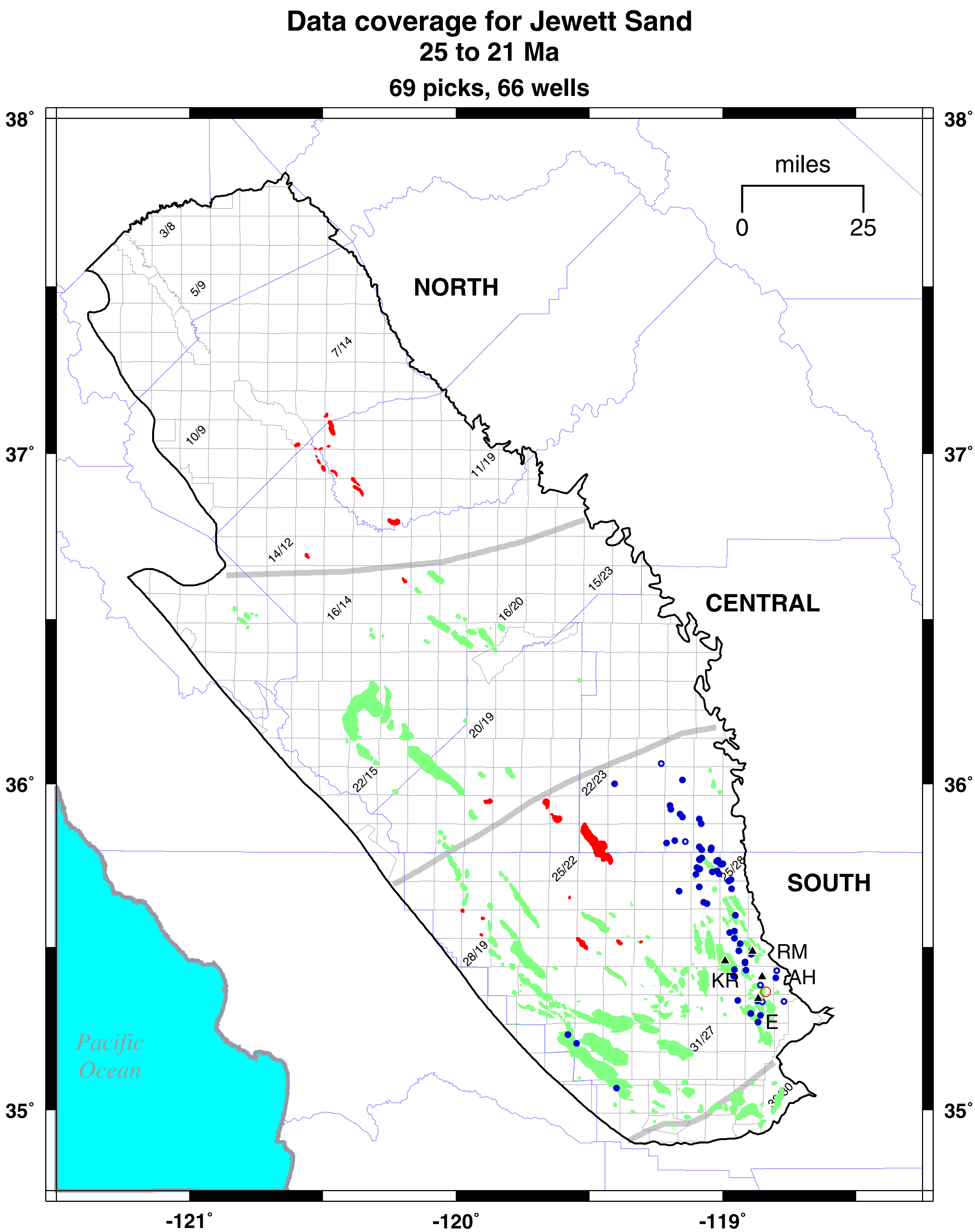


Figure 5.41. Same as figure 5.4, but for the Jewett Sand (open blue circles). Total age includes basal Pyramid Hill Sand Member (filled blue circles). AH, Ant Hill oil field; E, Edison oil field; KR, Kern River oil field; RM, Round Mountain oil field. Open red circle denotes location of Chevron 24-35 well (API number 02906398).

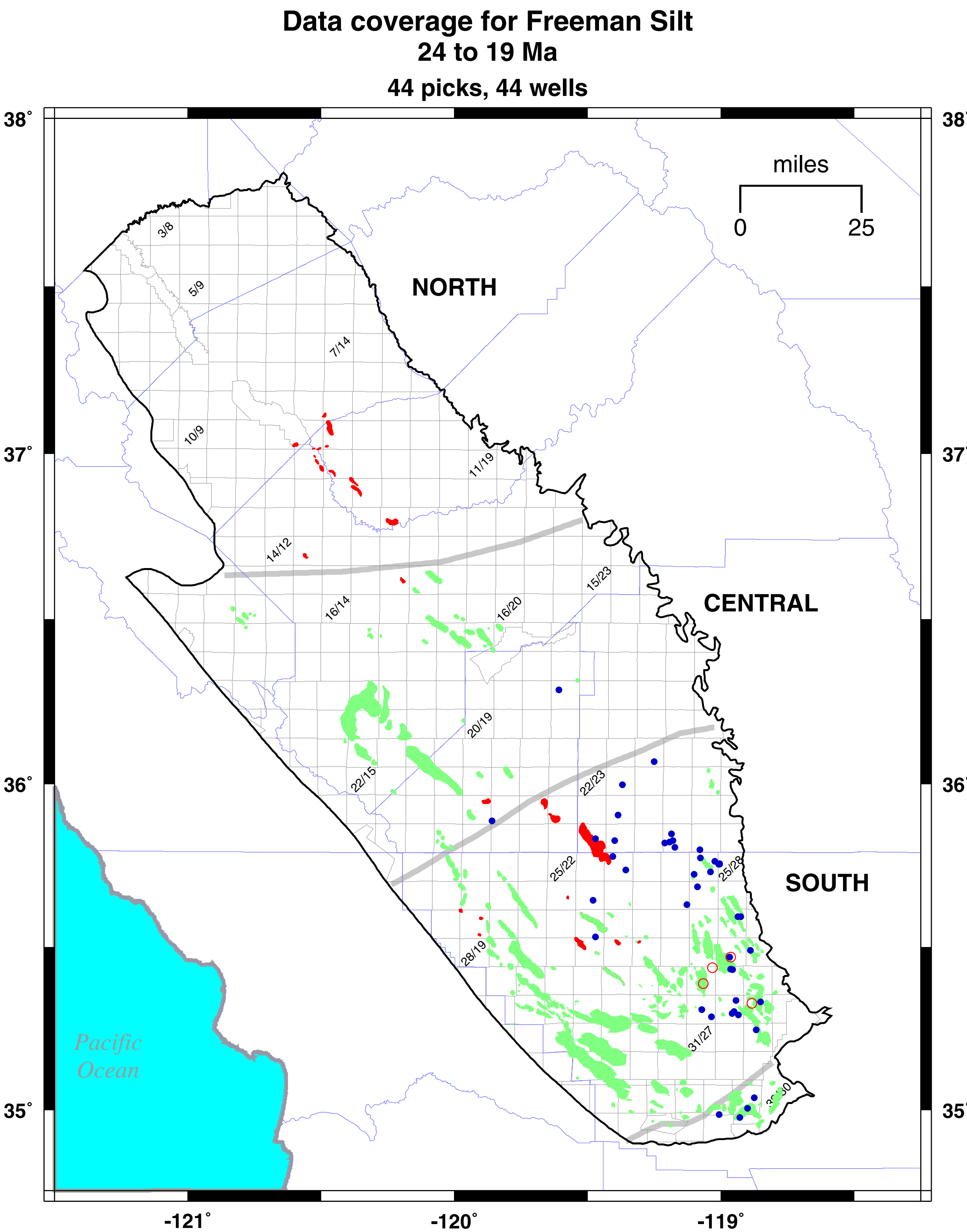


Figure 5.42. Same as figure 5.4, but for the Freeman Silt. Open red circles denote location of Gulf KCL-B 45, Chevron 33-1, Shell Fuhrman 1, and Standard Jeppi-Camp 67-8 wells (API numbers 02906949, 02930973, 02926316, and 02906412, respectively, from west to east).

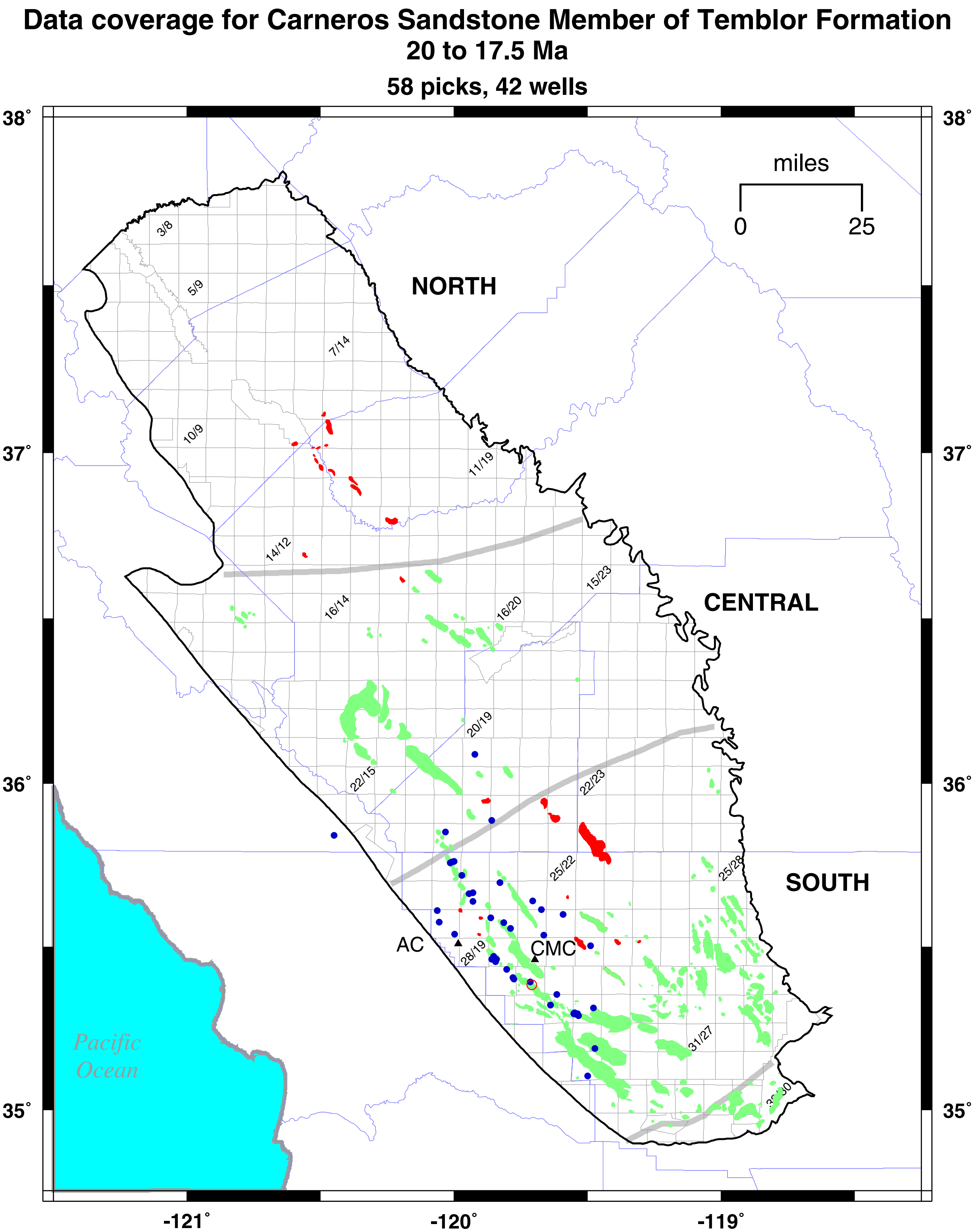


Figure 5.43. Same as figure 5.4, but for the Carneros Sandstone Member of the Temblor Formation. AC, Alex Cook Springs; CMC, Chico Martinez Creek. Open red circle denotes location of T.H. Purman Cymric 1 well (API number 02939376).

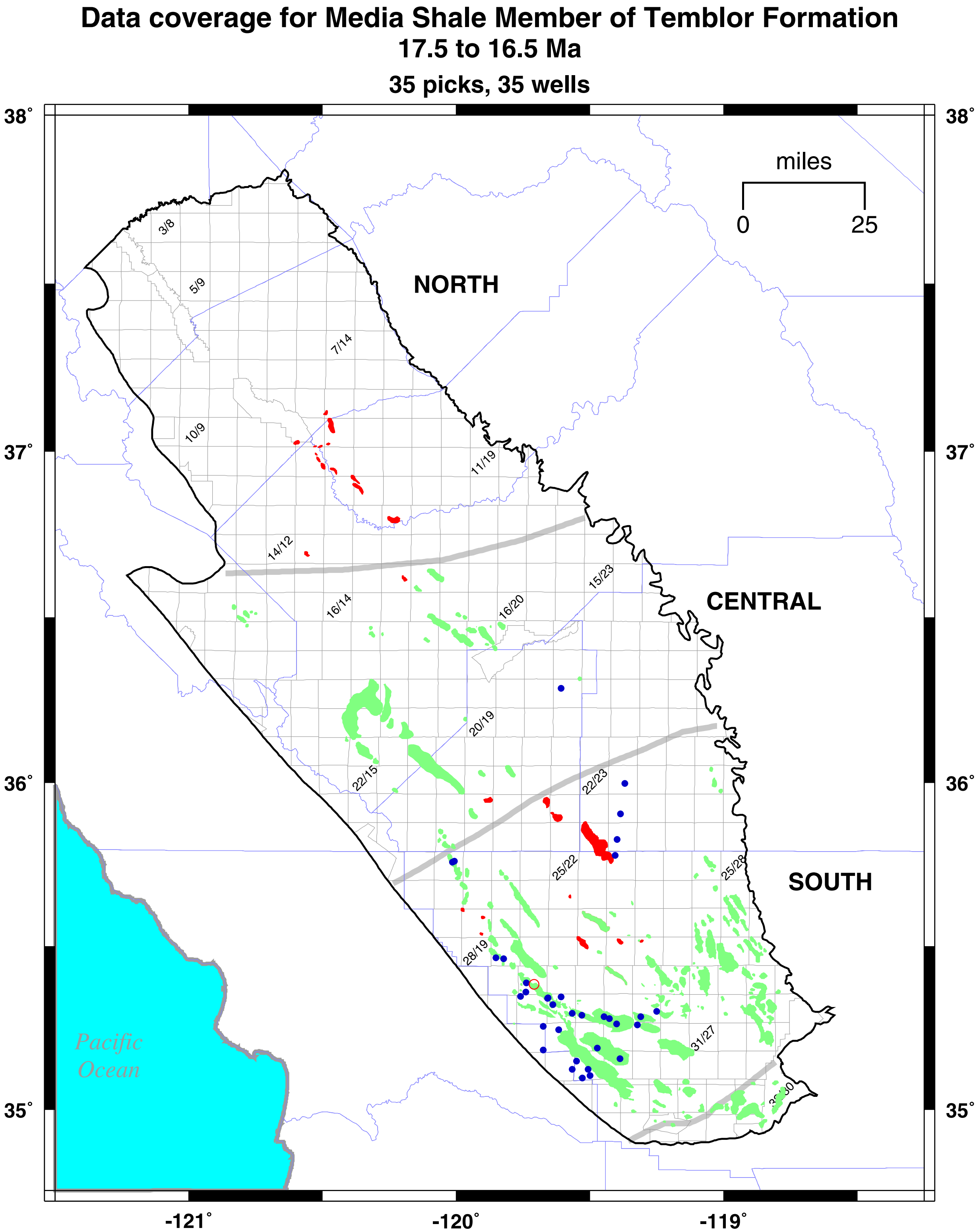


Figure 5.44. Same as figure 5.4, but for the Media Shale Member of the Temblor Formation. Open red circle denotes location of T.H. Purman Cymric 1 well (API number 02939376).

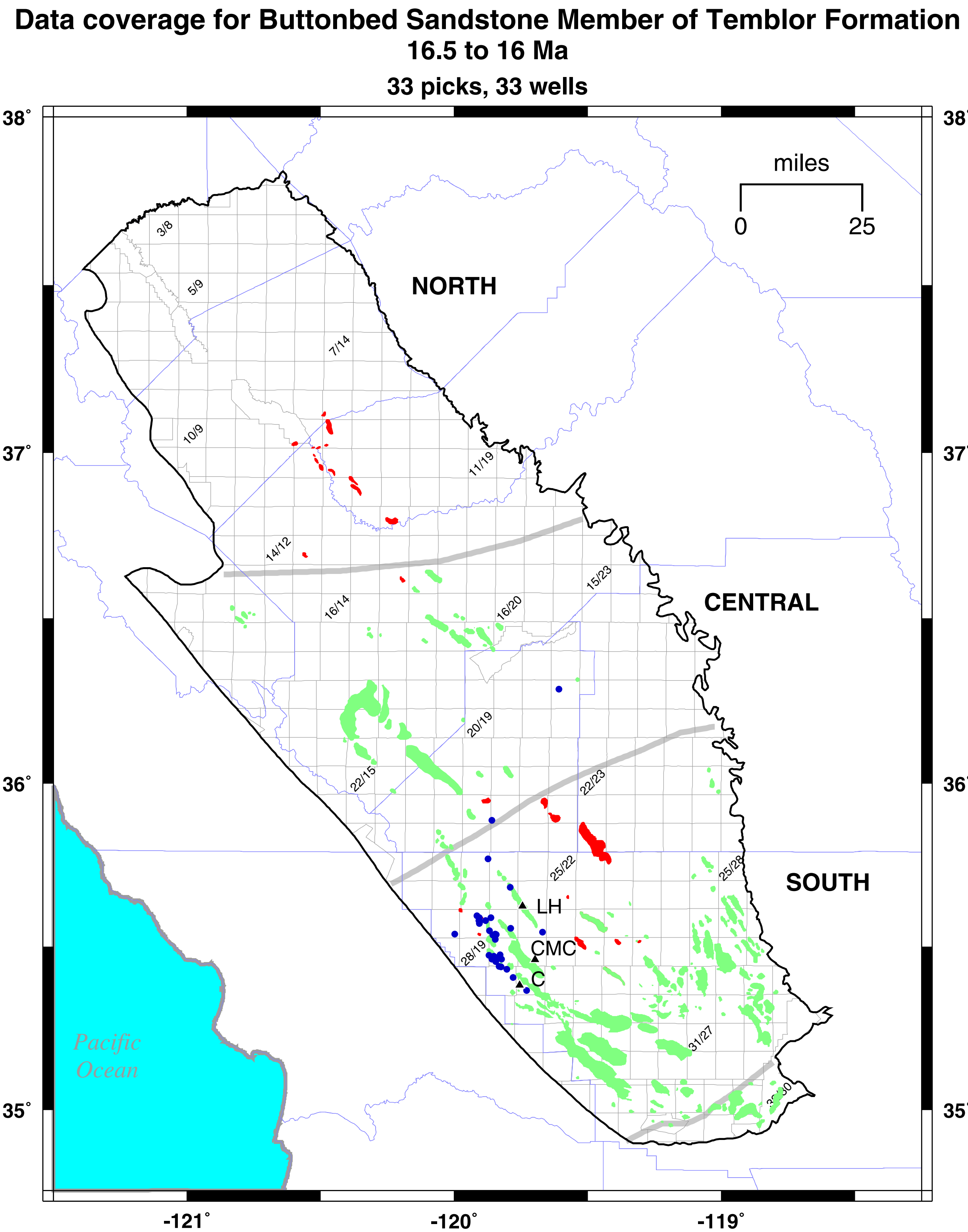


Figure 5.45. Same as figure 5.4, but for the Buttonbed Sandstone Member of the Temblor Formation. CMC, Chico Martinez Creek; C, Cymric oil field; LH, Lost Hills oil field.

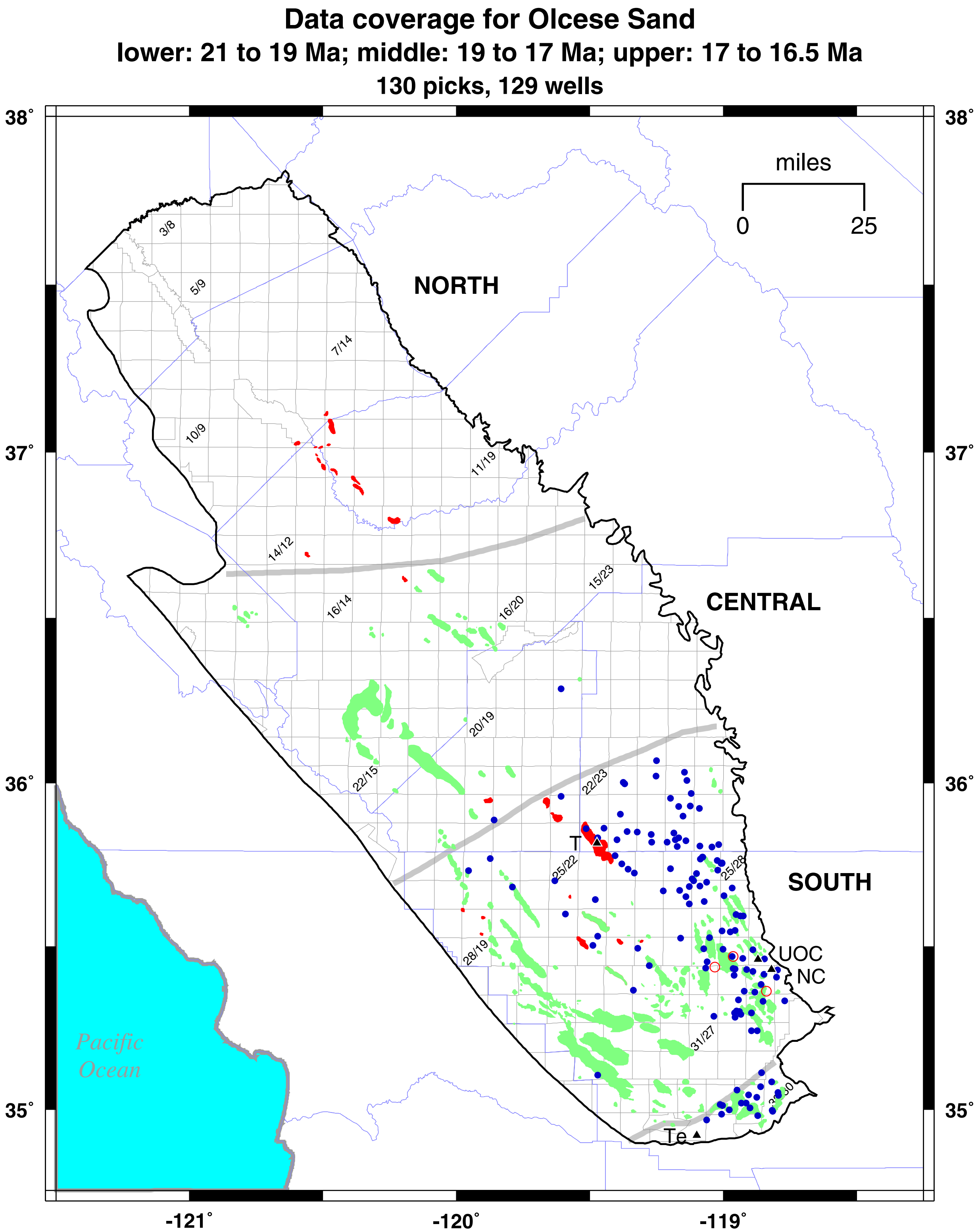


Figure 5.46. Same as figure 5.4, but for the Olcese Sand. Ages for individual sand units are 21 to 19 Ma for lower Olcese Sand, 19 to 17 Ma for middle Olcese Sand, and 17 to 16.5 Ma for upper Olcese Sand. Te, Tejon embayment; T, Trico gas field; NC, Nickel Cliff; UOC, Upper Olcese Creek. Open red circle denotes location of Chevron 33-1, Shell Fuhrman 1, and Chevron 24-35 wells (API numbers 02930973, 02926316, and 02906398, respectively, from west to east).

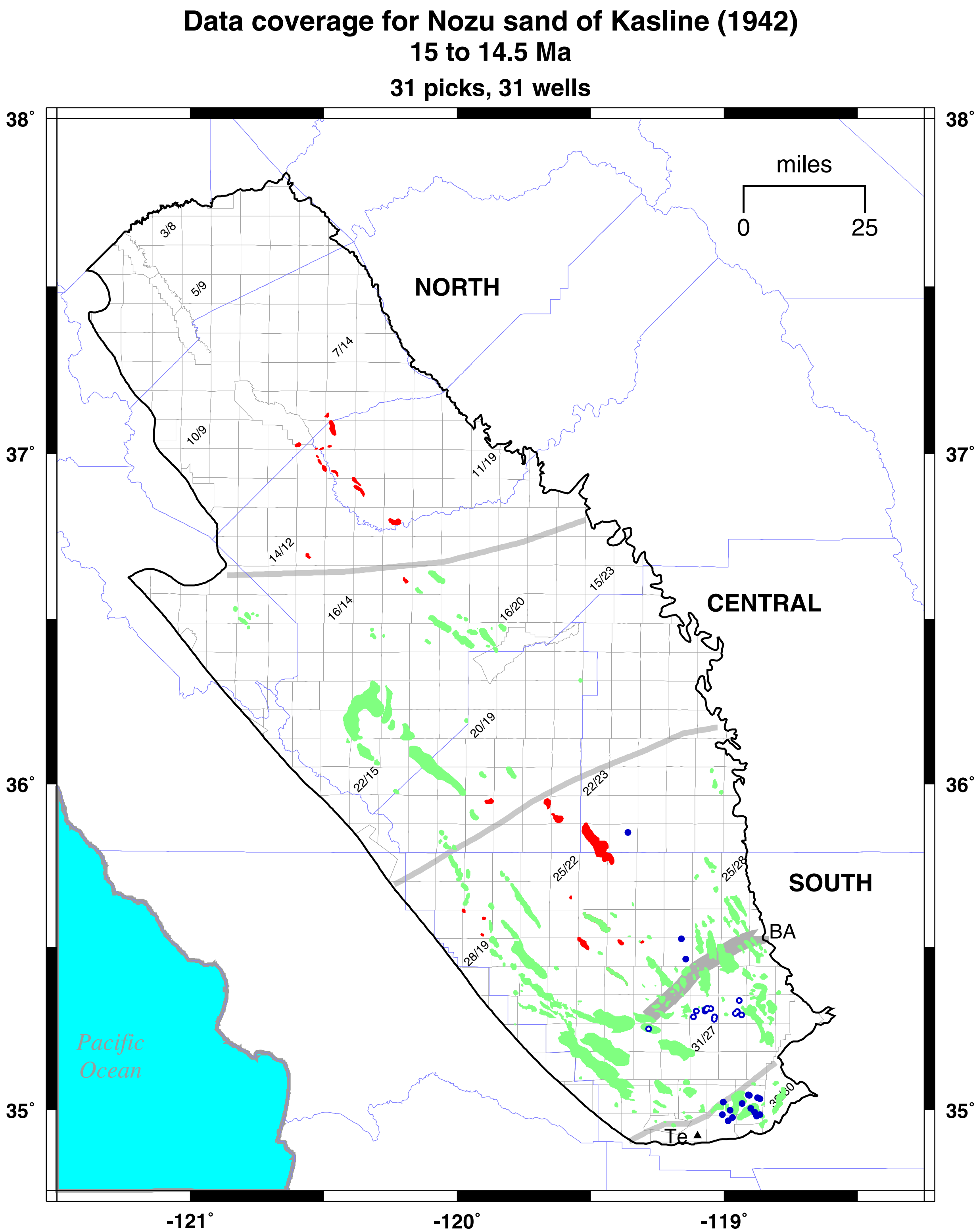


Figure 5.47. Same as figure 5.4, but for the Nozu sand of Kasline (1942; open blue circles). Well picks include Valv sandstone of MacPherson (1978; filled blue circles) in Tejon embayment (Te). Broad gray shading indicates location of the buried Bakersfield Arch (BA).

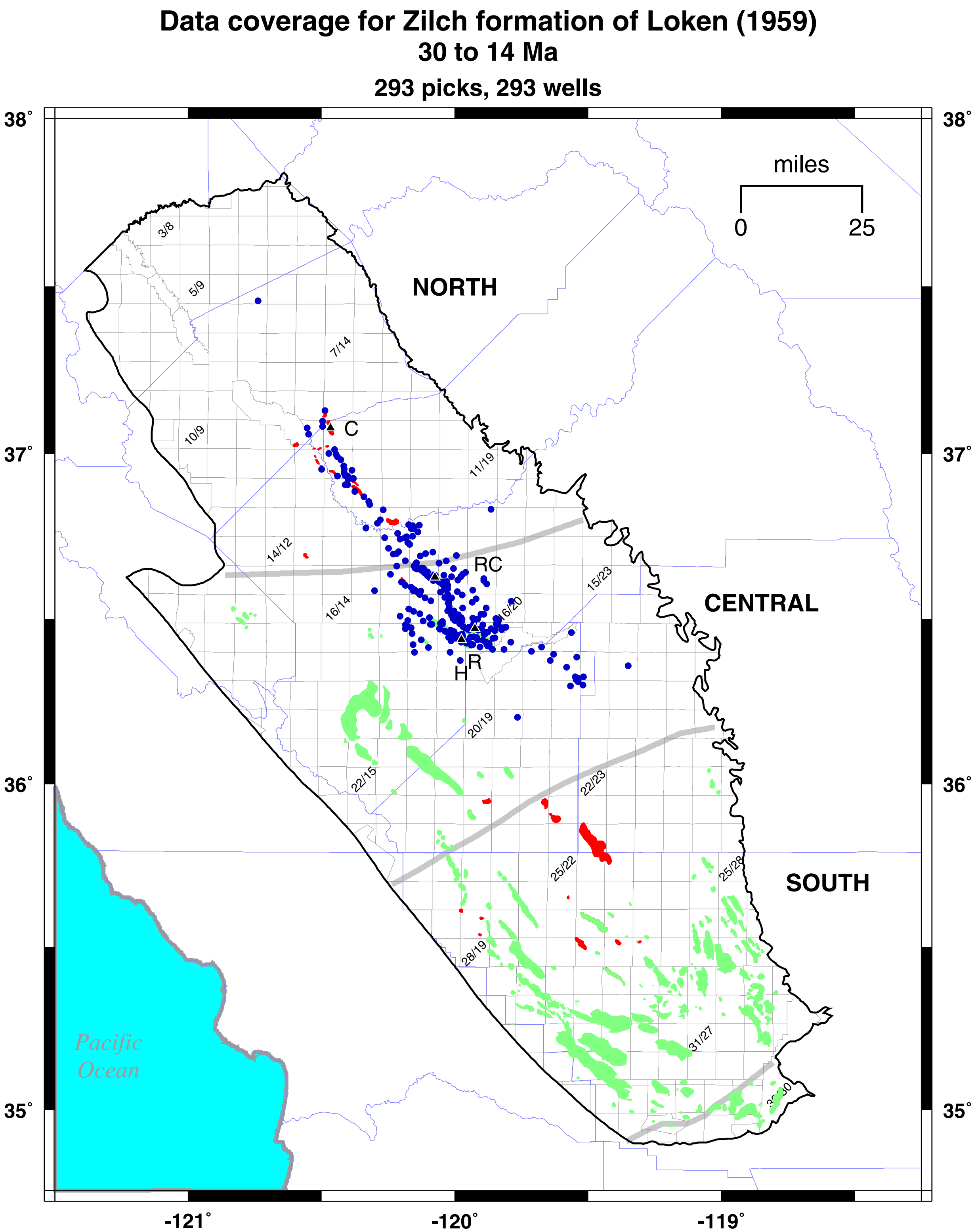


Figure 5.48. Same as figure 5.4, but for the Zilch formation of Loken (1959). R, Riverdale oil field; C, Chowchilla gas field; RC, Raisin City oil field; H, Helm oil field.

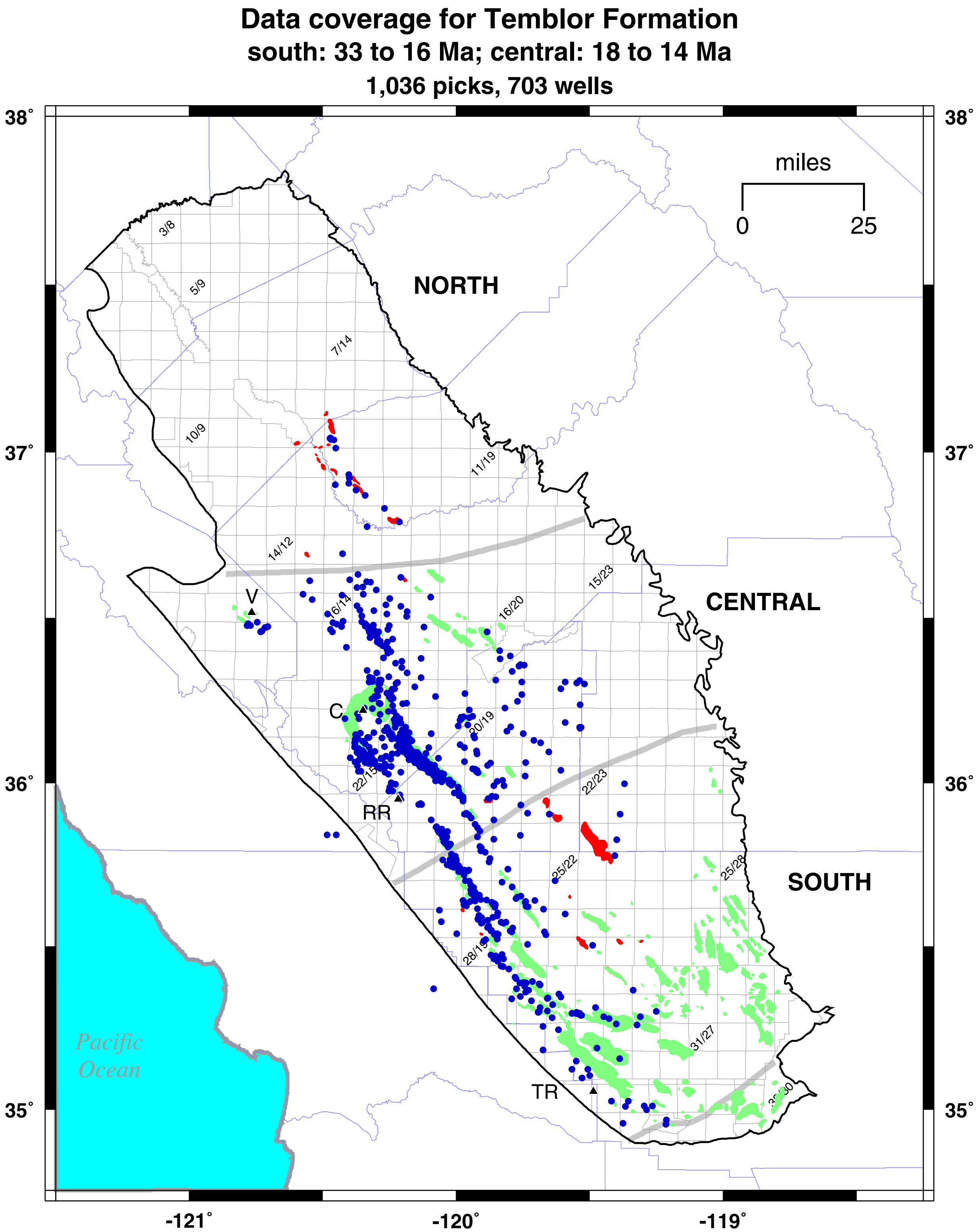


Figure 5.49. Same as figure 5.4, but for the Temblor Formation. TR, Temblor Range; V, Vallecitos oil field; C, Coalinga oil field; RR, Reef Ridge.

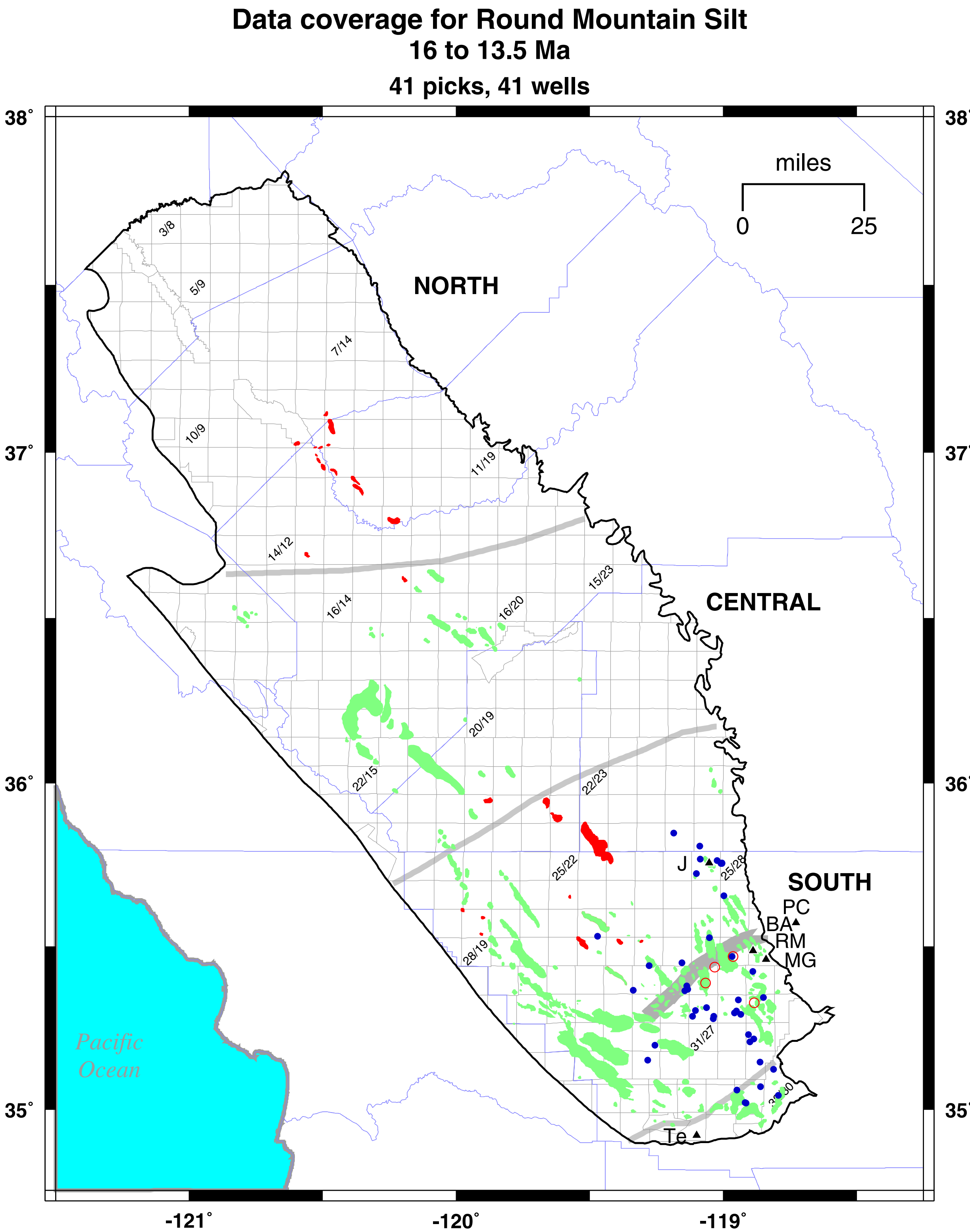


Figure 5.50. Same as figure 5.4, but for the Round Mountain Silt. Broad gray shading indicates location of the buried Bakersfield Arch (BA). Te, Tejon Embayment; J, Jasmin oil field; RM, Round Mountain oil field; MG, Miller Gulch; PC, Poso Creek. Open red circles denote location of Gulf KCL-B 45, Chevron 33-1, Shell Fuhrman 1, and Standard Jeppi-Camp 67-8 wells (API numbers 02926316, 02906398, 02930973, and 02906412, respectively, from west to east).

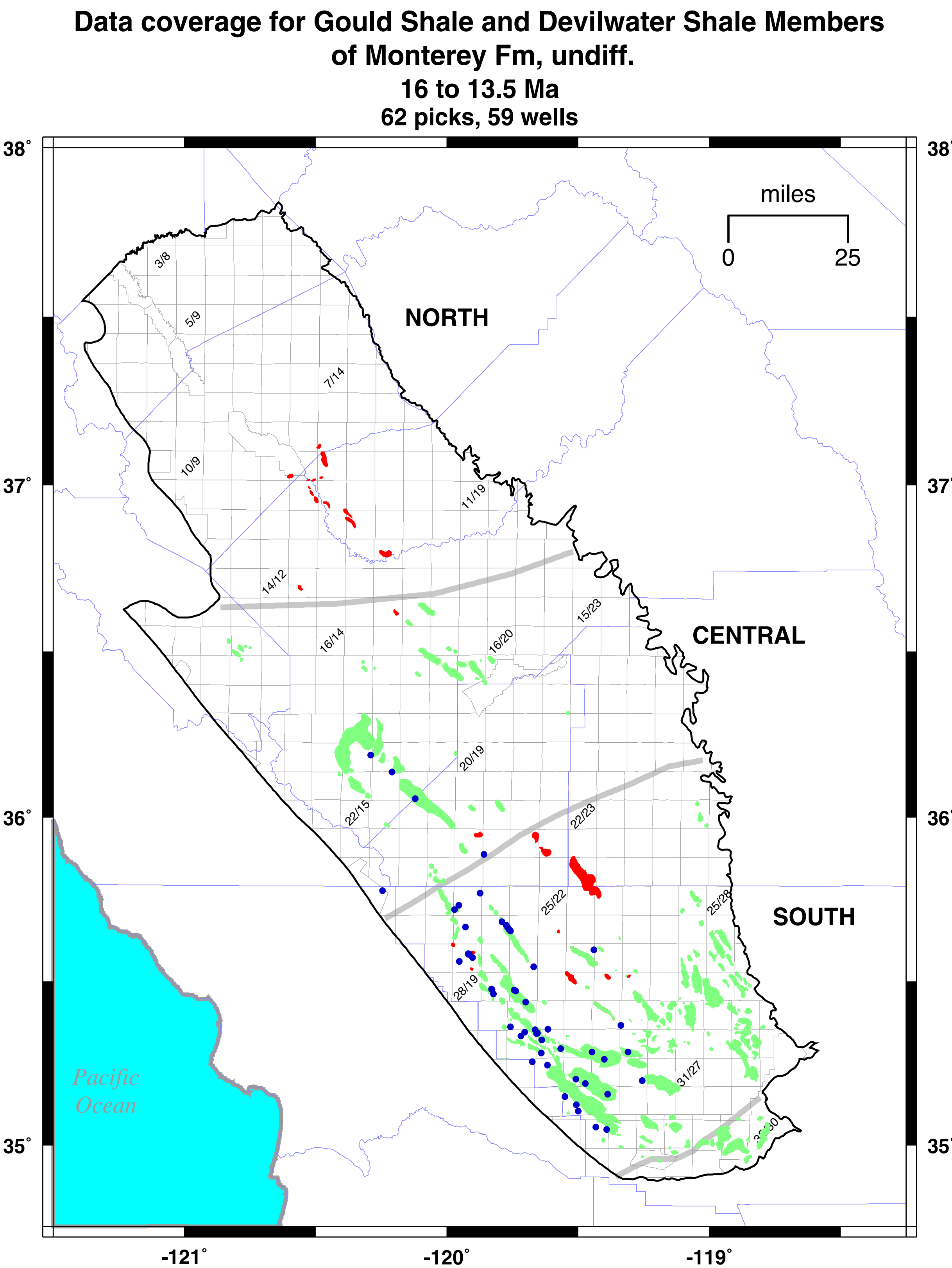


Figure 5.51. Same as figure 5.4, but for the Gould Shale and Devilwater Shale Members of the Monterey Formation.

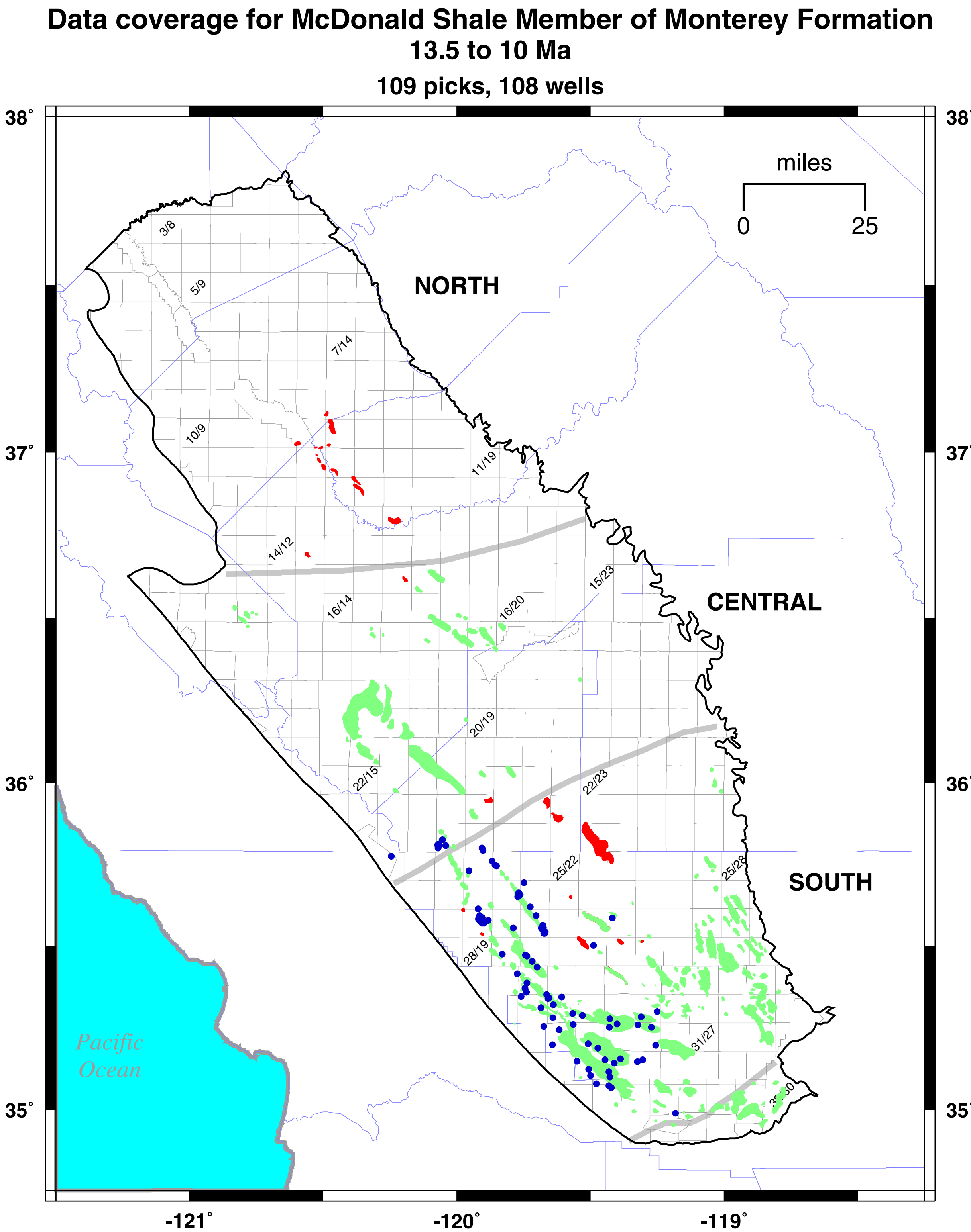


Figure 5.52. Same as figure 5.4, but for the McDonald Shale Member of the Monterey Formation.

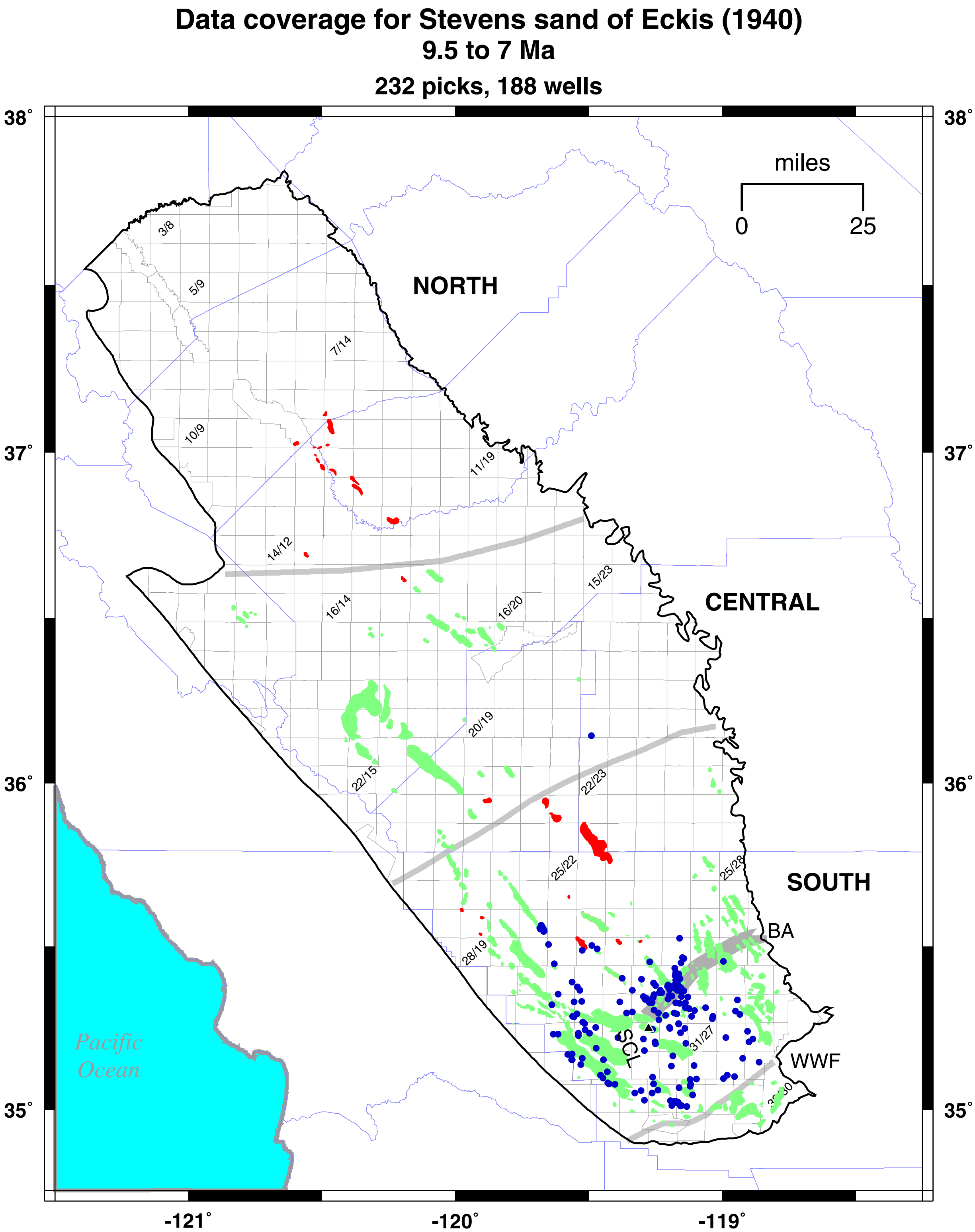


Figure 5.53. Same as figure 5.4, but for the Stevens sand of Eckis (1940). Broad gray shading indicates location of the buried Bakersfield Arch (BA). WWF, White Wolf Fault; SCL, South Coles Levee oil field.

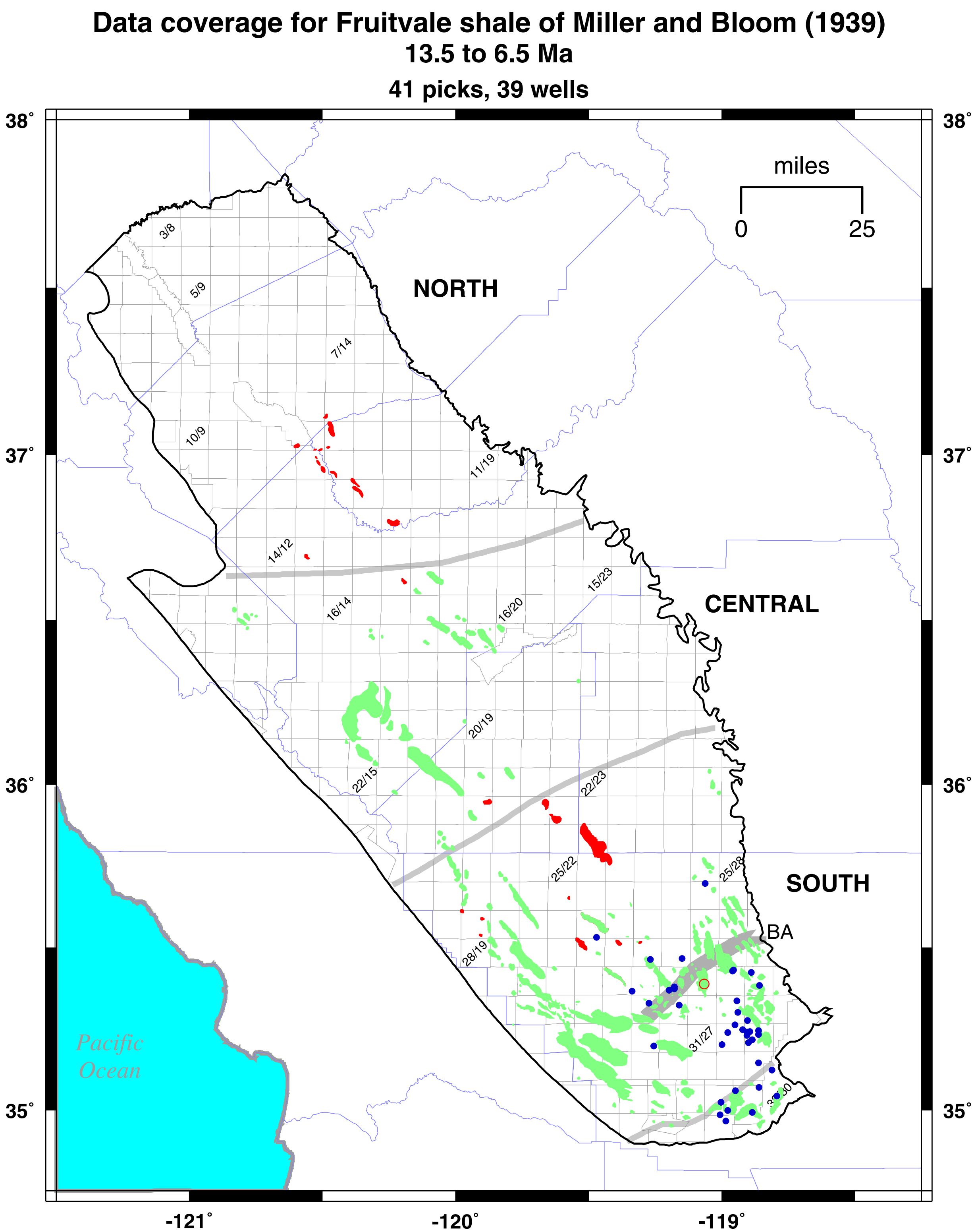


Figure 5.54. Same as figure 5.4, but for the Fruitvale shale of Miller and Bloom (1939). Broad gray shading indicates location of the buried Bakersfield Arch (BA). Open red circle denotes location of Gulf KCL-B 45 well (API number 02906949).

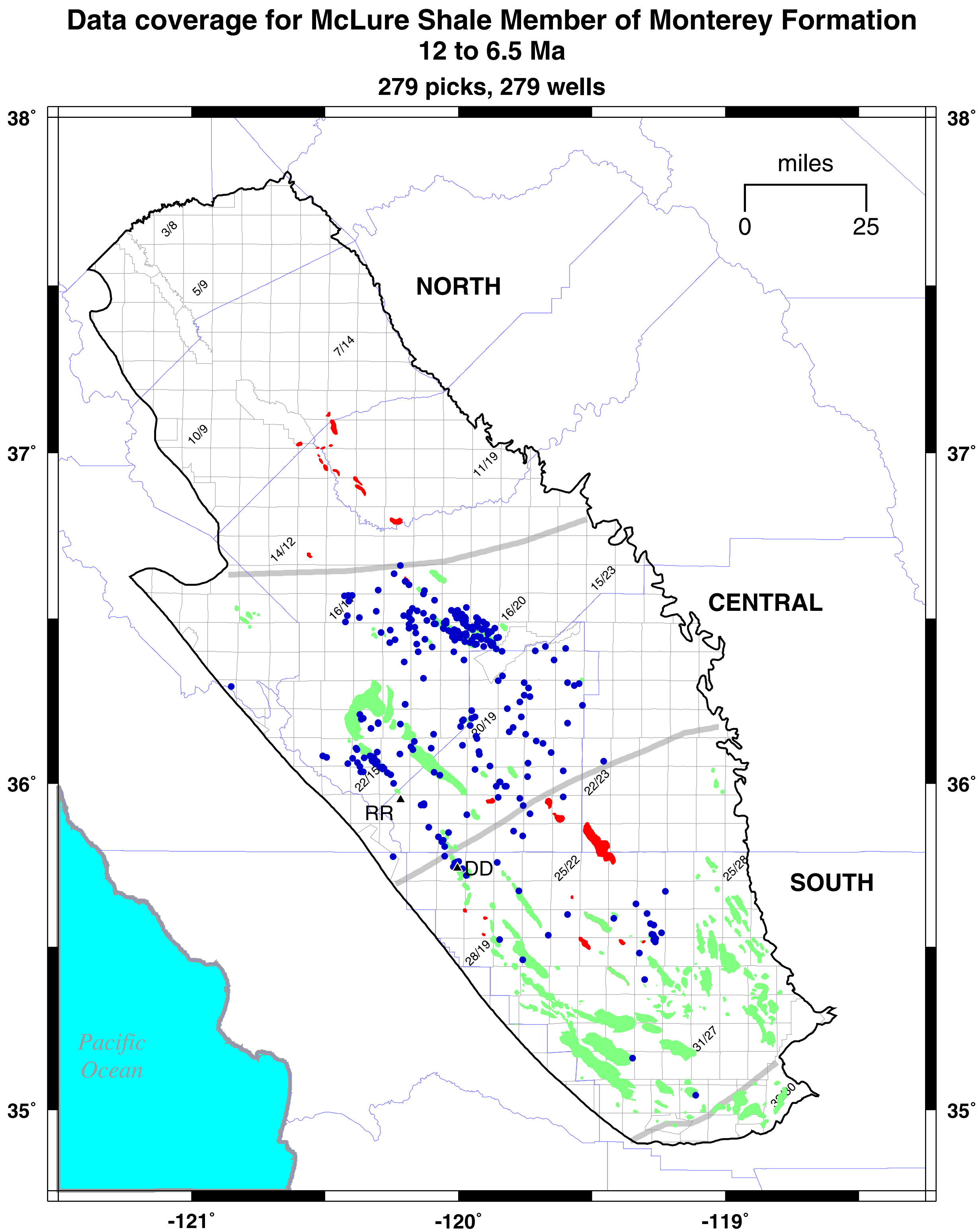


Figure 5.55. Same as figure 5.4, but for the McLure Shale Member of the Monterey Formation. RR, Reef Ridge; DD, Devils Den oil field.

Data coverage for Antelope shale of Graham and Williams (1985)
10 to 6.5 Ma
171 picks, 168 wells

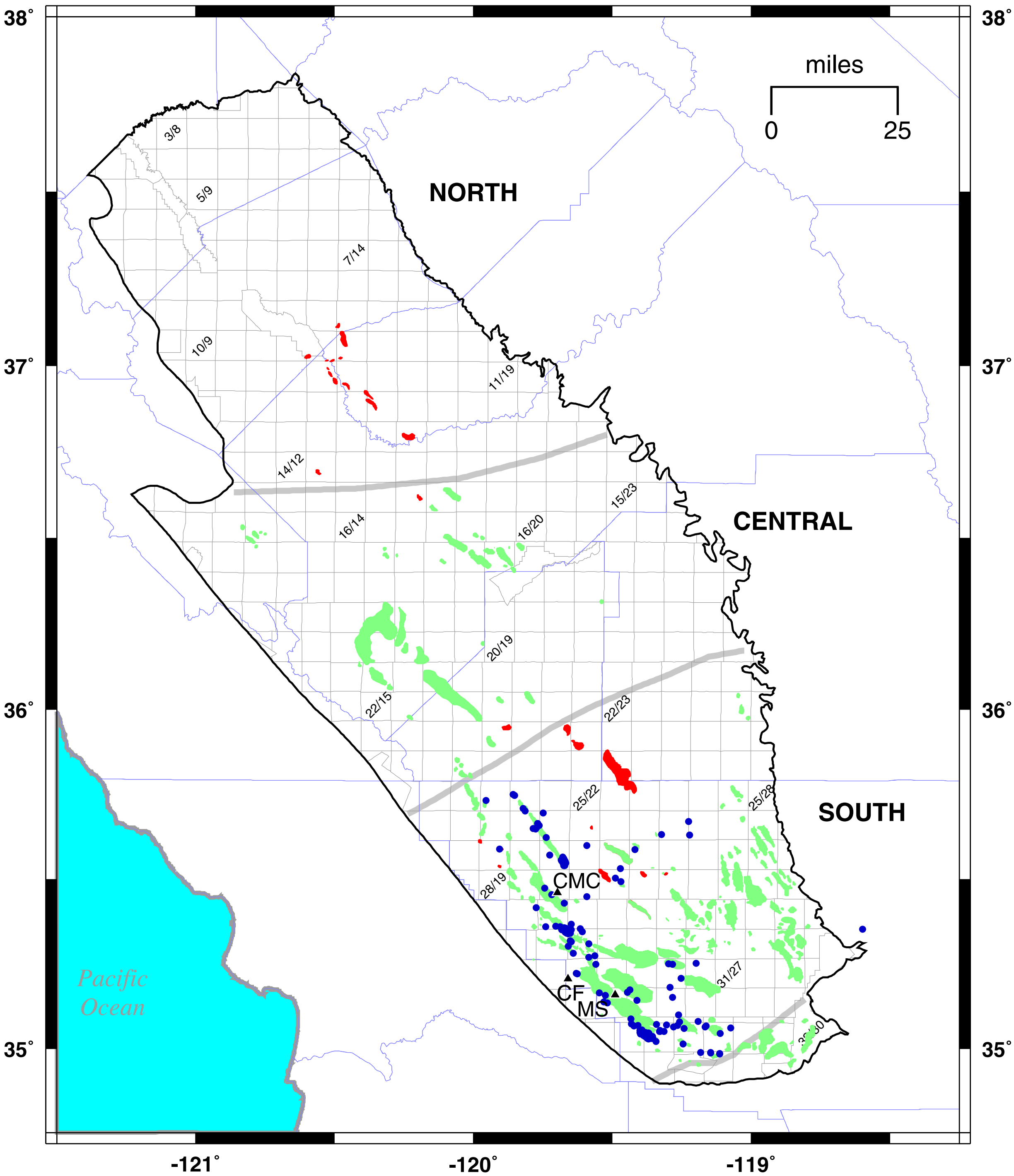


Figure 5.56. Same as figure 5.4, but for the Antelope shale of Graham and Williams (1985). CF, Crocker Flat; CMC, Chico Martinez Creek; MS, Midway-Sunset oil field.

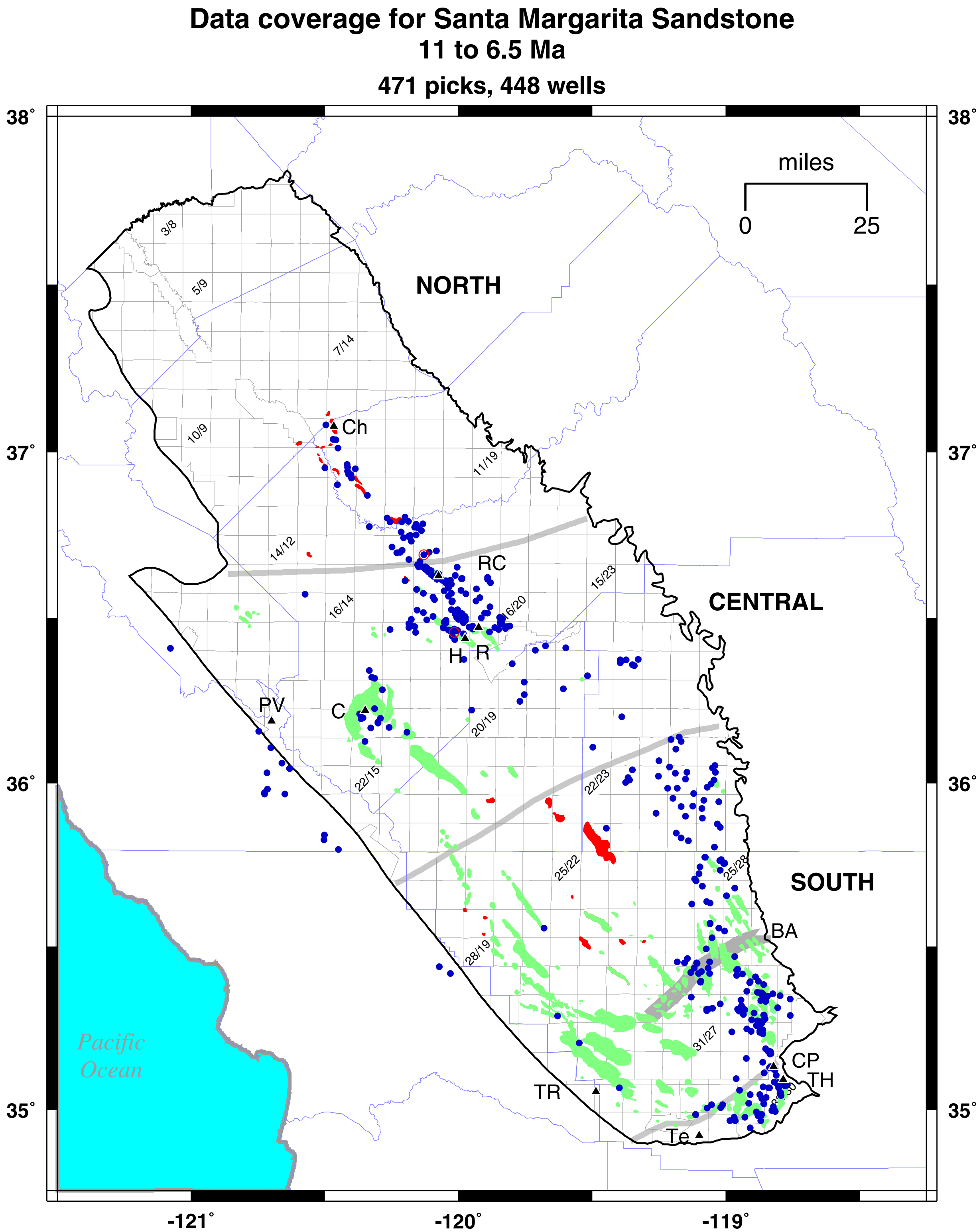


Figure 5.57. Same as figure 5.4, but for the Santa Margarita Sandstone. Broad gray shading indicates location of the buried Bakersfield Arch (BA). Te, Tejon embayment; Ch, Chowchilla gas field; C, Coalinga oil field; TR, Temblor Range; CP, Comanche Point; TH, Tejon Hills; H, Helm oil field; R, Riverdale oil field; RC, Raisin City oil field; PV, Priest Valley. Open red circles denote location of Amerada Hess Brix et al. 1-16 and Texaco Seaboard 1-28 wells (API numbers 01920771 and 01906054, respectively, from south to north).

Data coverage for Chanac Formation
9 to 6 Ma
58 picks, 46 wells

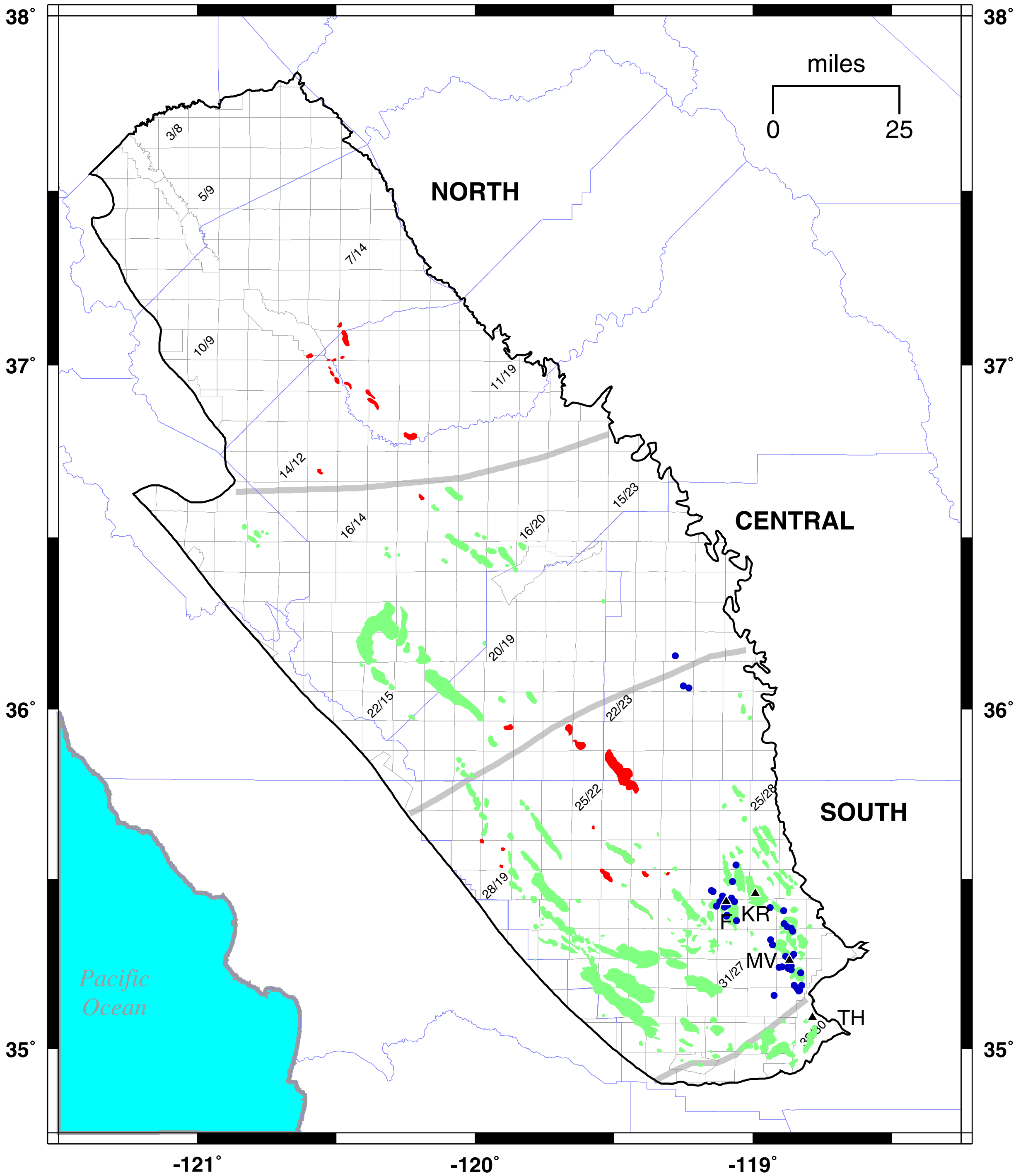


Figure 5.58. Same as figure 5.4, but for the Chanac Formation. MV, Mountain View oil field; F, Fruitvale oil field; KR, Kern River oil field; TH, Tejon Hills.

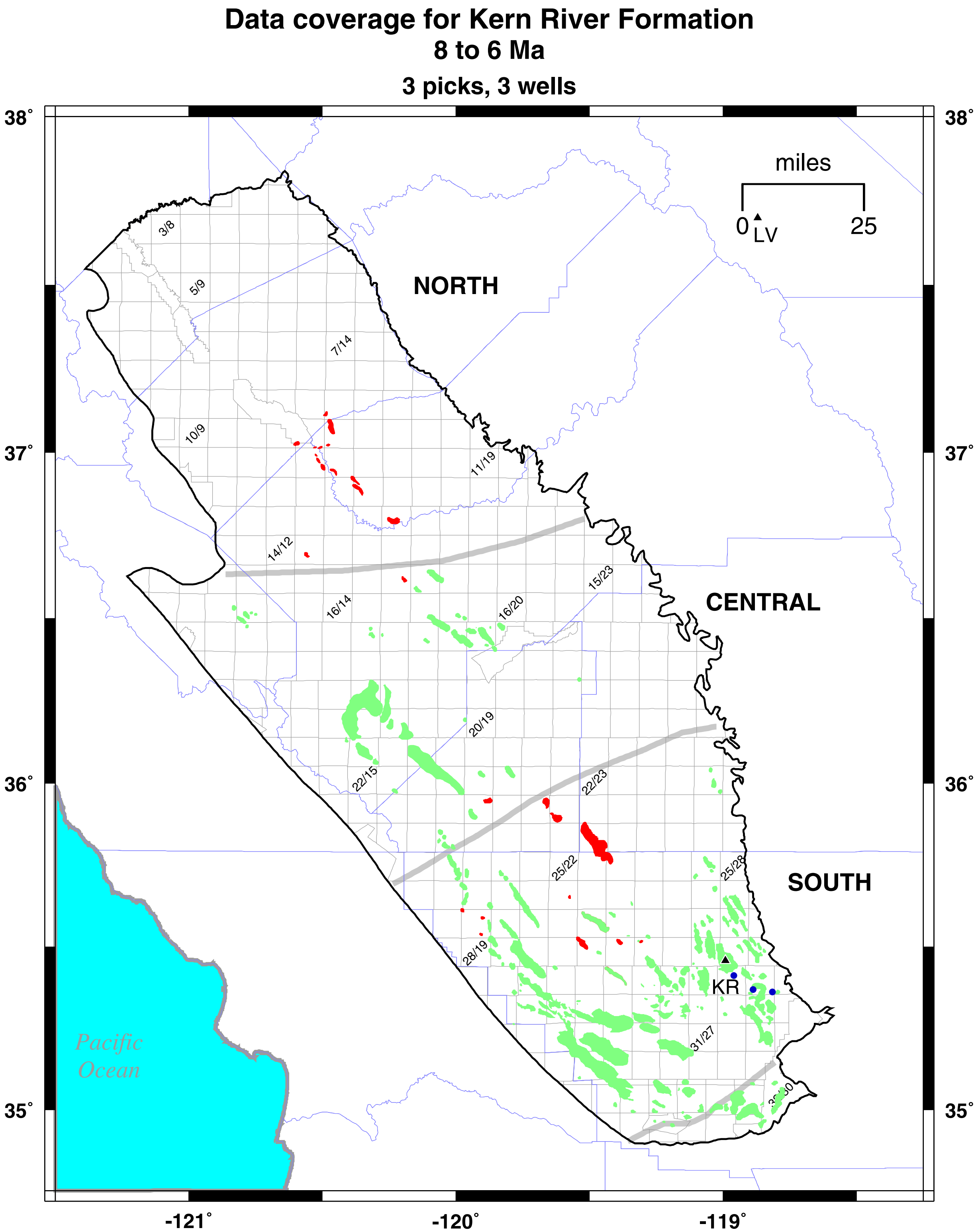


Figure 5.59. Same as figure 5.4, but for the Kern River Formation. KR, Kern River oil field; LV, Long Valley Caldera.

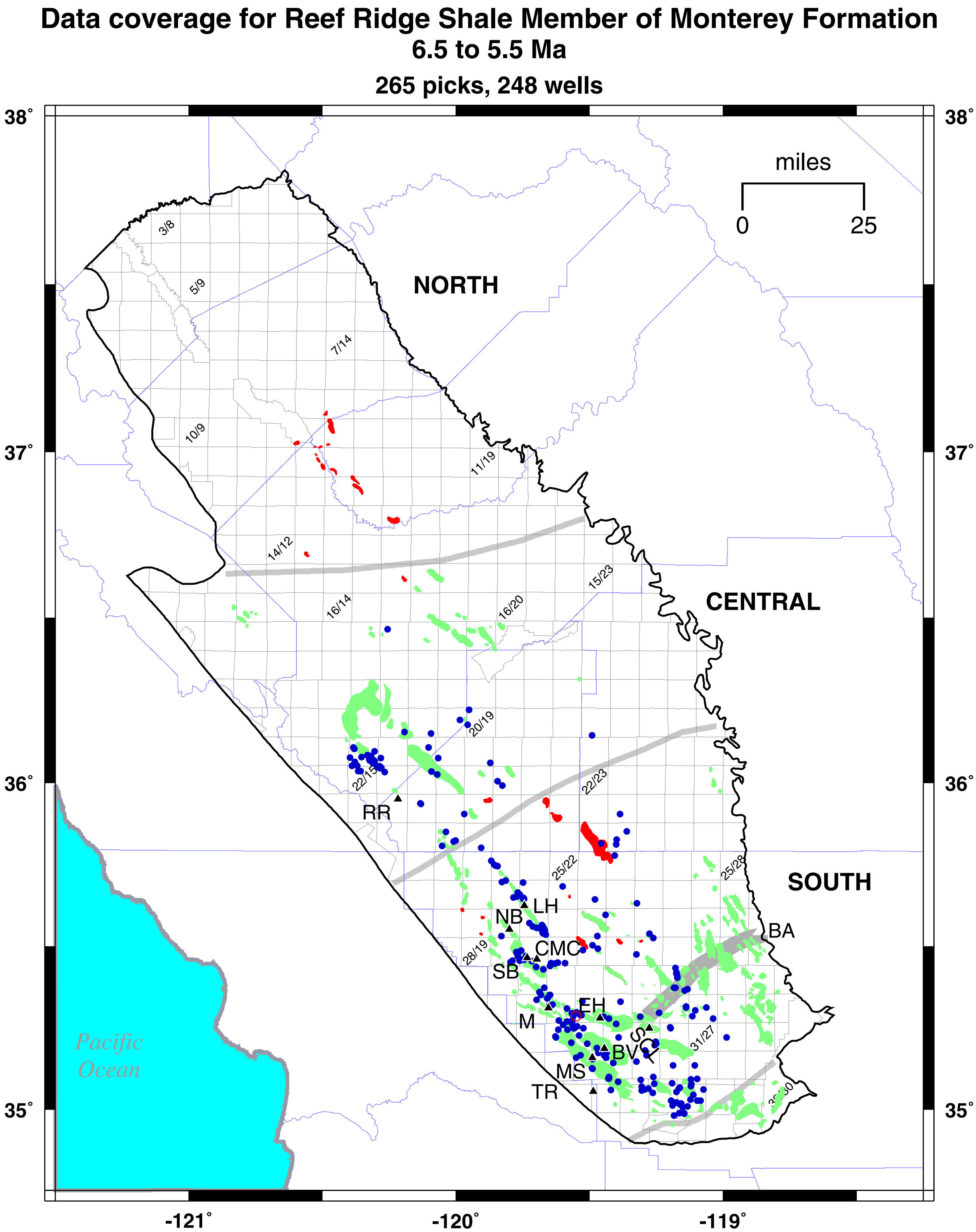


Figure 5.60. Same as figure 5.4, but for the Reef Ridge Shale Member of the Monterey Formation. Broad gray shading indicates location of the buried Bakersfield Arch (BA). SB, South Belridge oil field; CMC, Chico Martinez Creek; MS, Midway-Sunset oil field; M, McKittrick oil field; RR, Reef Ridge; LH, Lost Hills oil field; NB, North Belridge oil field; EH, Elk Hills oil field; BV, Buena Vista oil field; TR, Temblor Range; SCL, South Coles Levee oil field. Open red circle denotes location of Occidental 526-30R well (API number 02941949).

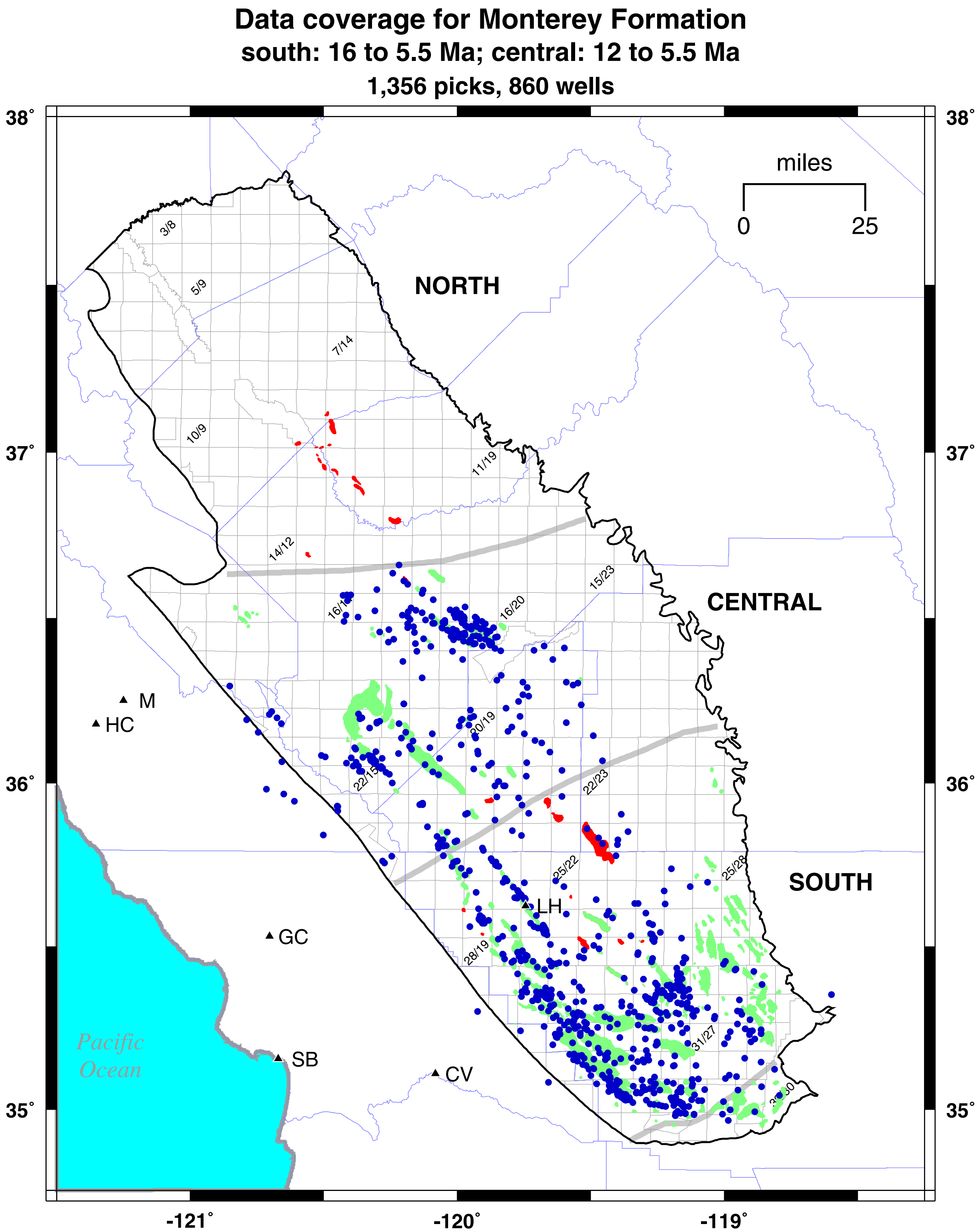


Figure 5.61. Same as figure 5.4, but for the Monterey Formation. LH, Lost Hills oil field; SB, Shell Beach; HC, Horse Canyon; M, Monterey County; CV, Cuyama Valley; GC, Graves Creek.

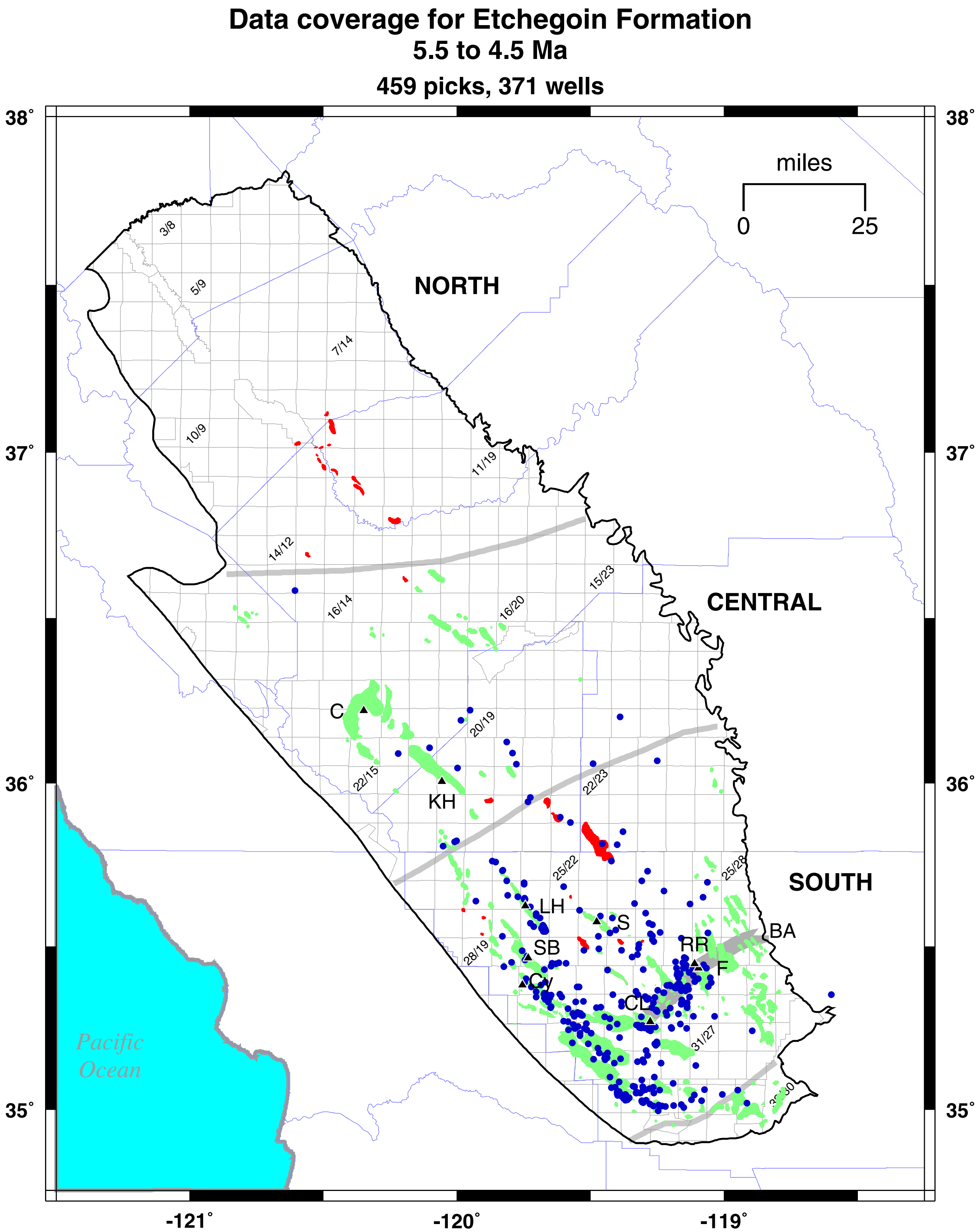


Figure 5.62. Same as figure 5.4, but for the Etchegoin Formation. Broad gray shading indicates location of the buried Bakersfield Arch (BA). F, Fruitvale oil field; RR, Rosedale oil field; S, Semitropic oil field; KH, Kettleman Hills; C, Coalinga oil field; LH, Lost Hills oil field; SB, South Belridge oil field; Cy, Cymric oil field; CL, Coles Levee area.

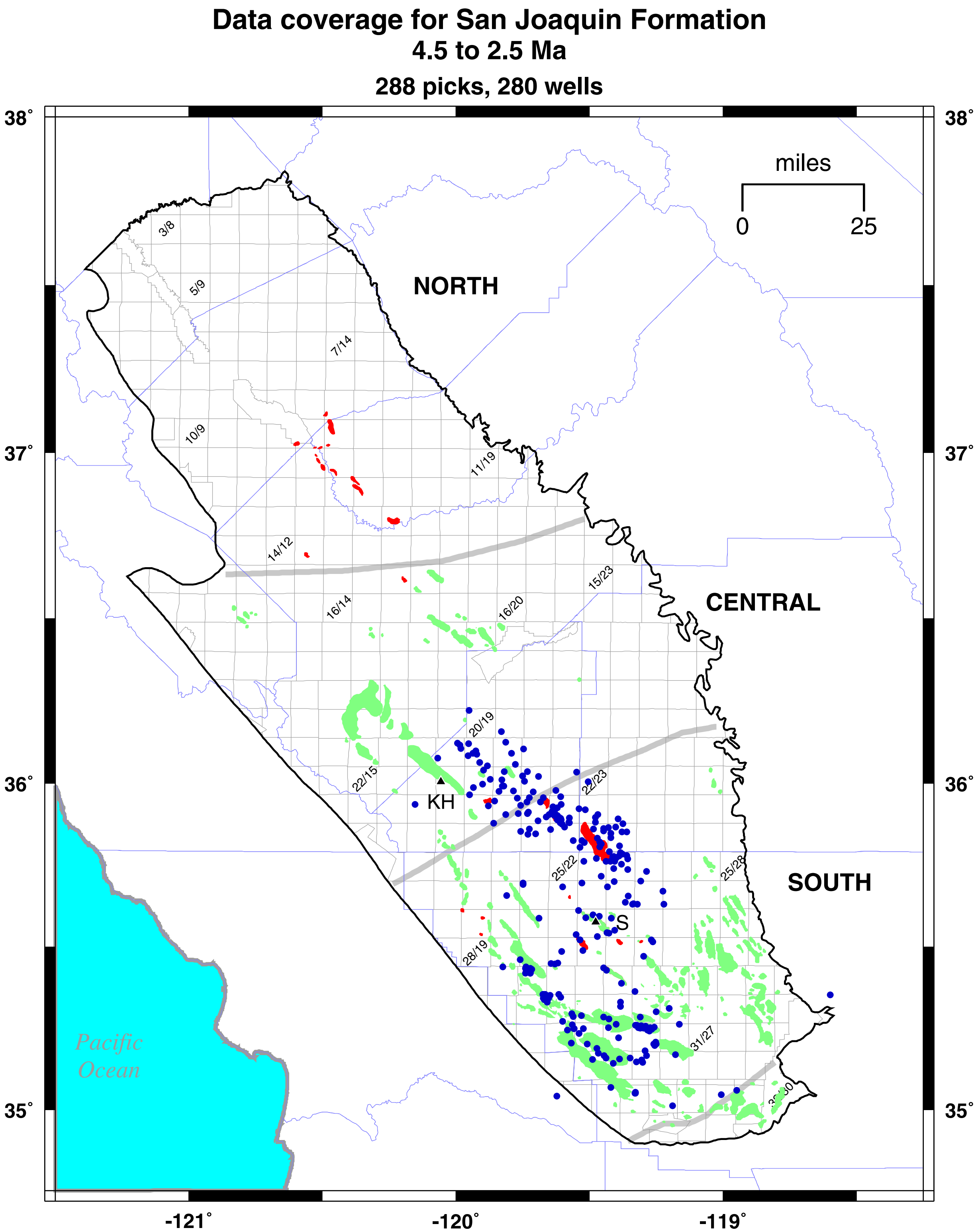


Figure 5.63. Same as figure 5.4, but for the San Joaquin Formation. S, Semitropic oil field; KH, Kettleman Hills.

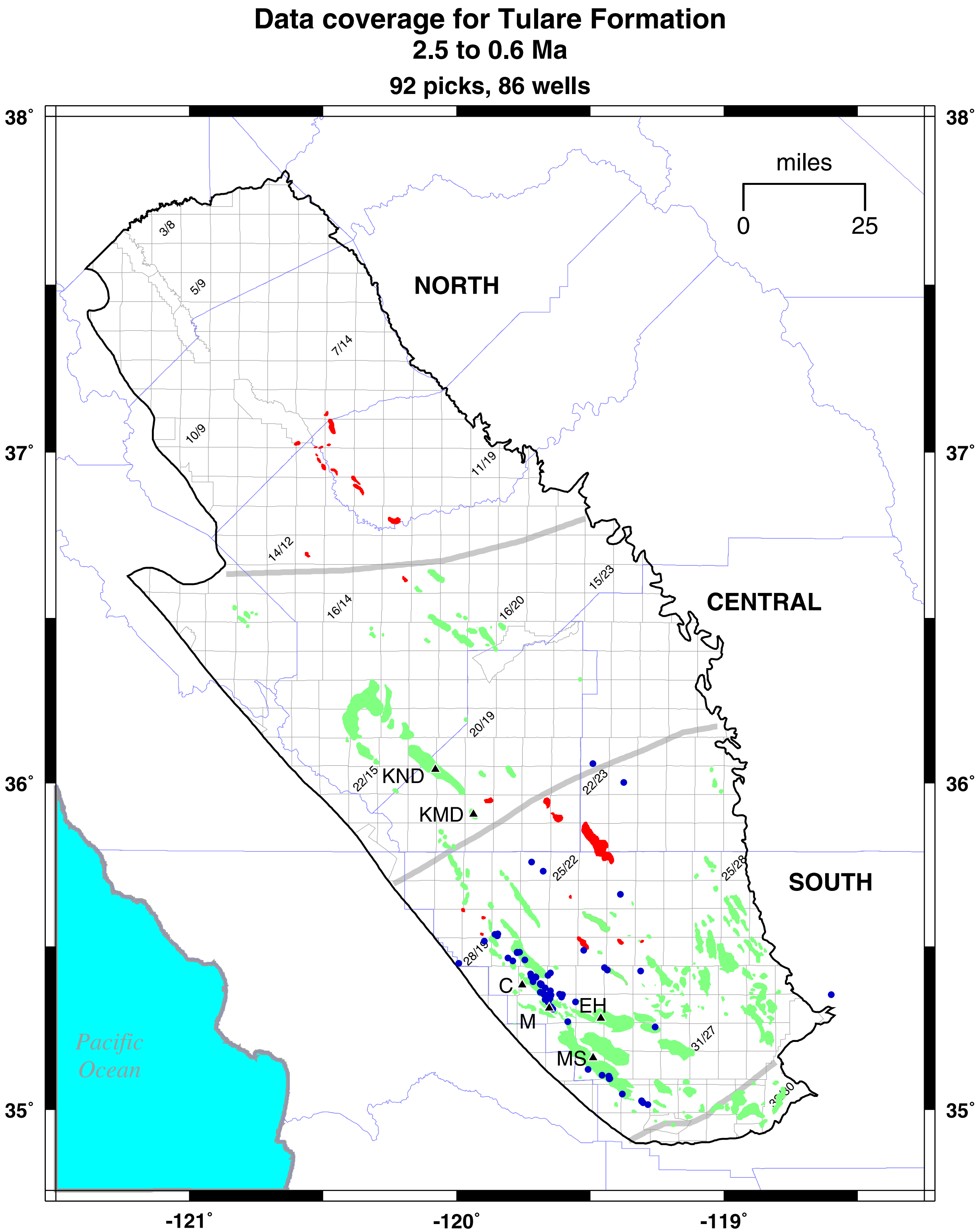


Figure 5.64. Same as figure 5.4, but for the Tulare Formation. KND, Kettleman North Dome; C, Cymric oil field; M, McKittrick oil field; KMD, Kettleman Middle Dome; EH, Elk Hills; MS, Midway-Sunset oil field.