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

Chapter 21

Winters-Domengine Total Petroleum System—Northern Nonassociated Gas Assessment Unit of the San Joaquin Basin Province

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Summary

Boundaries	Province boundary on the north; limit of petroleum system on the south and east; eastern flank of Diablo Range on the west; topographic surface to crystalline basement.
Source Rocks	Winters formation of Edmondson (1962) in Sacramento Valley or Moreno Formation in San Joaquin Valley.
Reservoir Rocks	Submarine fan-slope siliciclastic systems.
Traps	Structural, stratigraphic, and structural/stratigraphic.
Migration	Up-dip from submarine-fan complexes into submarine-canyon sandstone.
Timing	Gas generation began in Winters formation of Edmondson (1962) in Late Cretaceous; gas generation in Moreno Formation began in mid to late Paleocene and continues to present-day.
Existing Fields	Ash Slough, Cheney Ranch, Chowchilla, Gill Ranch, Merrill Avenue, Merrill Avenue Southeast, Mint Road, Moffat Ranch, Raisin City, San Joaquin Northwest.
Exploration Status	Lightly explored (0.1 well per square mile and 11 percent of all sections have at least one exploratory well).
Resource Potential	Potential for undiscovered fields in structural and stratigraphic traps of sizes similar to known fields.

Description

The Northern Nonassociated Gas Assessment Unit (AU) of the Winters-Domengine Total Petroleum System of the San Joaquin Basin Province consists of all nonassociated gas accumulations in Cretaceous, Eocene, and Miocene sandstones located north of township 15 South in the San Joaquin Valley. The northern San Joaquin Valley forms a northwest-southeast trending asymmetrical trough. It is filled with an alternating sequence of Cretaceous-aged sands and shales deposited on Franciscan Complex, ophiolitic, and Sierran basement. Eocene-aged strata unconformably overlie the thick Cretaceous section, and in turn are overlain unconformably by nonmarine Pliocene-Miocene sediments.

Nonassociated gas accumulations have been discovered in the sands of the Panoche, Moreno, Kreyenhagen, and

Domengine Formations and in the nonmarine Zilch formation of Loken (1959) (hereafter referred to as Zilch formation). Most hydrocarbon accumulations occur in low-relief, northwest-southeast trending anticlines formed chiefly by differential compaction of sediment and by northeast-southwest directed compression during the Paleogene (Bartow, 1991) and in stratigraphic traps formed by pinch out of submarine fan sands against slope shales. To date, 176 billion cubic feet (BCF) of nonassociated recoverable gas has been found in fields within the assessment unit (table 21.1). A small amount of biogenic gas forms near the surface of the AU.

Map boundaries of the assessment unit are shown in figures 21.1 and 21.2; in plan view, this assessment unit is identical to the Northern Area Nonassociated Gas play 1007 considered by the U.S. Geological Survey (USGS) in its 1995 National Assessment (Beyer, 1996). The AU is bounded on the east by the mapped limits of Cretaceous sandstone reservoir rocks and on the west by the east flank of the Diablo Range. The southern limit of the AU is the southernmost occurrence of nonassociated thermogenic-gas accumulations. The northern limit of the AU corresponds to the Stanislaus-San Joaquin county line, which also defines the northern boundary of the San Joaquin Basin Province. In the vertical dimension, the AU extends from the uppermost crystalline basement to the topographic surface (fig. 21.3), to allow for the possibility of down-section charge across fault surfaces and up-dip migration.

The gas in this AU may be sourced from the Winters-Domengine(?) petroleum system, located in the Sacramento Valley north of the San Joaquin Valley, as defined by Magoon and others (1994a,b) (question mark notation derives from convention of Magoon and Dow, 1994, and indicates speculative genetic relationship between hydrocarbons and source rock). The Winters-Domengine Total Petroleum System defined for this assessment contains about 7.2 trillion cubic feet (TCF) of known, recoverable gas and includes the Rio Vista gas field, which alone accounts for 4 TCF of recoverable gas through 2002 (CDOGGR, 2003). Alternatively, the northern nonassociated gas may be sourced from the Moreno Formation within the San Joaquin Valley itself.

Source Rocks

In general, gas source rock units are difficult to identify with confidence because they usually have low hydrogen index (<300 milligrams hydrocarbon per gram total organic carbon), the methane molecule is too simple to correlate with the organic matter in the source rock, and the carbon isotopic composition of thermogenic methane from all source rocks is similar (–40 per mil). Because the San Joaquin Valley lies adjacent to the prolific gas province in the Sacramento Valley, an obvious source of nonassociated gas in the assessment unit is one of the gas systems within the Sacramento Valley. Magoon and others (1994a,b) identified two gas-prone petroleum systems in that region—the Dobbins-Forbes(?) system, which totals about 2.3 TCF of recoverable gas and the Winters-Domengine(?) system, responsible for 7.2 TCF of known, recoverable gas. On the basis of chemical characteristics of the two petroleum systems, nonassociated gas in the San Joaquin Basin Province appears more similar to gas produced from the Winters-Domengine petroleum system than from the Dobbins-Forbes petroleum system (fig. 21.4).

The suspected source rock for the Winters-Domengine Total Petroleum System of this assessment is the shale facies of the Winters formation of Edmondson (1962) (hereafter referred to as the Winters formation) (Magoon and Valin, 1996). This gas-prone source rock generates mostly methane and some high API gravity (39 to 49 degrees) liquid within a mature pod adjacent to the Rio Vista gas field (fig. 21.5*A*). Condensate produced in this region lacks aromatic hydrocarbons and has an isotopic composition of saturated hydrocarbons of about –26 per mil. However, this information is insufficient to definitively identify the source rock for the petroleum system, except to say that it is Cretaceous in age.

Several factors favor the Sacramento Valley as the source for nonassociated gas in the northern San Joaquin Valley. First, gas compositions vary systematically from relatively wet gas (less than 95 percent methane) in the source region to very dry gas (99.00 to 99.99 percent methane) in the gas fields of the southern Sacramento Valley. Gas samples from fields in the northern San Joaquin Valley similarly exhibit very dry compositions (Lillis and others, this volume, chapter 10). Second, gas reservoirs in the northern San Joaquin Valley occur in Late Cretaceous and Eocene-aged sandstones, which lie stratigraphically above the suspected source rock in the Winters formation.

Despite these positive factors, a distal source rock for the nonassociated gas in the northern San Joaquin Valley is problematic for several reasons. First, the Stockton Arch, a buried anticline that physically separates the Sacramento Valley from the San Joaquin Valley (fig. 21.1), formed in latest Cretaceous or early Tertiary time (Bartow, 1991), or about coincident with initial gas generation in the Sacramento Valley. Although subsurface structure across the arch records a complicated deformation history in the Late Cretaceous, post-Cretaceous offset occurred in a reverse sense, with down-to-the-north motion (Bartow, 1991). Thus, structural complexity across the arch may have barred southward migration of gas produced from the Winters formation to the north. Further, the geometry of producing formations in the northern San Joaquin Valley had not yet been established at the time of initial hydrocarbon generation in the Sacramento Valley; gas was generating for about 40 m.y. prior to deposition of the prolific Eocene-aged sandstones in the San Joaquin Valley. Additionally, gas pools in the northern San Joaquin Valley lie between 100 and 140 miles south of the pod of active source rock of the Winters formation (fig. 21.5*A*). Such large geographic distances require lengthy and complicated migration paths from source to reservoir, even if stratigraphic dip and lithology are favorable. Stratigraphic dip is not favorable, however, as strata tilt southward from the Sacramento Valley to the San Joaquin Valley, thereby requiring down-dip migration. Finally, the absence of discovered gas fields north of Chowchilla field in the San Joaquin Valley suggests that gas did not migrate from a more northern source.

An alternative source rock for the nonassociated gas in the northern San Joaquin Valley is the Moreno Formation within the province itself (figs. 21.5*B* and 21.6). Shale facies of the Moreno Formation contain “fair” to “very good” (according to the qualitative scale of Peters and Cassa, 1994) values of total organic carbon (Peters, Magoon, Valin, and Lillis, this volume, chapter 11). Initial study of the Moreno Formation emphasized its source rock properties for oil generation, as oil samples from the Oil City pool near Coalinga field appear to have been sourced from the nearby pod of active source rock of the Moreno Formation (McGuire, 1988). Further examination of the Moreno Formation, however, revealed several properties favorable for gas generation, including the presence of gas-prone type III organic matter (Magoon and others, this volume, chapter 8).

The proximity (20 to 60 miles) of the Moreno pod of active source rock to the gas fields of the northern San Joaquin Valley (fig. 21.5*B*) argues against the distal Winters formation as the source for the basin’s dry gas. Stratigraphic relationships further favor the Moreno Formation as the source of the basin’s thermogenic gas, as the accumulation of thick sedimentary sequences during the Miocene and Pliocene created dip reversal, allowing for up-dip migration from a source southwest of the AU to the northern gas fields. Additionally, the geometry of the producing formations was established prior to, or coincident with, hydrocarbon generation in the Moreno Formation. For all of these reasons the Moreno Formation seems to be the most likely source of thermogenic gas in the northern San Joaquin Valley.

Although we favor the local Moreno Formation as the source of the San Joaquin Valley’s nonassociated gas, this determination was made after the 2003 assessment of undiscovered hydrocarbon resources. Thus, we retain the name Winters-Domengine Total Petroleum System, as used in the assessment, but acknowledge that the system is probably better described as the Moreno-Nortonville Total Petroleum System (see Magoon and others, this volume, chapter 8, for details of the Moreno-Nortonville system).

Maturation and Migration

On the basis of the burial history curve of Zieglar and Spotts (1978), significant thermogenic gas generation from Cretaceous-aged source rocks in the Sacramento Delta depocenter began 70 to 80 Ma and may continue to the present day in regions where burial depths exceed 13,000 to 15,000 feet. If the Winters formation is the source of nonassociated, thermogenic gas within the San Joaquin Valley, migration distances exceed 100 miles from source to trap. Geochemical relationships indicate that separation of generated liquid and gas occurred just beyond the source area, near the Rio Vista field (fig. 21.5*A*), and methane subsequently may have migrated south to gas fields in the assessment unit.

As discussed above, the Moreno Formation is a more likely candidate for the source of thermogenic gas in the northern San Joaquin Valley. According to numerical petroleum systems modeling, burial depths of 15,000 feet are needed to generate gas and light oil from Moreno Formation source rock (Peters, Magoon, Lampe, and others, this volume, chapter 12). At the deepest point in the depocenter, oil and gas generation began about 58 Ma, peaked about 54 Ma, and ended about 46 Ma (Peters, Magoon, Lampe, and others, this volume, chapter 12). Within the pod of active source rock as a whole, maturation progressed from southwest to northeast, in the direction of the northern gas fields; hydrocarbon generation continues to the present day in the northeast portion of the pod (fig. 21.5*B*). Gas generation probably occurred in a similar manner as in the Sacramento Valley, with relatively wet gas and liquids forming in the pod (for example, 33 to 40 degrees API gravity oil in the Oil City pool; CDOGGR, 1998) and separation of liquids and gas occurring progressively during migration between source and reservoir. Indeed, gas-oil ratios (GOR) support this scenario, as fields become progressively more gas rich from west to east—GOR averages 20,025 cubic feet per barrel (ft^3/bbl) at Cantua Creek field (just south of the assessment unit), 25,915 ft^3/bbl at Cheney Ranch field, and 820,000 ft^3/bbl in the dry gas reservoir at Raisin City field (CDOGGR, 2003).

Reservoir Rocks

The rocks that volumetrically constitute the bulk of the assessment unit are Late Cretaceous siliciclastic lithofacies derived from the Sierran magmatic arc on the eastern margin of the San Joaquin Valley and possibly from the Diablo Range to the west. A thinner sequence consisting of the Eocene Domengine and Kreyenhagen Formations and the shallow marine and nonmarine Oligocene to Miocene Zilch formation overlie the thick Cretaceous section within the assessment unit (fig. 21.6).

Reservoir characteristics of Cretaceous rocks within the assessment unit are best understood in terms of their depositional environments. Because of pronounced facies changes within the subsurface and because of a long history of inconsistent nomenclature applied to these rocks (see for example, Bishop, 1970; Nilsen and Moore, 1997), we adopted the stratigraphic framework for Late Cretaceous strata in the San Joaquin Valley as summarized by Nilsen and Moore (1997; fig. 21.7). Hosford Scheirer and Magoon (this volume, chapter 5) and Hosford Scheirer (this volume, chapter 7) describe the age, geographical extent, subsurface depth, and thickness of each unit in detail.

In addition to the reservoir rocks discussed below, minor production also occurs from the Moreno Formation at Cheney Ranch and Chowchilla fields (3.3 BCF for both fields), from the Ragged Valley silt of Hoffman (1964) at Gill Ranch field (7.3 BCF), and from the Zilch formation at Chowchilla field (4.6 BCF) (all volumes are through 2002 and derive from CDOGGR, 2003).

Delta Facies

Subsurface strata along the eastern margin of the northern San Joaquin Valley contain two major deltaic complexes, the Starkey sands of Hoffman (1964; hereafter referred to as Starkey sands) and the Garzas Sandstone Member of the Moreno Formation. Both deltas prograded southwestward into deep-water settings during lowstand conditions and thus record the filling of the basin to sea level (Nilsen and Moore, 1997). In geographical extent, the Starkey sands are restricted to the subsurface, whereas the Garzas Sandstone Member crops out on the basin's west side. Both delta systems grade laterally into slope shales, submarine fans, and basin-plain shales (figs. 21.7 and 21.8). Turbidites typically interbed with these facies.

The Starkey sands consist of a series of four cuspate, wave-dominated delta systems (Cherven, 1983) (fig. 21.8). Each deltaic deposit is separated from the next by intervening, transgressive shale; together each sand-shale pair represents one cycle of sea level regression and transgression (Cherven, 1983). From east to west, facies of the Starkey sands vary from braided-stream deposits near the eastern basin margin to delta-front deposits in the vicinity of Gill Ranch and Chowchilla fields to offshore deep marine deposits near the basin axis (Philbrick, 1997). Starkey sands generally pinch out in the subsurface along the basin's northwest-southeast structural trend, indicating that their Sierra Nevada source was aligned much as it is today (Callaway, 1964). The distal edge of Starkey sands deposition, or delta front, marks the shelf-slope break, where Starkey sands grade laterally into slope shales and basinal submarine-fan deposits, such as the Blewett and Tracy sands of Hoffman (1964; hereafter referred to as Blewett sands and Tracy sands) and the Lathrop sand of Callaway (1964; hereafter referred to as Lathrop sand; figs. 21.6 through 21.8). Starkey sands contain benthic Foraminifera of Almgren's (1986) lower D-1 to D-2 zones, implying deposition from about 75 to 71.5 Ma. Undifferentiated E- and F-zone shelf sand facies underlie the Starkey sands on the eastern margin of the basin (Callaway, 1990; fig. 21.7).

Gas production from Starkey sands occurs at Chowchilla, Gill Ranch, and Moffat Ranch fields; typically these sands are referred to on well logs at these fields as "Panoche sands." In those reservoirs, porosity ranges from about 26 to 36 percent, average reservoir depth varies between 5,400 and 7,500 feet, and average net pay thickness varies between 7 and 50 feet (CDOGGR, 1998). Through 2002, gas production from reservoirs in Starkey sands totaled about 50 BCF (CDOGGR, 2003).

Submarine Fan Systems

Three submarine-fan systems are found southwest (seaward) of the marginal delta facies in the northern San Joaquin Valley. In ascending order, these are the Lathrop, Tracy, and Blewett sands (Nilsen and Moore, 1997; figs. 21.7 and 21.9). Deposition of each fan system was followed by a relative sea-level highstand, during which a condensed section of shale was deposited. The Sacramento shale of Callaway (1964) forms the base of this alternating sequence of basinal shales and submarine fans, and unnamed lower shale members of the Moreno Formation cap the Cretaceous-aged sequence (figs. 21.6 and 21.7).

The Blewett sands represent a deep-water submarine-fan system that is either time-equivalent to (Nilsen and Moore, 1997) or stratigraphically younger than (Philbrick, 1997) the first member of the Starkey sands. Although Callaway (1964) asserted that the Blewett, Tracy, and Lathrop submarine-fan systems were supplied with sediment shed from the Coast Ranges west of the San Joaquin Valley, Suchsland and Peters (1997) and Philbrick (1997) believe that all three sand systems were sourced from the Sierra Nevada to the east and were transported westward to the basin floor through submarine canyons eroded into the Starkey sands (fig. 21.9). Fan deposits generally form convex-upward, radially directed mounds. These deposits are further classified by Nilsen and Moore (1997) as mud and sand filled inner-fan channels, middle-fan sandstone bodies, and outer-fan mud-rich facies. Blewett sands contain benthic fauna from the D-1 zone (Almgren, 1986), indicating deposition from about 72 to 68 Ma.

Exploration of the Blewett sands trend in the San Joaquin Basin Province has yielded three new field discoveries in the past 15 years—the Ash Slough, Merrill Avenue, and Mint Road fields. Average properties of Blewett sands pools in these fields include porosity values of 27 to 35 percent, reservoir depths of 5,500 to 6,600 feet, and net pay thicknesses of 15 to 28 feet (CDOGGR, 1998). Through 2002, gas production from reservoirs in Blewett sands totaled nearly 34 BCF (CDOGGR, 2003; table 21.1). Unlike the Sacramento Valley, the Lathrop and Tracy sands submarine-fan systems produce little to no gas where tested in currently known fields.

Domengine and Kreyenhagen Formations

The most prolific reservoirs in the gas fields of the northern San Joaquin Valley to date are Eocene-aged sands, with nearly 72 BCF of gas produced through 2002 (CDOGGR, 2003; table 21.1). In the northern San Joaquin Valley, the Domengine Formation unconformably overlies the Garzas Sandstone Member, indicating complete erosion of Paleocene-aged units and undoubtedly some erosion of Late Cretaceous strata (fig. 21.6). The upper productive portion of the Domengine Formation is a widespread blanket sand consisting of fine- to coarse-grained, dark green, glauconitic sandstone, locally known as the Green sand of Loken (1959). This sand is interbedded with thin, brown siltstones (Loken, 1959). The thickness of the Domengine Formation ranges between about 60 and 150 feet in the northern gas fields of the San Joaquin Basin Province (CDOGGR, 1998). The Kreyenhagen Formation conformably overlies the Green sand of Loken (1959). It is comprised of firm, brown shale containing thin, lenticular gas-bearing sands (Loken, 1959). In the gas fields of the northern San Joaquin Valley, the thickness of the Kreyenhagen Formation ranges between 150 and 400 feet (CDOGGR, 1998).

Strata of the Kreyenhagen and Domengine Formations produce (or produced in the past) dry gas at Gill Ranch (56.6 BCF), Moffat Ranch (10.6 BCF), San Joaquin Northwest (3.7 BCF), Chowchilla (0.7 BCF), and Raisin City (0.4 BCF) fields (CDOGGR, 2003). Average reservoir properties in those fields include porosity values of 26 to 33 percent, reservoir depths of 3,000 to 6,800 feet, and net sand thicknesses of 10 to 45 feet (CDOGGR, 1998).

Traps and Seals

In the northern San Joaquin Valley, gas is produced primarily from structural traps in deltaic deposits, such as the Starkey sands at Chowchilla field (fig. 21.10); from structural and stratigraphic traps in submarine fan deposits, such as the Blewett sands at Merrill Avenue field (fig. 21.11); and from blanket and lenticular sands in the Domengine and Kreyenhagen Formations at Gill Ranch field (fig. 21.12). All seals on these accumulations consist of shale or silty shale. Structural traps form by down-to-the-basin faults, by sedimentary compaction over anticlines, and by pinch-out of sandstone beds across structural noses. Unlike the Sacramento Valley, where large-offset faults such as the Midland, Vernalis, and Stockton faults significantly influence hydrocarbon accumulation (for example, Cherven, 1983), no major subsurface faults are recognized in the northern San Joaquin Valley (Bartow, 1991). Small-offset faults, however, may play a role in hydrocarbon trapping (figs. 21.10 and 21.12).

Stratigraphic traps form in a variety of ways within the Northern Nonassociated Gas Assessment Unit. The most common type of stratigraphic trap occurs where submarine fans pinch out against flanking shale facies up-dip, as at Merrill Avenue (fig. 21.11) and Ash Slough fields (fig. 21.13). At Ash Slough field, the Moffat Ranch submarine canyon supplied sediment to the Blewett sands fan system (Suchsland and Peters, 1997). Shale of the Moreno Formation seals the gas accumulation up-dip (fig. 21.13). A similar stratigraphic trap exists where outer-fan sandstone pinches out against basinal shale, as at Cheney Ranch field, where the Jergins sand of Payne (1974) truncates against the Tierra Loma Shale Member of the Moreno Formation (fig. 21.14). Because this field lies west of the basin axis (unlike all other known fields in the assessment unit), the eastward, rather than westward, dip of basinal shale seals the gas accumulation.

Exploration Status and Resource Potential

The USGS assessment of the Northern Nonassociated Gas Assessment Unit was driven by several scenarios under which additional dry gas, perhaps as much or more as is already known, may be discovered. Undiscovered gas accumulations may exist in a variety of trap styles throughout the large area between the northernmost gas field of the San Joaquin Valley (Chowchilla) and the southernmost gas fields of the Sacramento Valley (Vernalis and McMullin Ranch; fig. 21.15). Cretaceous and Eocene strata continue northwards toward the fault-bounded Stockton Arch in much the same geometry and facies as at existing fields, but this 50 mile stretch contains areas that remain untested by exploratory wells (fig. 21.15). The general exploration scenario would be to test, with seismic technology and wildcat drilling, a swath of land perhaps several miles wide and oriented along the northwest-southeast trend of known fields to identify additional structural and stratigraphic traps.

Figure 21.15 summarizes on a regional scale the geographic distribution of potential stratigraphic and structural traps in the northern San Joaquin Valley. Additional structurally trapped accumulations probably exist in much the same geometry as at known fields (blue shading, fig. 21.15). Structural domes and anticlines formed by differential compaction, such as at Chowchilla field (fig. 21.10), may exist in the Starkey sands and Garzas Sandstone Member delta systems and in overlying Tertiary strata. Varied types of stratigraphic traps provide favorable exploration targets in the AU, especially because the last several new field discoveries include stratigraphic trapping components. In the Sacramento Valley, the Winters formation fan system forms stratigraphic traps where turbidite sands pinch out up-dip against slope shales (Cherven, 1983). Exploration for this trap type has also proved successful in the northern San Joaquin Valley, where submarine fan deposits of the Blewett sands intersect interchannel or slope shales—nearly 34 BCF of gas (through 2002) has been produced from Blewett sands reservoirs in Mint Road, Merrill Avenue, Merrill Avenue Southeast, and Ash Slough fields (CDOGGR, 2003). Submarine-fan systems that lie stratigraphically below the Blewett sands, such as the Tracy and Lathrop sands (figs. 21.6 and 21.7), may prove similarly productive, as their depositional environments resemble that of the Blewett sands fan. Successful exploration for this type of stratigraphic accumulation will depend on accurate paleogeographic mapping of sand and slope facies within submarine channels and turbidite fans. These types of accumulations likely lie along a northwest-southeast trend between the basin axis and the seaward (southwestward) extent of paleodelta fronts (green shading, fig. 21.15; Suchsland and Peters, 1997). Minor normal faulting within these fans may also provide low relief closures for structural trapping (Suchsland and Peters, 1997).

A second type of stratigraphic trap occurs west of the basin axis, where outermost submarine-fan deposits pinch out against east-dipping basin-plain shale, as at Cheney Ranch field (pink shading, fig. 21.15). However, traps in distal submarine sands may contain only small volumes of gas, as at Cheney Ranch field, because of thin productive intervals and/or reduced permeability due to fine grain size of distal fan sands. Philbrick (1997) suggested a third type of stratigraphic accumulation in the San Joaquin Valley whereby overlap of submarine fans from different slope channels produces vertical permeability variations and thus multiple potential gas reservoirs.

In summary, the USGS assessment of undiscovered gas accumulations in the northern San Joaquin Basin Province depends on the integration of the discovery history of known fields with the geological likelihood of potential targets. Our forecast from this exercise is rather positive compared with estimates for other assessment units in the province because of favorable geological scenarios and new field discoveries in the last twenty years. Indeed, the Northern Nonassociated Gas Assessment Unit differs markedly from most of the other assessment units in the basin (such as the Southeast Stable Shelf, this volume, chapter 13, and the Miocene West Side Fold Belt, this volume, chapter 15) in that statistical analyses of drilling and discovery history reveal a relatively random population of gas discoveries, by volume, through time (fig. 21.16). In contrast, statistical treatments of the discovery process within most of the other assessment units exhibit a pattern wherein the largest fields were found first and subsequent discoveries decreased markedly in size. Exploration activity within the Northern Nonassociated Gas Assessment Unit appears to be on the rise—20 exploratory wells were drilled between the years 2000 and 2003 (CDOGGR, 2001, 2002, 2003, 2004), which is more than had been drilled since the flurry of new field and pool discoveries in the late 1980's and early 1990's.

On the basis of all of these factors, we estimate that the most likely number of gas fields larger than 3 BCF yet to be discovered in the Northern Nonassociated Gas Assessment Unit is just smaller than the number of known fields—about six or seven. Further, we estimate that undiscovered gas field size ranges from 3 to 60 BCF, with a median value of 10 BCF; this median matches the median accumulation size for the second half of discovered fields within the AU. The potential additions to reserves from new-field discoveries range from about 200 BCF at the F5 level to 33 BCF at the F95 level, with a mean of 106 BCF (fig. 21.17).

USGS assessments of undiscovered hydrocarbon resources at the assessment unit level, described by Gautier and others (this volume, chapter 2) and Schmoker and Klett (this volume, chapter 24), do not specifically address additions to reserves that may occur by the discovery of deeper pools in existing fields. Reserve growth via new pool discoveries nevertheless provides additional exploration strategies for the Northern Nonassociated Gas Assessment Unit—a deeper pool discovery in sands of the Panoche Formation occurred at Gill Ranch field in 1989. Even deeper Cretaceous strata may prove to be potential sources of undiscovered gas pools, as strata containing benthic fauna representative of Goudkoff's (1945) F-zone are productive in the Chowchilla field and in the Sacramento Valley to the north but are generally underexplored throughout most of the AU. Reservoir quality may deteriorate with depth, however, making the success of these potential reservoirs uncertain.

All assessment results and supporting documentation for the Northern Nonassociated Gas Assessment Unit of the San Joaquin Basin Province are available in files c100101.pdf (data form for conventional assessment unit), d100101.pdf (summary of discovery history), em100101.pdf (probabilistic estimates), g100101.pdf (graphs of exploration and discovery data for grown volumes), and k100101.pdf (graphs of exploration and discovery data for known volumes). Klett and Le (this volume, chapter 28) summarize the contents of these files.

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Figures

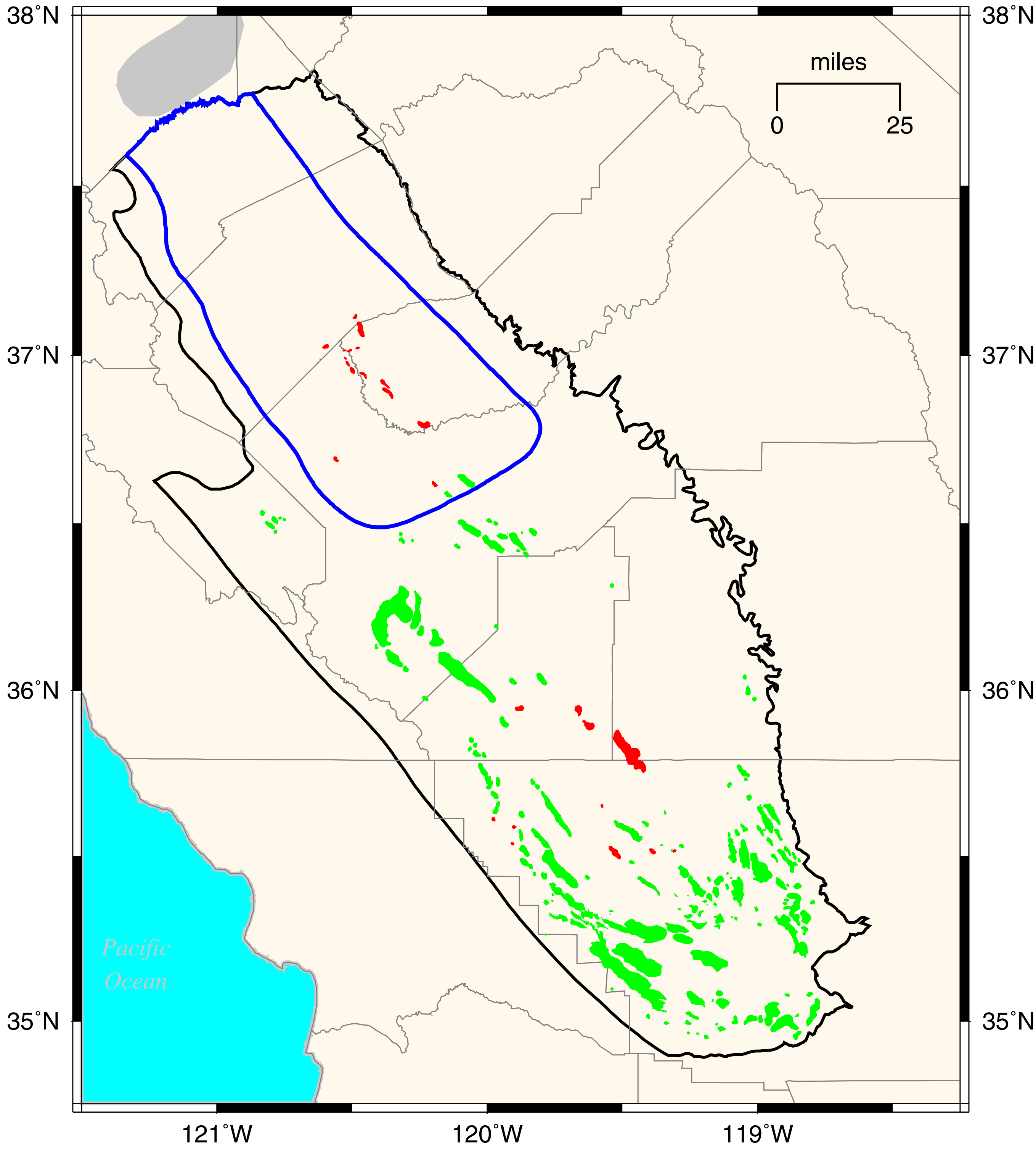


Figure 21.1. Location map of the San Joaquin Valley, illustrating San Joaquin Basin Province boundary (bold line), county boundaries (thin gray lines), Northern Nonassociated Gas Assessment Unit boundary (blue line), and oil (green) and gas (red) fields in the province. Gray shading shows the location of the Stockton Arch, which is mapped on the basement surface in a three-dimensional geologic model of the basin (Hosford Scheirer, this volume, chapter 7).

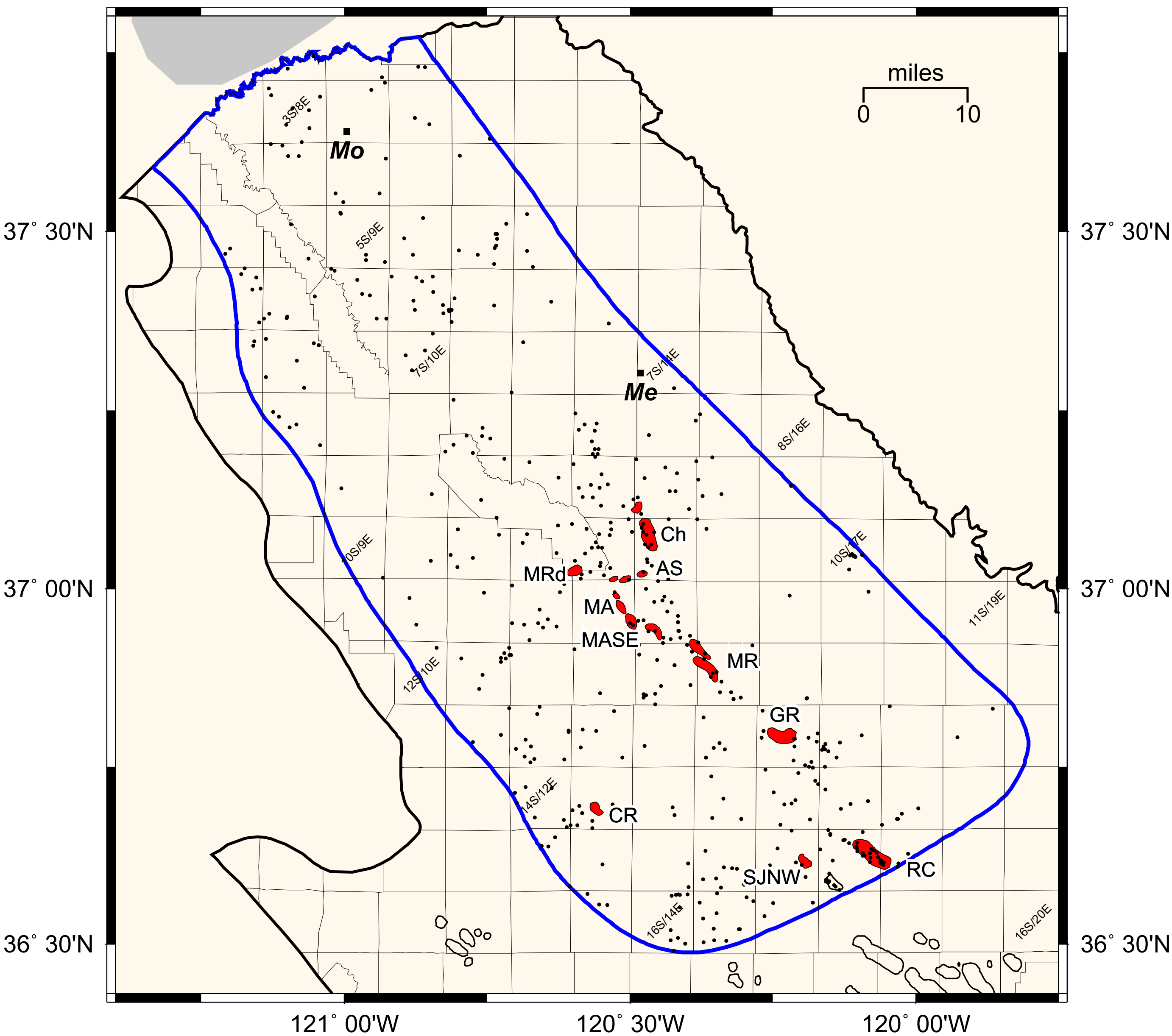


Figure 21.2. Detailed map of Northern Nonassociated Gas Assessment Unit (AU). The blue line indicates the geographic limit of the AU. Gas fields and pools in the AU are colored red. Fields outside the AU, or within the map boundaries of the AU but assigned to a different assessment unit, are outlined in black. Filled circles represent 503 exploratory wells drilled for petroleum within the AU between 1922 and 1996. Well locations are from the California Department of Conservation, Division of Oil, Gas, and Geothermal Resources, and are available at ftp://ftp.consrv.ca.gov/pub/oil/maps/dist5. Township and range grid is indicated for scale and location; scattered labels are relative to the Mount Diablo baseline and meridian. Gray shading shows the location of the Stockton Arch, which is mapped on the basement surface in a three-dimensional geologic model of the basin (Hosford Scheirer, this volume, chapter 7). Cities of Modesto (Mo) and Merced (Me) are denoted with filled squares. Gas field labels are: Ch=Chowchilla, AS=Ash Slough, MRd=Mint Road, MA=Merrill Avenue, MASE=Merrill Avenue Southeast, MR=Moffat Ranch, GR=Gill Ranch, CR=Cheney Ranch, SJNW=San Joaquin Northwest, and RC=Raisin City.

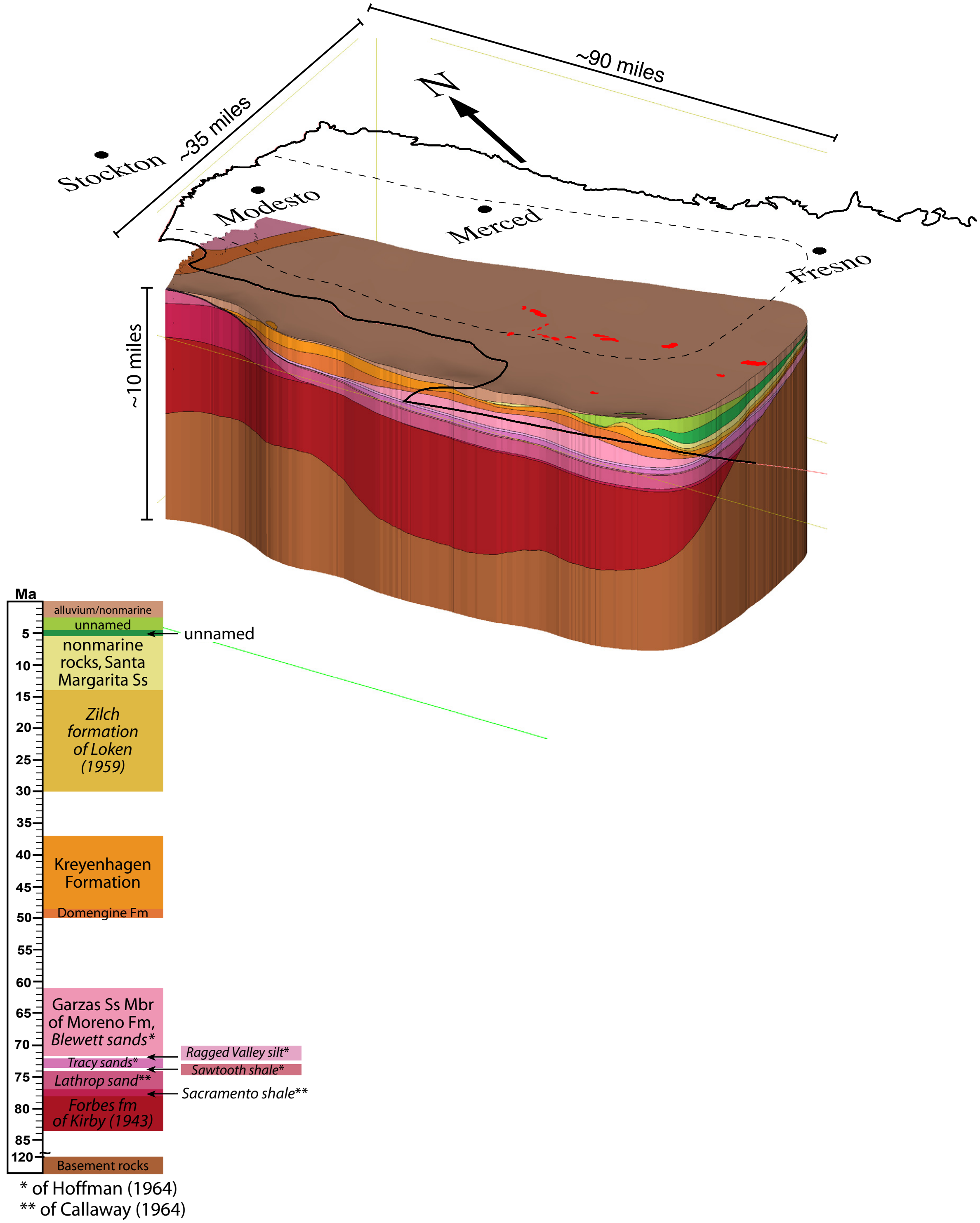


Figure 21.3. Three-dimensional stratigraphy model of the Northern Nonassociated Gas AU extracted from the EarthVision® model of the basin by Hosford Scheirer (this volume, chapter 7). The major stratigraphic units within the AU are listed; see figure 21.6 for stratigraphic relationships between the units. Formation names in italics are informal. Informal names not previously defined include the Forbes formation of Kirby (1943). Gas fields and pools (red) in the AU are draped on the topographic surface. The San Joaquin Basin Province boundary (bold line), AU boundary (dashed line), and city names and locations float above the surface of the model. View is from the southwest at a 30° inclination angle. Vertical exaggeration is 4. Fm, Formation; fm, formation; Mbr, Member; Ss, Sandstone. EarthVision is a registered trademark (Marca Registrada) of Dynamic Graphics, Inc., Alameda, Calif.

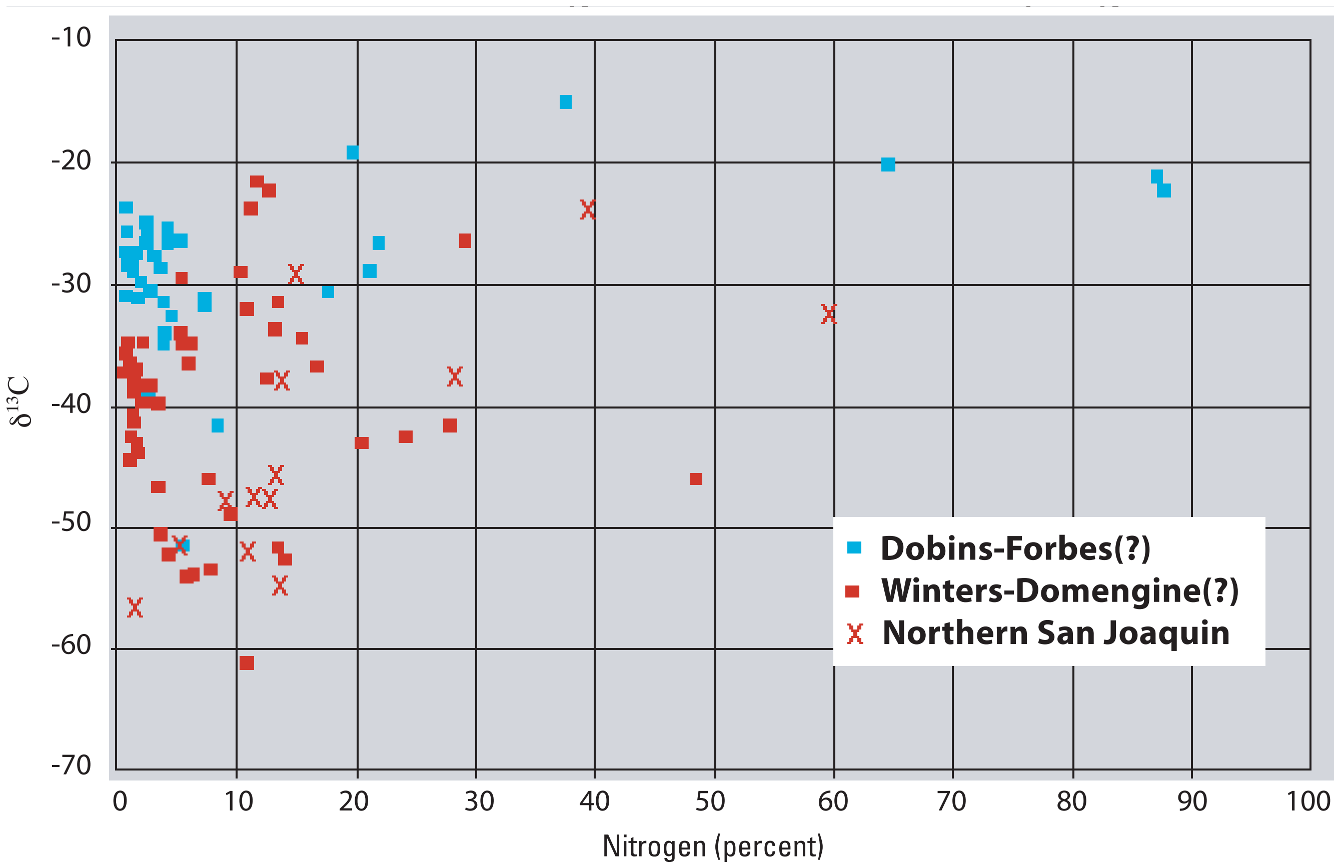


Figure 21.4. Percent nitrogen versus delta Carbon 13 of gas samples from the Dobbins-Forbes(?) and Winters-Domengine(?) gas-prone petroleum systems in the Sacramento Basin Province and from the dry gas fields in the northern San Joaquin Basin Province.

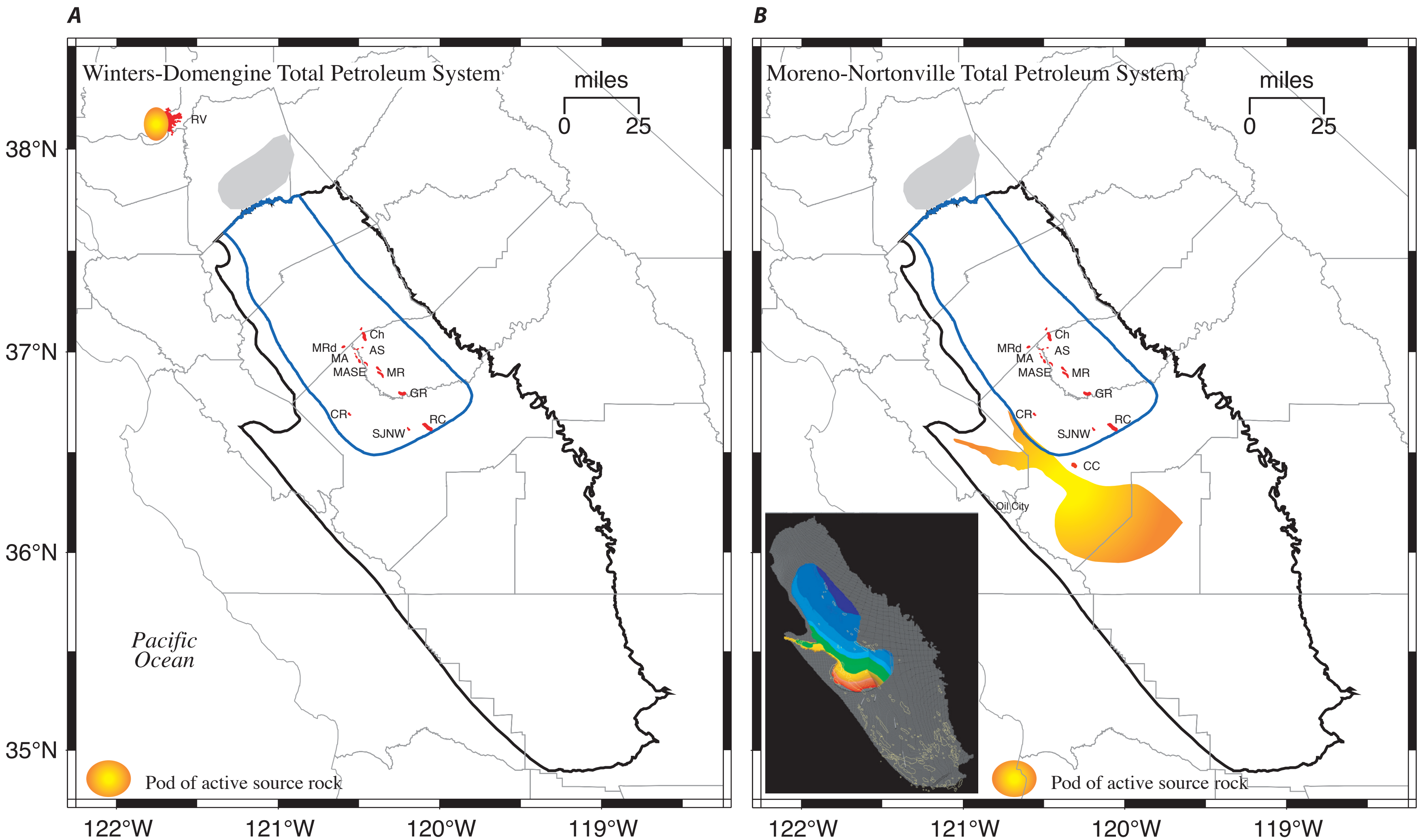


Figure 21.5. *A*, Location of Northern Nonassociated Gas AU (blue line) with respect to the pod of active source rock of the Winters-Domengine Total Petroleum System. Rio Vista (RV) gas field is partially hidden by the Winters formation pod of active source rock. *B*, Location of Northern Nonassociated Gas AU (blue line) with respect to the pod of active source rock of the Moreno-Nortonville Total Petroleum System. Note that Cantua Creek field (CC) is located between the Moreno Formation pod of active source rock and the AU. Inset image, from Peters, Magoon, Lampe, and others (this volume, chapter 12), of present-day thermal maturity of the Moreno Formation (expressed as calculated vitrinite reflectance) indicates the geographic progression of source-rock maturation from southwest (warm colors) to northeast (cool colors). The 0.6 percent reflectance value (color change from blue to green), approximately indicative of initial hydrocarbon expulsion, occurs along the southwest boundary of the AU. In both panels the bold line is the San Joaquin Basin Province boundary, thin gray lines are county boundaries, and gray shading shows the location of the buried Stockton Arch. Gas field labels are as in figure 21.2.

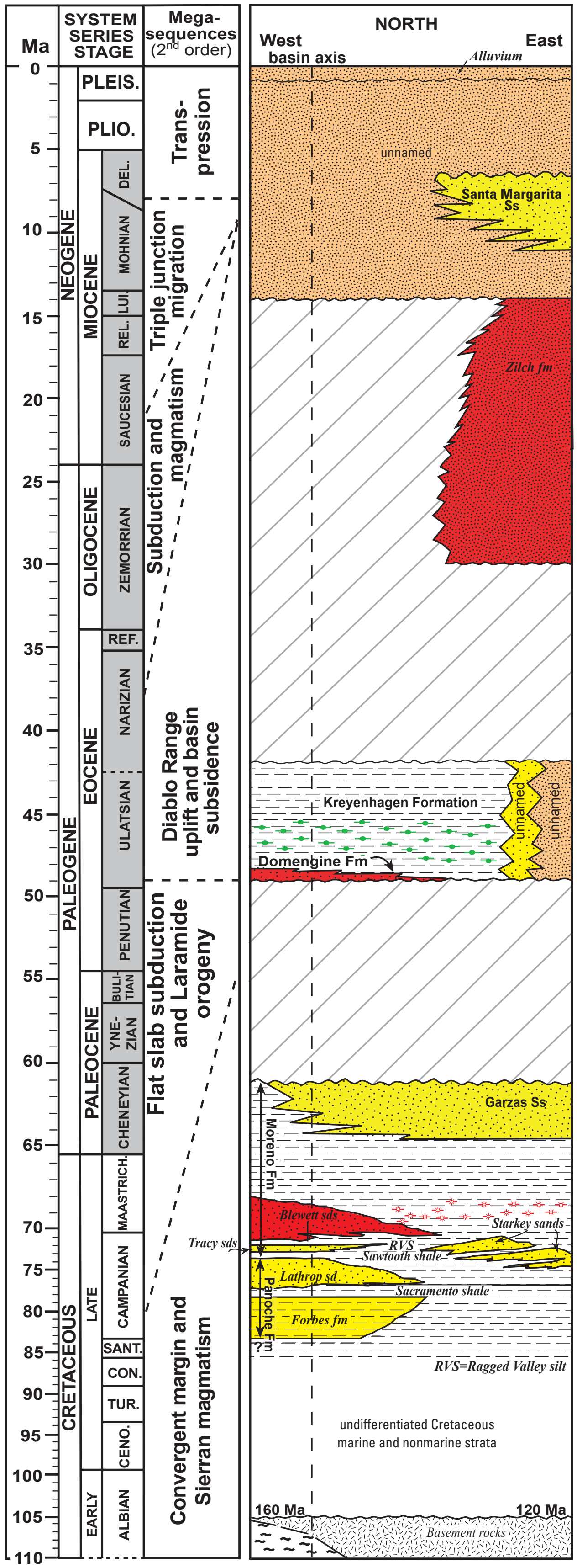
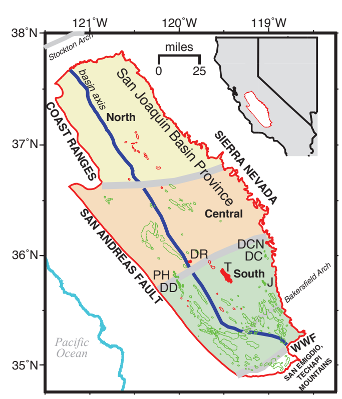
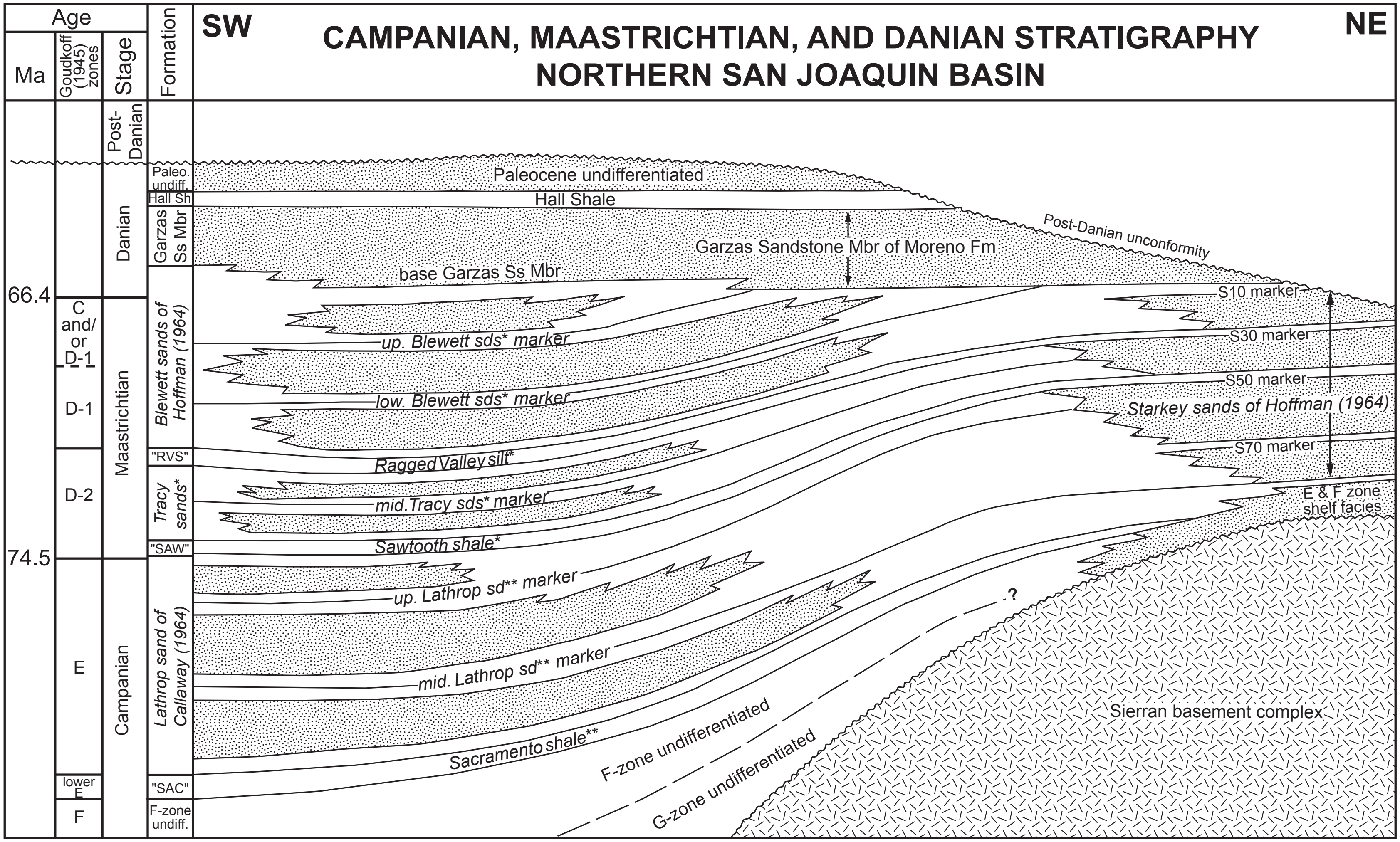


Figure 21.6. Generalized stratigraphic column for the northern San Joaquin Basin, showing hydrocarbon reservoir rocks and potential hydrocarbon source rocks. See Hosford Scheirer and Magoon (this volume, chapter 5) for complete explanation of the figure. Formation names in italics are informal and are defined as follows: Forbes formation of Kirby (1943); Sacramento shale and Lathrop sand of Callaway (1964); Sawtooth shale, Tracy sands, Ragged Valley silt, Starkey sands, and Blewett sands of Hoffman (1964); and Zilch formation of Loken (1959).





"RVS"=Ragged Valley silt of Hoffman (1964)
** of Hoffman (1964)*
"SAW"=Sawtooth shale of Hoffman (1964)
"SAC"=Sacramento shale of Callaway (1964)
*** of Callaway (1964)*

Figure 21.7. Depositional framework and stratigraphic relationships for the Late Cretaceous sedimentary sequence in the northern San Joaquin Valley. Figure by Nilsen and Moore (1997) is reprinted with permission from the Pacific Section of the American Association of Petroleum Geologists. Formation names in figure are modified in accordance with standard U.S. Geological Survey geologic names usage; italics denote informal geologic names. "Goudkoff (1945) zones" refers to the benthic foraminiferal zonation for Late Cretaceous-aged rocks in the Great Valley by Goudkoff (1945). "E & F zone shelf facies," "F-zone undifferentiated," and "G-zone undifferentiated" refer to unnamed strata containing benthic Foraminifera referable to the zones of Goudkoff (1945). "S10 marker," "S30 marker," "S50 marker," and "S70 marker" refer to intraformational markers identified on well logs by Nilsen and Moore (1997). Mbr, Member; low., lower; mid., middle; sd, sand; sds, sands; Sh, Shale; Ss, Sandstone; up., upper.

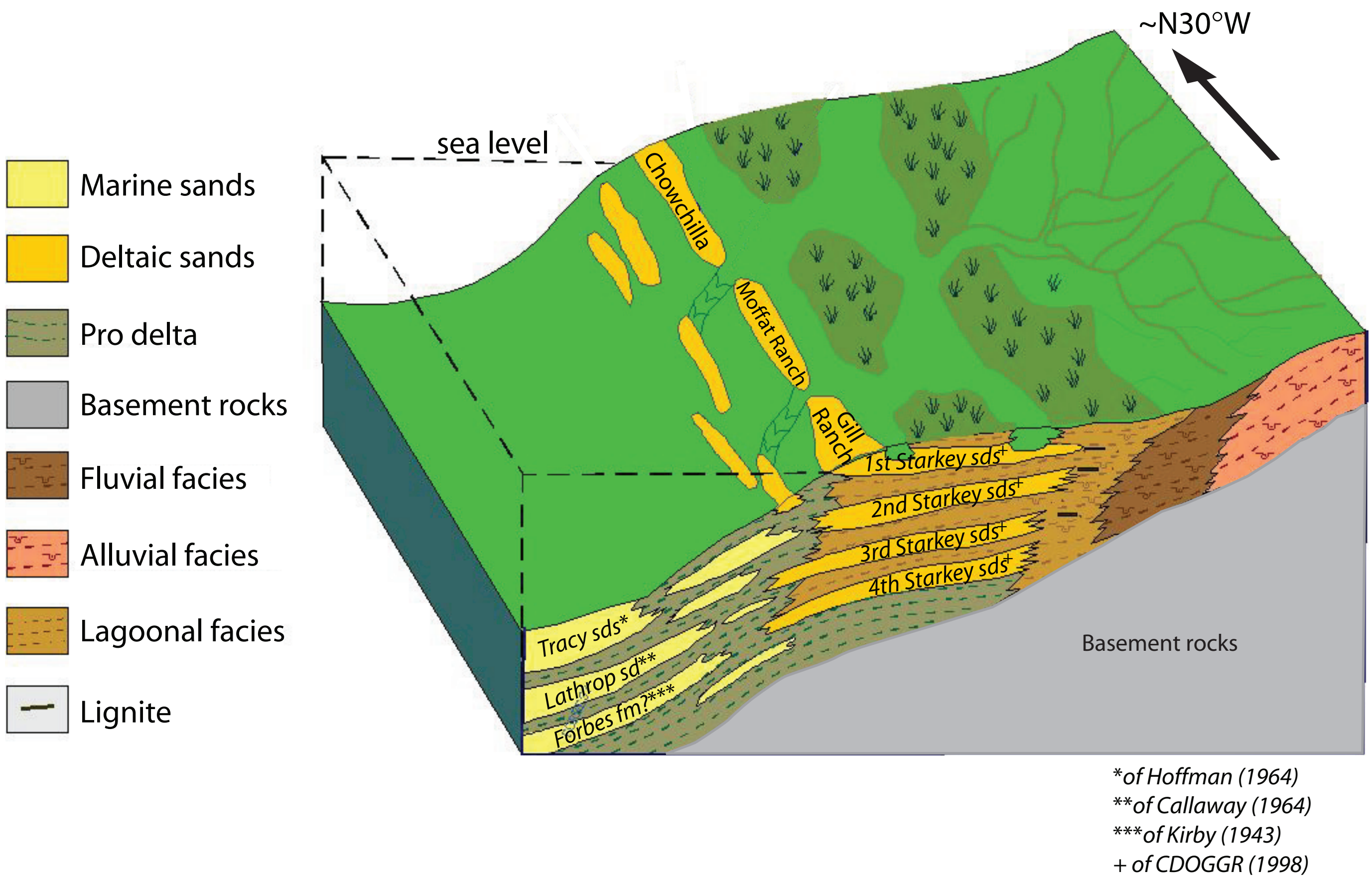


Figure 21.8. Schematic figure indicating the paleoenvironment of the northern San Joaquin Valley in the Late Cretaceous during deposition of Starkey sands. Figure by Philbrick (1997) is reprinted with permission from the Pacific Section of the American Association of Petroleum Geologists. Formation names in figure are modified in accordance with standard U.S. Geological Survey geologic names usage; italics denote informal geologic names. Note that in figures 21.8, 21.9, 21.10, and 21.13, the Starkey sands delta complex is divided into discrete sand bodies, as specified by the CDOGGR (1998). Direction arrow is aligned with general N30°W trend of San Joaquin Valley. fm, formation; sd, sand; sds, sands.

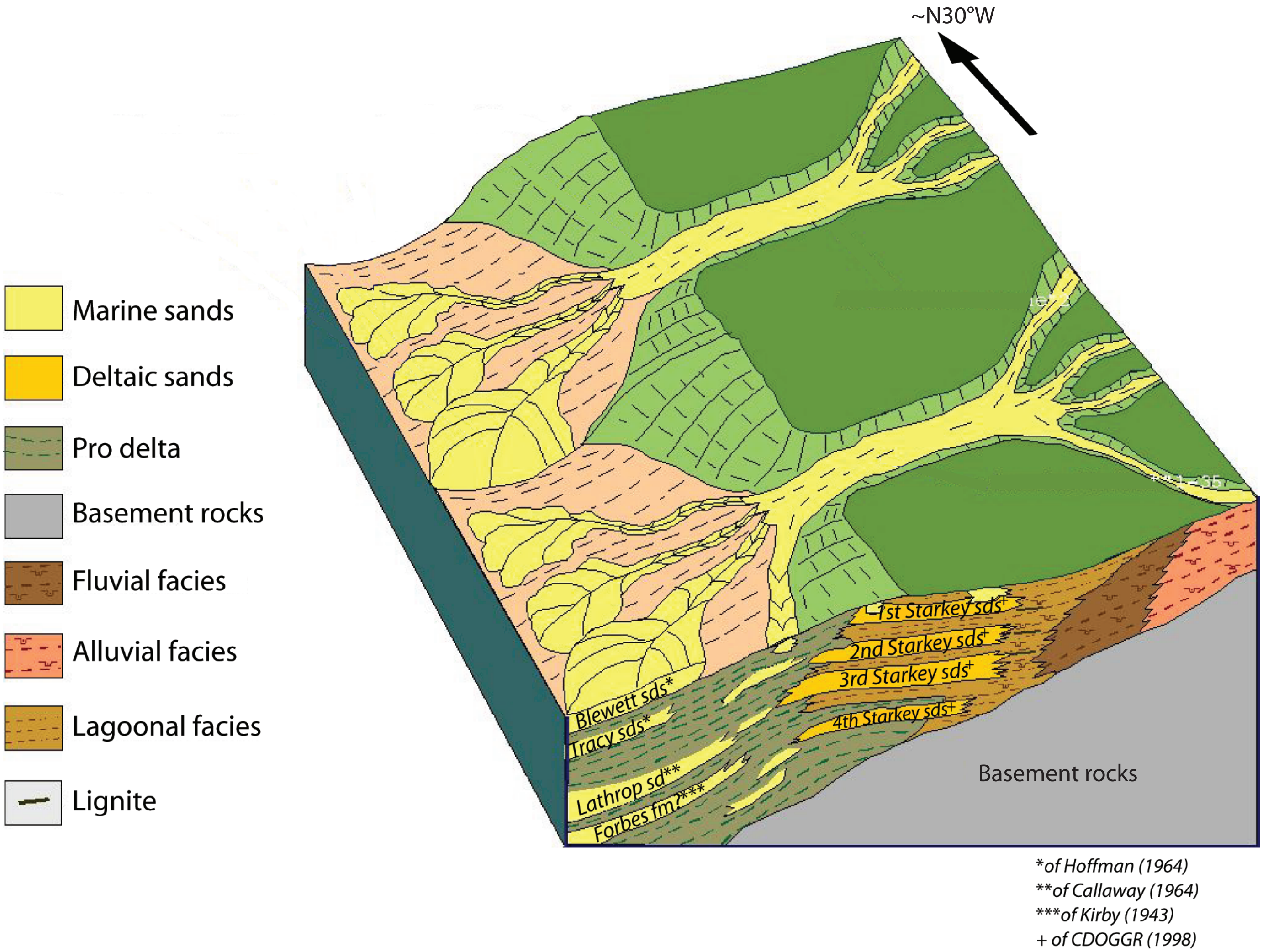


Figure 21.9. Schematic figure indicating the paleoenvironment of the northern San Joaquin Valley in the Late Cretaceous during deposition of the Blewett sands submarine fan. Figure by Philbrick (1997) is reprinted with permission from the Pacific Section of the American Association of Petroleum Geologists. Formation names in figure are modified in accordance with standard U.S. Geological Survey geologic names usage; italics denote informal geologic names. Direction arrow is aligned with general N30°W trend of San Joaquin Valley. fm, formation; sd, sand; sds, sands.

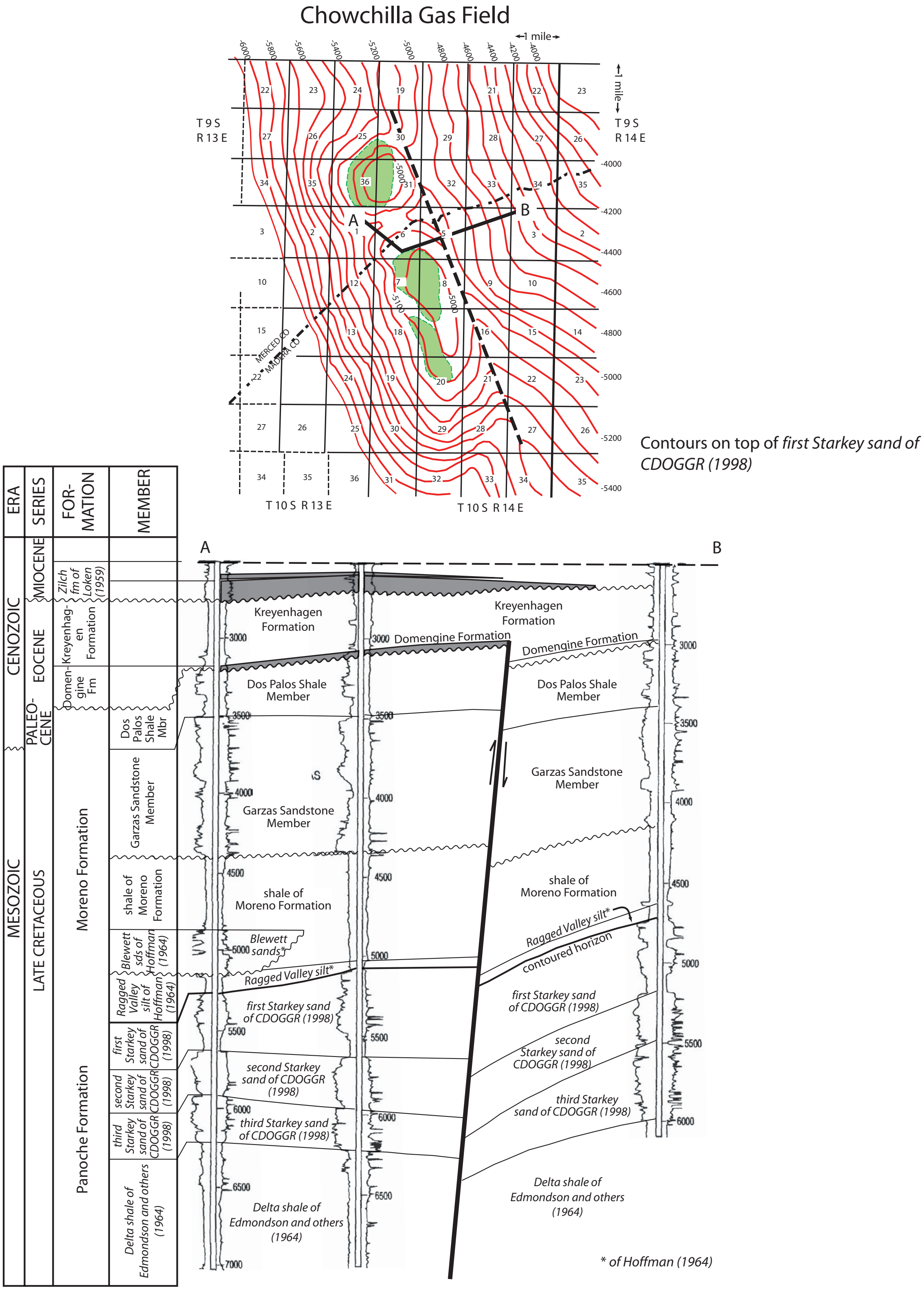
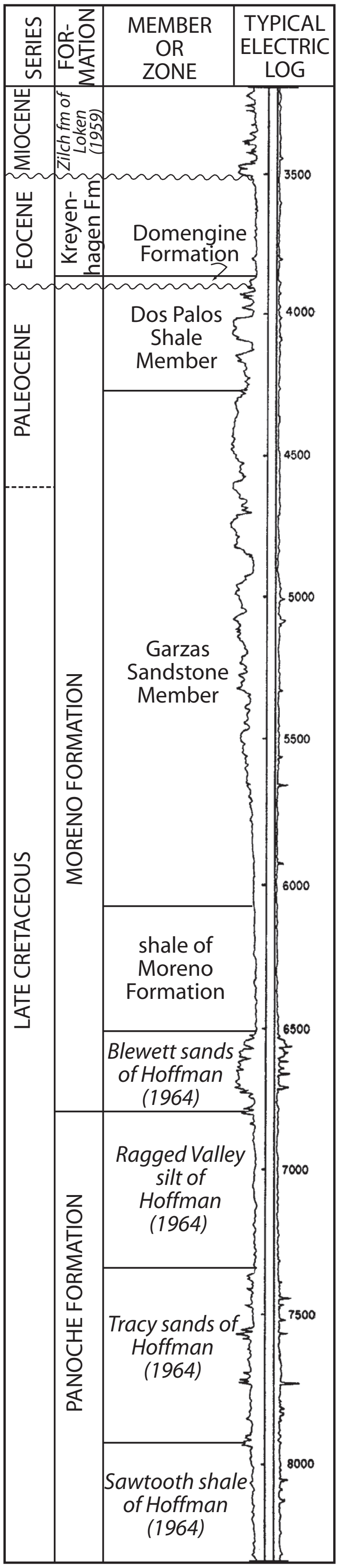
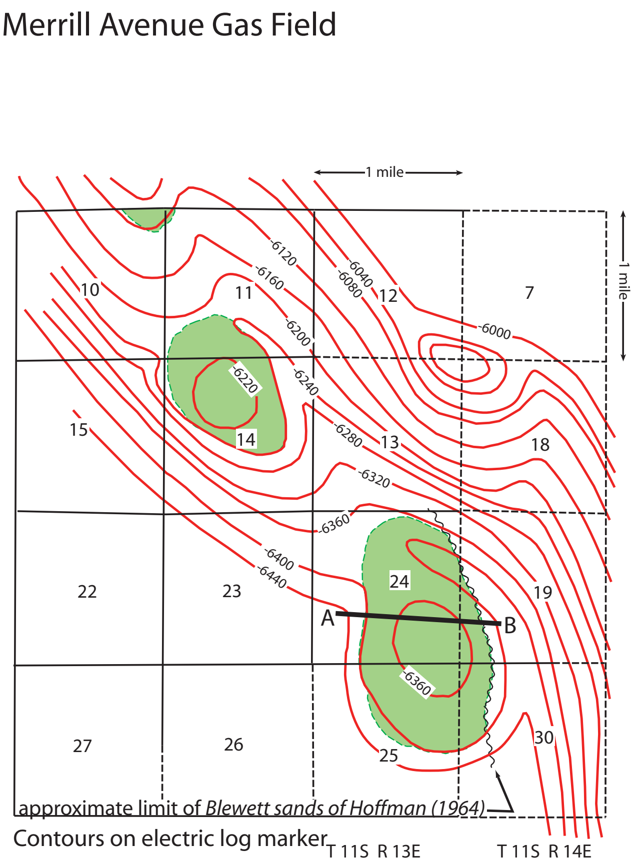


Figure 21.10. Figure of Chowchilla gas field, illustrating typical structural trap in the AU. Green shading (underlying township-range grid) denotes reported 1998 limits of productive sand units within the field. All depths are in feet. Formations in italics denote informal geologic names. Informal units not previously defined include the Delta shale of Edmondson and others (1964). Township-range grid in figures 21.10 through 21.14 is relative to the Mount Diablo baseline and meridian. See figure 21.2 for location of field. Figure redrafted from CDOGGR (1998). Fm, Formation; fm, formation; Mbr, Member; sds, sands.





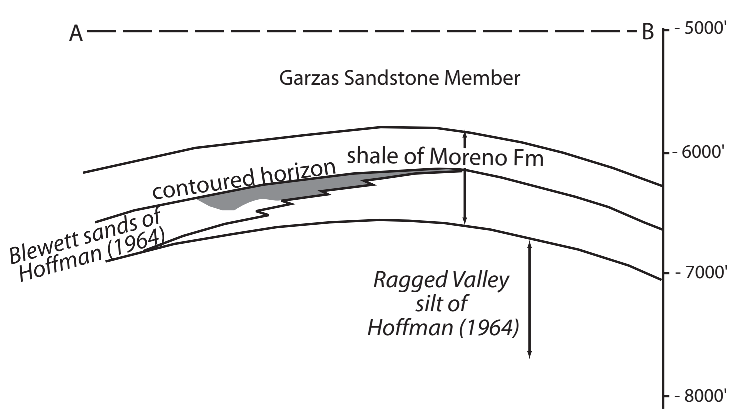


Figure 21.11. Figure of Merrill Avenue gas field, illustrating typical stratigraphic trap in the AU. Green shading (underlying township-range grid) denotes reported 1998 limits of productive sand units within the fields. All depths are in feet. Formations in italics denote informal geologic names. See figure 21.2 for location of field. Figure redrafted from CDOGGR (1998). Fm, Formation; fm, formation.

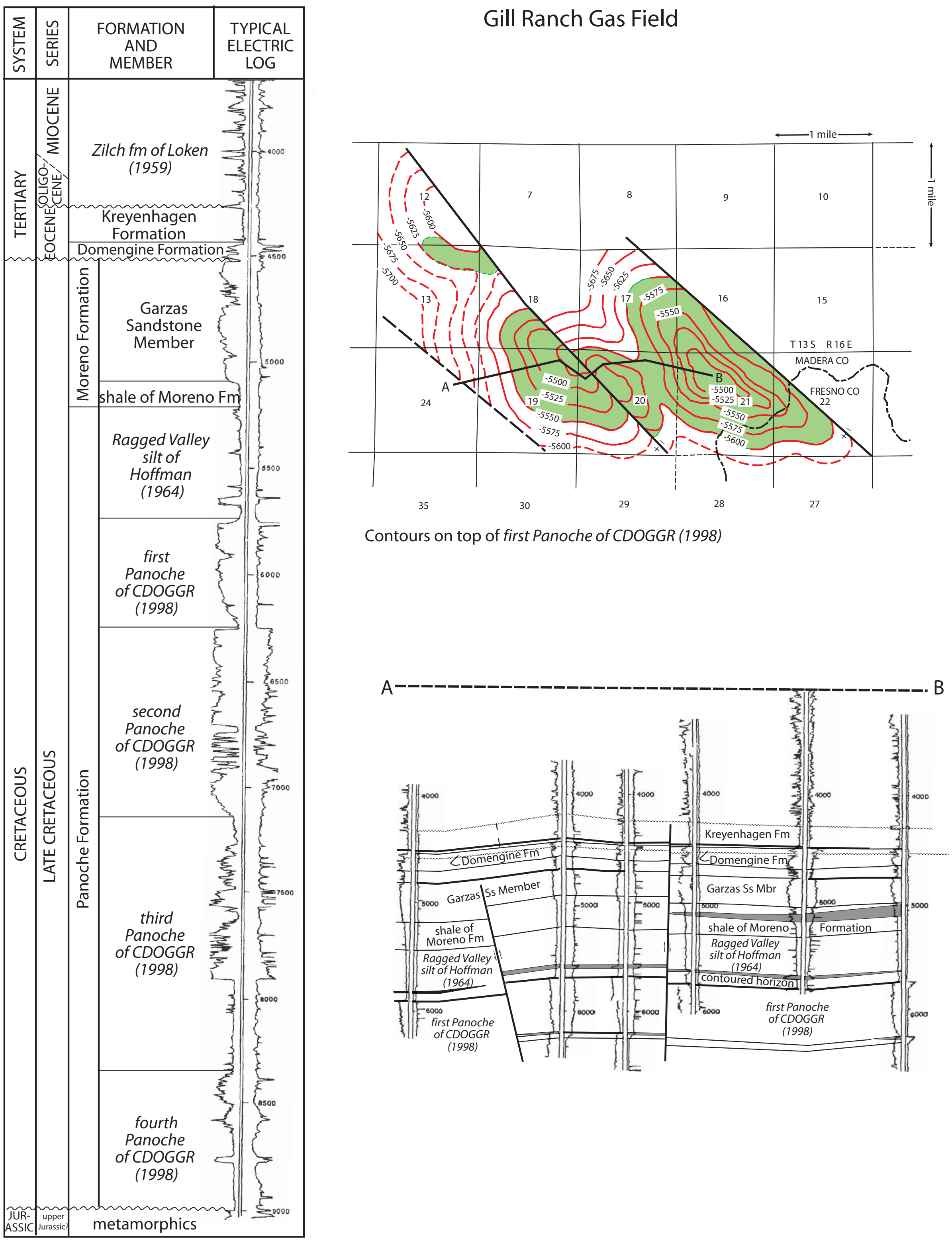


Figure 21.12. Figure of Gill Ranch gas field, illustrating typical structural trap in the AU. Green shading (underlying township-range grid) denotes reported 1998 limits of productive sand units within the fields. All depths are in feet. Formations in italics denote informal geologic names. See figure 21.2 for location of field. Figure redrafted from CDOGGR (1998). Fm, Formation; fm, formation; Mbr, Member; Ss, Sandstone.

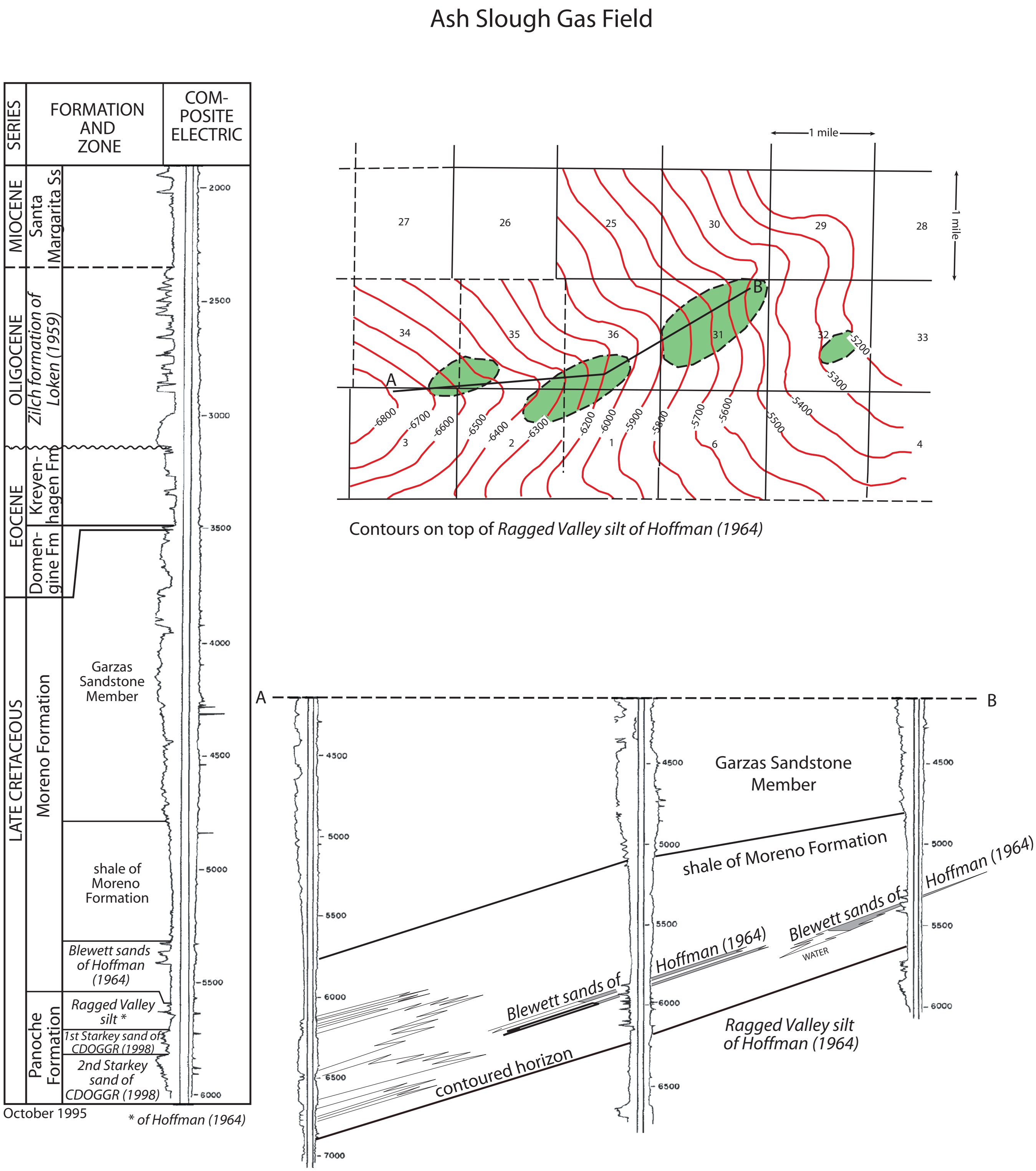


Figure 21.13. Figure of Ash Slough gas field, illustrating typical stratigraphic trap in the AU. Green shading (underlying township-range grid) denotes reported 1998 limits of productive sand units within the fields. All depths are in feet. Formations in italics denote informal geologic names. See figure 21.2 for location of field. Figure redrafted from CDOGGR (1998). Fm, Formation; Ss, Sandstone.

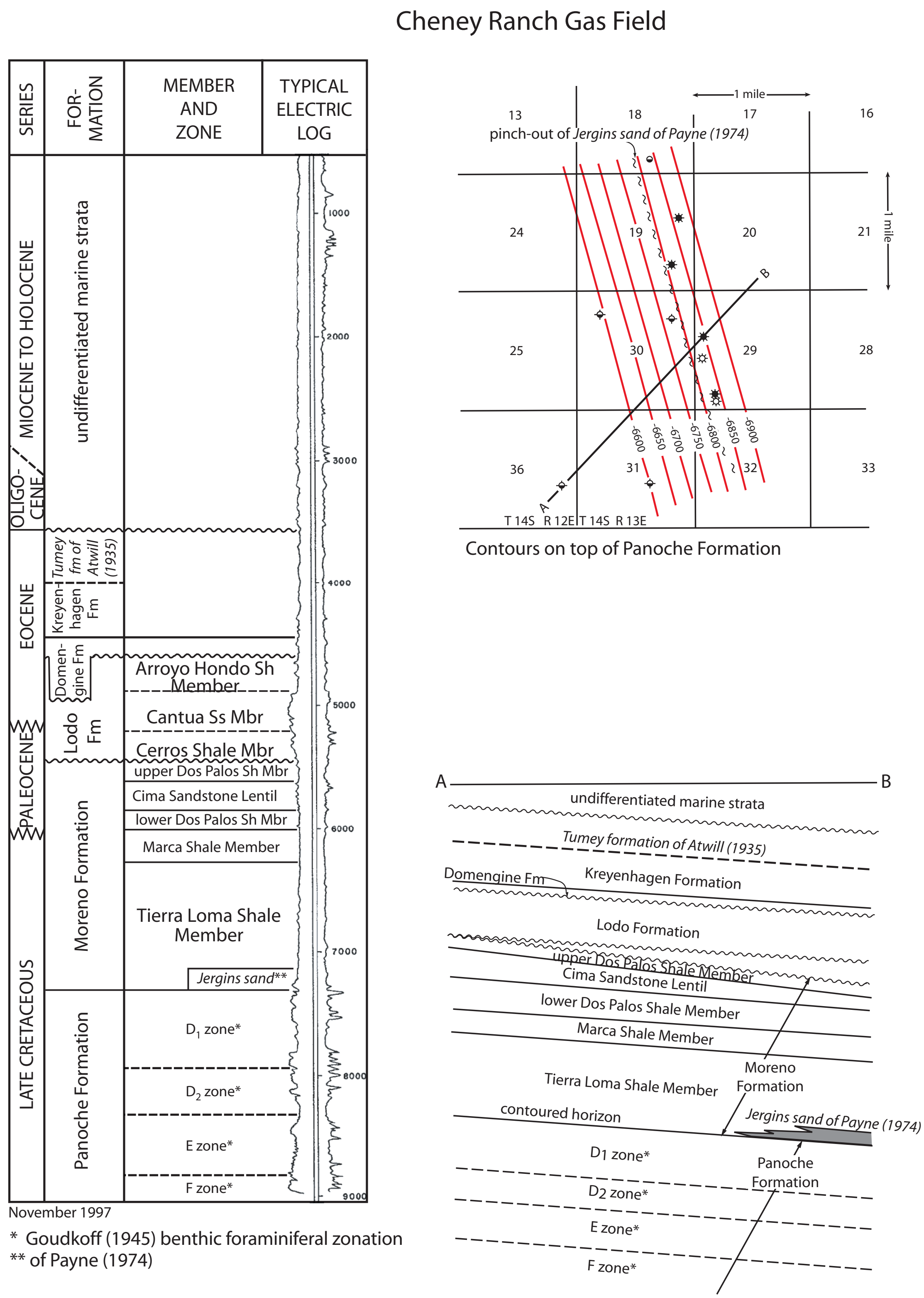


Figure 21.14. Figure of Cheney Ranch gas field, illustrating typical stratigraphic trap located west of the basin axis in the AU. Structural depth contours underlie township-range grid. All depths are in feet. Formations in italics denote informal geologic names. Informal units not previously defined include the Tumey formation of Atwill (1935) and the Jergins sand of Payne (1974). Note that the nomenclature for members of the Moreno Formation in this figure follows the nomenclature defined by Payne (1951) for outcrop sections of the formation on the valley's west side. See figure 21.2 for location of field. Figure redrafted from CDOGGR (1998). Fm, Formation; fm, formation; Mbr, Member; Ss, Sandstone; Sh, Shale.

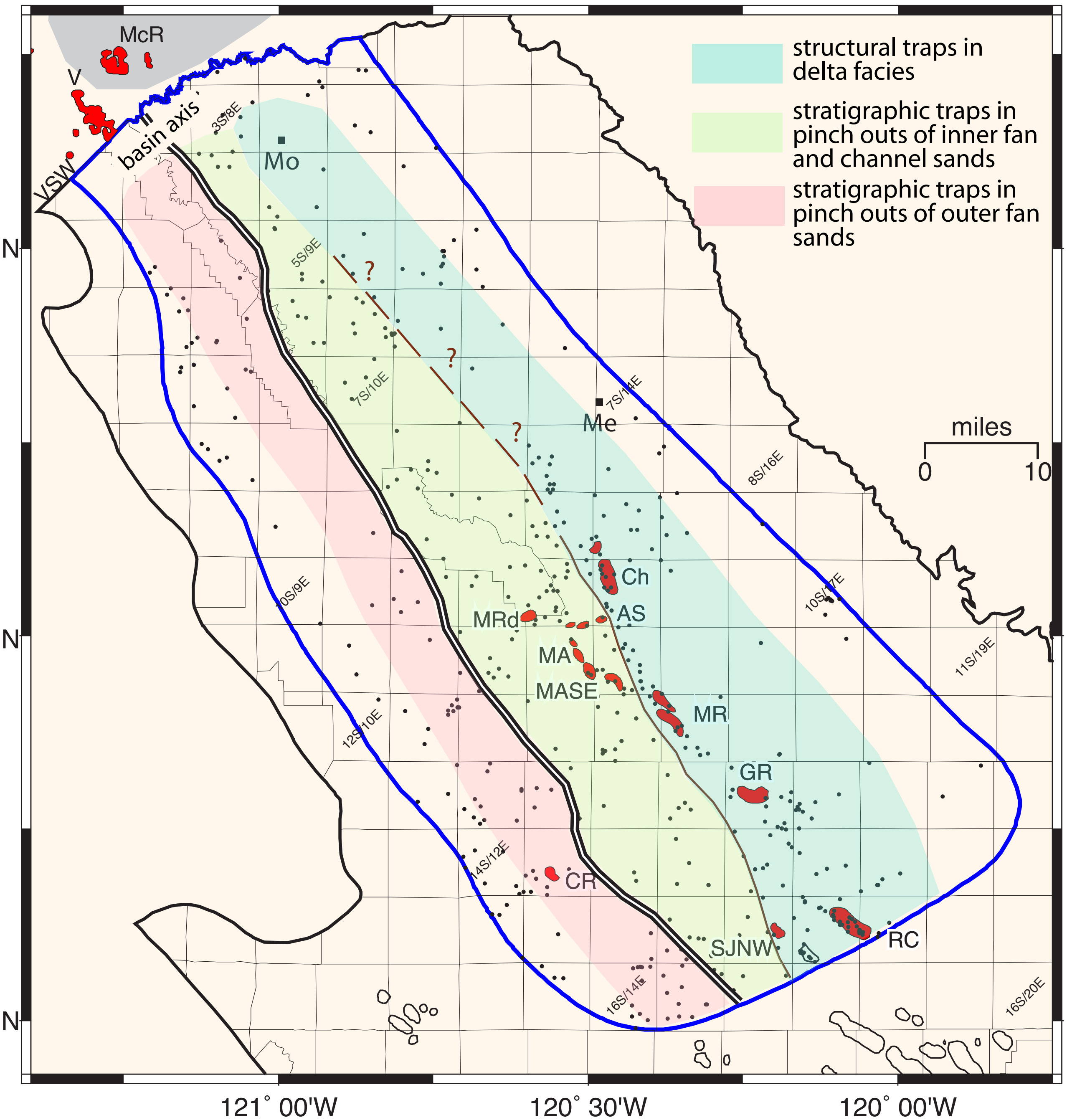


Figure 21.15. Schematic depiction of potential structural and stratigraphic traps in the Northern Nonassociated Gas AU (blue line) on the basis of trap types in known fields. Wildcat wells, gas-field labels, gray shading, and basemap are as in figure 21.2. Solid brown line marks the seaward depositional edge of the youngest of the Starkey sands and separates known structural traps from known stratigraphic traps. Dashed brown line marks the schematic northwestward trend of Cretaceous delta fronts. Double lines represent basin-axis location during the Late Cretaceous as mapped on a three-dimensional geologic model of the basin (Hosford Scheirer, this volume, chapter 7). Gas field abbreviations not previously defined are: McR=McMullin Ranch, V=Vernalis, and VSW=Vernalis Southwest.

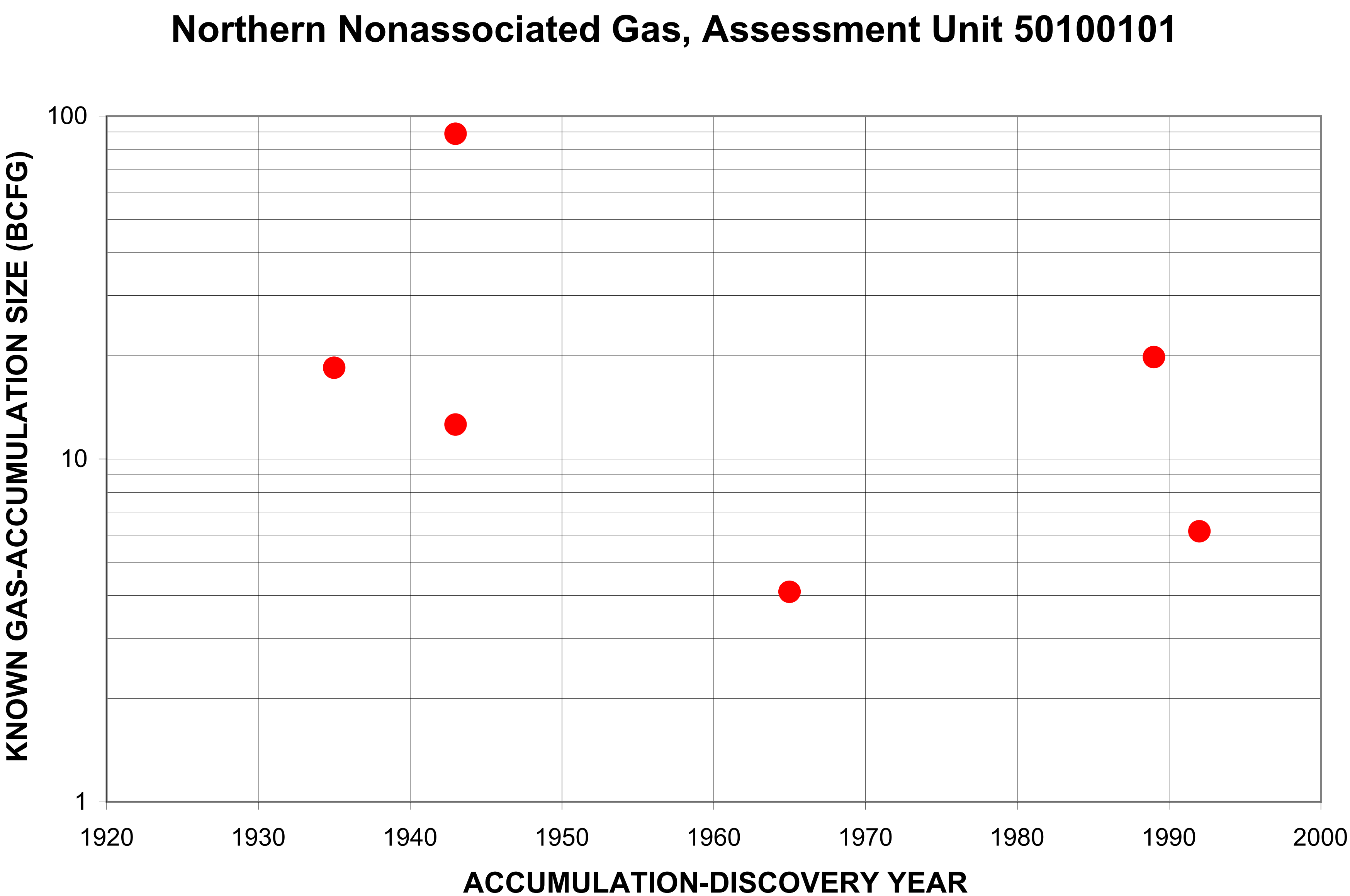


Figure 21.16. Size of discovered gas accumulations in the Northern Nonassociated Gas Assessment Unit (AU) versus their discovery year. Figure is excerpted from data file k100101.pdf (see Klett and Le, this volume, chapter 28, for explanation of data file).

50100101
Northern Nonassociated Gas
Monte Carlo Results

Forecast: Gas in Gas Fields

Summary:
Display range is from 0.00 to 250.00 BCFG
Entire range is from 3.93 to 340.41 BCFG
After 50,000 trials, the standard error of the mean is 0.23

Statistics:	Value
Trials	50000
Mean	105.78
Median	98.76
Mode	---
Standard Deviation	51.30
Variance	2,631.64
Skewness	0.54
Kurtosis	2.79
Coefficient of Variability	0.48
Range Minimum	3.93
Range Maximum	340.41
Range Width	336.49
Mean Standard Error	0.23

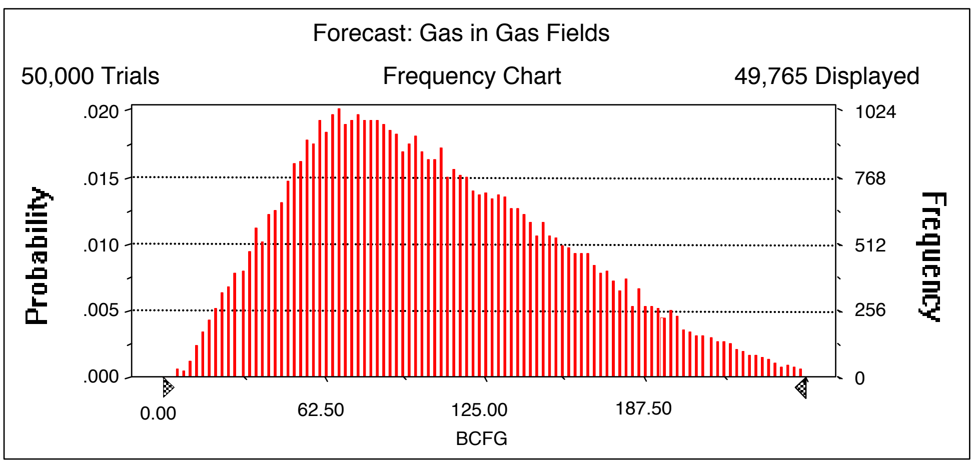


Figure 21.17. Probabilistic estimate of total gas volume in undiscovered gas fields in the Northern Nonassociated Gas Assessment Unit (AU). Figure is excerpted from data file em100101.pdf (see Charpentier and Klett, this volume, chapter 26, for details of the calculation and Klett and Le, this volume, chapter 28, for explanation of data file).

Table 21.1. Production statistics for primary fields in the Northern Nonassociated Gas Assessment Unit.

[Recoverable gas is the sum of cumulative production and estimated proved reserves. Data source is CDOGGR (2003). BCF, billion cubic feet. Primary fields are defined as those with recoverable gas equal to or greater than 3 BCF. Fields with zero producing wells are abandoned. Largest pool is cumulative production only. Pool designations follow naming conventions of the California Department of Conservation, Division of Oil, Gas, and Geothermal Resources]

Field	Recoverable Gas through 2002 (BCF)	Percent of Total	Number of Producing Wells in 2002	Largest Pool (BCF)
Gill Ranch	90.8	51.6	2	Eocene (56.6)
Chowchilla	30.7	17.4	1	Cretaceous (25.1)
Merrill Avenue	19.5	11.1	0	Blewett (19.5)
Moffat Ranch	12.6	7.2	2	Kreyenhagen (9.5)
Ash Slough	6.1	3.5	1	Blewett (5.9)
Merrill Avenue Southeast	6.0	3.4	4	Blewett (6.0)
San Joaquin Northwest	3.7	2.1	0	Eocene (3.7)
Mint Road	3.5	2.0	1	Blewett (2.0)
Cheney Ranch	3.1	1.7	0	Cretaceous (3.1)
Total	176.0	100	11	