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

Chapter 14

Miocene Total Petroleum System—Lower Bakersfield Arch Assessment Unit of the San Joaquin Basin Province

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Contents

Summary

Boundaries	San Joaquin Basin axis/west-side structural deformation on the west; Neogene-age shelf-slope break on the east; White Wolf Fault on the south; limit of Stevens sand of Eckis (1940) on the north; topographic surface to crystalline basement.
Source Rocks	Miocene Monterey Formation; possibly minor other sources.
Reservoir Rocks	Deep-sea channel and fan deposits of Stevens sand of Eckis (1940); minor older sandstones.
Traps	Stratigraphic and structural/stratigraphic (pinch out, compaction, faults).
Migration	Up-dip through feeder systems of submarine channel and fan deposits.
Timing	Oil generation from mid-Pliocene to present from Monterey Formation.
Existing Fields	Bellevue West, Bellevue, Calders Corner, Canal, Canfield Ranch, English Colony, Goosloo, Greeley, Kernsumner, McClung, Rosedale, Seventh Standard, Stockdale, Strand, Ten Section.
Exploration Status	Moderately explored (0.7 wells per square mile and 33 percent of all sections have at least one exploratory well).
Resource Potential	Small stratigraphic traps remain undiscovered, especially on south flank of Bakersfield Arch; Maricopa deep largely untested.

Description

The Lower Bakersfield Arch Assessment Unit (AU) of the Miocene Total Petroleum System (San Joaquin Basin Province) is primarily defined by the distribution of hydrocarbons generated from biosiliceous shale of the Monterey Formation and by the distribution of basinal-facies sandstones of the Stevens sand of Eckis (1940; hereafter referred to as Stevens sand). Traps are principally stratigraphic and structural/stratigraphic, with most discovered accumulations occurring in deep-sea channel, fan, and braided submarine channel deposits of the late Miocene Stevens sand. Smaller and fewer accumulations are found in older sandstones such as the Vedder and Jewett Sands of Oligocene to Miocene age. Compared to the west side of the basin, the AU is largely unstructured, except for localized down-to-the-basin normal faults.

Map boundaries of the assessment unit are shown in figures 14.1 and 14.2; this assessment unit supersedes the Lower Bakersfield Arch play 1003 considered by the U.S. Geological Survey (USGS) in the 1995 National Assessment (Beyer, 1996). Stratigraphically, the AU extends from the uppermost crystalline basement to the topographic surface (fig. 14.3). The AU is bounded on the east and north by the limit of basinal-facies sandstones of the Stevens sand; this eastern boundary corresponds to the approximate location of the shelf-slope break of the San Joaquin Basin in late Miocene time. The western boundary of the AU is the approximate eastern limit of structural deformation on the basin's west side. The White Wolf Fault bounds the AU on the south.

Source Rocks

Oil correlation analyses conducted for the San Joaquin Basin Province assessment (Lillis and Magoon, this volume, chapter 9) confirm earlier studies (Peters and others, 1994), which indicate that all known oil and gas accumulations in this AU are derived from source rocks of middle and late Miocene age (fig. 14.4). The predominant source for oil in this AU is the fine-grained, biosiliceous, organic-rich facies of the Monterey Formation locally known as the Fruitvale shale of Miller and Bloom (1939; hereafter referred to as Fruitvale shale). Total organic carbon (TOC) values for organic-rich shales of the Monterey Formation range from less than one to nearly six percent (Peters, Magoon, Valin, and Lillis, this volume, chapter 11).

The southern half of the Lower Bakersfield Arch AU lies within the pod of active source rock that formed in the Tejon depocenter (fig. 14.5). This area generated hydrocarbons within the Miocene Total Petroleum System (Magoon and others, this volume, chapter 8). Presumably most oil in this assessment unit derives from the Tejon depocenter, although thermally mature, organic-rich shale of the Monterey Formation in the Buttonwillow depocenter may also have contributed oil and gas to the AU (fig. 14.5).

Pre-Monterey Formation organic-carbon-rich shales such as those of the Kreyenhagen Formation could also serve as source rocks to reservoirs in this AU, especially for sandstones that lie stratigraphically below the Stevens sand. However, oils analyzed to date are sourced entirely from Miocene-age source rocks (Lillis and Magoon, this volume, chapter 9).

Maturation

The Monterey Formation may have generated small amounts of sulfur-rich liquids early in its burial history (Fischer and others, 1988), but burial depths of 3 to 4 kilometers are generally thought necessary for significant oil generation from the Monterey Formation in the San Joaquin Basin (Graham and Williams, 1985; Kruge, 1985). Geochemical analyses and petroleum systems modeling conducted for the San Joaquin Basin Province assessment confirm this interpretation and constrain burial depths of Monterey Formation source rocks to 4 to 4.6 kilometers (Peters, Magoon, Lampe, and others, this volume, chapter 12). By these criteria, the oldest members of the Monterey Formation are currently in the oil-generation window throughout much of the Lower Bakersfield Arch AU. In the deeper parts of the basin, especially in the vicinity of the Tejon depocenter, the youngest strata of the Monterey Formation also probably lie within the oil window. Thus, the Monterey Formation that underlies and is interbedded with most of the reservoir rocks in this AU probably achieved thermal maturation sufficient for significant oil generation. Reconstructed burial histories suggest that Monterey Formation source rocks were thermally mature with respect to oil generation by early Pliocene time (4.6 Ma) and that oil generation continues to the present (Peters, Magoon, Lampe, and others, this volume, chapter 12).

Migration

Within the AU, the Stevens sand is interbedded with biosiliceous shales, such as the Fruitvale shale of the Monterey Formation (fig. 14.4). The complex depositional systems of the Stevens sand and the interbedding of Stevens sand reservoirs with Monterey Formation source rocks are believed to provide ample conduits for oil migration to sandstone reservoirs throughout the AU. Submarine braided channels and feeder systems are highly interconnected, so that most potential reservoir lithologies of the Stevens sand are believed to have been exposed to hydrocarbon charge.

Reservoir Rocks

Laterally persistent fine-grained facies of the Monterey Formation, which separate sandstone complexes, can be correlated widely throughout the central and eastern basin. The complex sandstones are commonly described as "submarine fans" in the literature. In this respect, as well as many others, the Stevens sand on the east side of the basin differs significantly from the Stevens sand on the west side, where local structures, topography, and tectonic events exerted primary control on the distribution of reservoir lithologies, and reliable stratigraphic markers are difficult to identify and correlate. Because of the possibility of establishing time-stratigraphic control, reservoirs on the east side of the basin are much more amenable to traditional sequence stratigraphic analysis than are those of the west side.

Although some oil in the Lower Bakersfield Arch AU has been found in and produced from the Vedder and Jewett Sands of late Oligocene to early Miocene age, more than 95 percent of known hydrocarbons in this AU are contained within and produced from the late Miocene Stevens sand. On the Bakersfield Arch, the Stevens sand consists of a complex submarine fan system deposited on the eastern slope and floor of the San Joaquin Basin. Sediment derived from erosion of Sierran granitic rocks was transported westward to the basin floor via the ancestral Kern River and subsequently through a complex of coalescing fan-delta aprons (Harrison and Graham, 1999). The interpretation of the sediment feeder system as coalescing aprons represents a revision of previous views that generally interpreted the Stevens sand as a complex of submarine fans, sourced through large submarine canyons that cut deeply into the eastern sedimentary shelf of the basin (for example, Webb, 1981; Hewlett and Jordan, 1993).

Figure 14.6 illustrates the paleogeography of the San Joaquin Basin during late Miocene time (~9 Ma), when the lower Stevens sand facies locally called the Coulter sandstone of MacPherson (1978) was deposited (Clark and others, 1996). At that time, the San Joaquin Basin was becoming increasingly isolated from the Pacific Ocean to the west. On the east, accelerated uplift of the Sierra Nevada provided voluminous coarse sediments to the Stevens sand submarine fan system (fig. 14.6; Bartow, 1991). The location of the marine shelf edge (hachured line) within the Lower Bakersfield Arch Assessment Unit indicates that sediment of the lower Stevens sand system was deposited in bathyal conditions, which may have been as deep as ~3,300 feet (Webb, 1981). Water depths may have shoaled by upper Stevens sand time (~7 Ma); recent work indicates upper bathyal to neritic depths in the Bakersfield Arch region at that time (Harrison and Graham, 1999).

At the pool level, Stevens sand reservoirs in the Lower Bakersfield Arch AU consist of complex stacks of fining-upward braided submarine channel sandstone deposits, separated by fine-grained biosiliceous shales. These sandstone complexes are genetically related and are interpreted to have been deposited in several submarine depositional environments, including turbidite lobes and mounds, fills of submarine channels and canyons, turbidite wedges, and amalgamated coarse-grained sandstones and conglomerates deposited in topographic lows on slopes of the submarine shelf (Lamb and others, 2003). Differing reservoir architecture between the upper and lower Stevens sand interval records a change in the paleoenvironment in the Bakersfield Arch region between about 8 and 7.5 Ma. Whereas lower Stevens sand reservoirs exhibit northwest-southeast trending lobate geometry indicative of deposition from a submarine fan, reservoirs within the upper Stevens sand consist of east-west trending linear sandstone bodies indicative of deposition via channel networks (Clark and others, 1996).

The average depth for all Stevens sand reservoirs in the assessment unit ranges between about 5,500 feet and 9,500 feet (CDOGGR, 1998). Within these reservoirs, average oil gravity ranges between 27 degrees API in the lower Stevens sand pool at Seventh Standard field to a maximum of 60 degrees API in the upper Stevens sand pool at Ten Section field. Oil gravity commonly averages 35 degrees from all Stevens sand pools (CDOGGR, 1998).

Traps and Seals

In addition to serving as the source rock for hydrocarbon accumulations in the Lower Bakersfield Arch AU, fine-grained siliceous facies of the Monterey Formation form highly effective permeability barriers that encase individual sandstones, partition sandstone complexes, and provide the top seals on hydrocarbon pools. Traps include depositional pinchouts of channel sandstones, up-dip overlap of sandstones and mudstones, differential compaction of fine-grained facies around reservoir sandstones, and down-to-the-east extensional faults that juxtapose porous and permeable reservoirs with low-permeability facies of the Monterey Formation. In general, hydrocarbon accumulations in the lower Stevens sand occur in anticlinal closures within sheet-like sand bodies while accumulations in the more prolific upper Stevens sand are trapped stratigraphically or by faulting of ribbon-like sand bodies (Clark and others, 1996).

Figure 14.7 illustrates the structure and local geology at Ten Section field, from which more than a quarter of the total known oil in the assessment unit derives (table 14.1). The main producing interval is the upper Stevens sand, which ranges from 1,700 to 2,400 feet in thickness, and is encased entirely within and interbedded with hard, brown Fruitvale shale (Hluza, 1968). Oil is trapped in the main area of the field primarily by moderate structural closure as well as by facies changes and permeability barriers (Hluza, 1968).

Although the Stevens sand at Greeley field has produced nearly 10 million barrels of oil, reserves of nearly ten times that amount have been found in the deeper Rio Bravo sand of Noble (1940)-Vedder Sand pool (fig. 14.8). Geologic structure at depth in the Greeley Field consists of a northwest-southeast trending anticline that averages about 4 miles long and 1 to 2 miles wide. The Greeley fault bounds the field to the east; down-to-the-east offsets across the fault range from about 2,000 feet on the basement surface to zero in late Miocene strata (Bartow, 1991). These fault relationships indicate that the productive Rio Bravo sand of Noble (1940)-Vedder Sand and Olcese Sand intervals are limited by the fault, whereas the stratigraphically higher Stevens sand pool is constrained by structural closure across the anticline.

Exploration Status and Resource Potential

The USGS assessment of the petroleum resource potential of the Lower Bakersfield Arch AU relies heavily upon the density of exploratory drilling within the assessment unit and upon its mature discovery history. Twelve fields larger than 0.5 million barrels of oil (MMBO) are reported within the AU, the largest of which, in terms of recoverable oil, are Greeley, Ten Section, and Canfield Ranch (table 14.1). More than 275 exploratory wells were drilled to discover the known accu-

Table 14.1. Production statistics for primary fields in the Lower Bakersfield Arch Assessment Unit

[Recoverable oil is the sum of cumulative production and estimated proved reserves. Data source is CDOGGR (2003). MMB, millions of barrels. Primary fields are defined as those with recoverable oil equal to or greater than 0.5 MMB]

Field	Recoverable Oil through 2002 (MMB)	Percent of Total	Number of Producing Wells in 2002
Greeley	116.9	36.0	21
Ten Section	86.5	26.7	37
Canfield Ranch	41.0	12.6	33
Canal	26.3	8.1	11
Strand	22.1	6.8	11
Rosedale	8.3	2.6	14
Bellevue	7.9	2.4	12
Bellevue West	7.3	2.2	8
Stockdale	4.7	1.4	14
English Colony	1.6	0.5	0
Seventh Standard	1.5	0.5	0
Calders Corner	0.6	0.2	2
Total	324.7	100	163

mulations, the largest five of which were found by the first 50 wells (fig. 14.9). These five accumulations, all discovered before 1940, account for about 90 percent of the known oil in the assessment unit. The remaining 225 wells drilled since 1940 found eight accumulations, none of which have recoverable oil greater than 10 MMBO (fig. 14.9). Since 1960 only three fields have been found; one of these, Kernsumner, is below the minimum field size considered for this assessment (0.5 MMBO) and is not listed in table 14.1.

Existing fields are located primarily on the Bakersfield Arch at depths of 6,000 to 12,000 feet. On the arch itself, the Stevens sand has been extensively drilled (figs. 14.2 and 14.3) and is considered highly mature as an exploration play in the north-central part of the Lower Bakersfield Arch AU. Nevertheless, the complex depositional geometries of the Stevens sand make it likely that numerous small, stratigraphically trapped accumulations remain to be found. Our assessment assumes that some of these subtle undiscovered accumulations may exceed the USGS minimum field size of 0.5 MMBO.

South of the arch, exploratory wells are much more widely spaced than on the arch itself (figs. 14.2 and 14.3). Significantly, this southernmost part of the assessment unit includes deeply buried rocks of late Miocene age that are stratigraphically equivalent to the Monterey Formation and Stevens sand. Further, petroleum systems modeling shows that the Monterey Formation is thermally mature and actively generating petroleum south of the arch in the deepest parts of the southern San Joaquin Basin (fig. 14.5; Peters, Magoon, Lampe, and others, this volume, chapter 12). This area, which is locally referred to as the Maricopa depocenter or the Maricopa deep, remains largely unexplored, perhaps because depths to the Stevens sand and equivalent sandstone targets exceed 12,000 feet, making exploration expensive and technically difficult.

Additionally, reservoir quality in the Stevens sand is known to decline markedly south of the crest of the Bakersfield Arch, and it is generally believed that reservoir-quality sandstones of eastern, Sierran provenance are not abundant in the Maricopa depocenter. While this may be true, our assessment was predicated on the possibility of the existence of basinal-facies submarine fan and channel sandstones, most likely with a southern provenance, in the Maricopa deep. The southern part of the San Joaquin Basin may have been bathymetrically low in the late Miocene, thus permitting the existence of significant oil-charged sandstone reservoirs in the largely unexplored parts of the Maricopa deep. This possibility is considered significant and is reflected in the current assessment of the Lower Bakersfield Arch AU.

The assessment results for this AU are relatively optimistic given the discovery history of the known fields, primarily because of the relatively untested southern half of the AU. The estimated absolute maximum size of undiscovered accumulations, 50 MMBO, allows for the possibility of a significant Stevens sand-type reservoir in the Maricopa deep (fig. 14.10). More realistically, the predicted median size of undiscovered accumulations, 2 MMBO, is somewhat smaller than the median accumulation size discovered in the AU since 1940 (fig. 14.10). The estimated number of undiscovered accumulations ranges from a minimum of one to a maximum of 60, with a mode of eight. Thus we believe it is likely that the number of undiscovered fields in the AU approximates the number that has been found since 1940. In summary, we allow for a relatively large number of small oil fields to be found within the assessment unit.

Because of the occurrence of gas accumulations in the neighboring area west of the basin axis and because the pod of active Monterey Formation source rock lies within the assessment unit, we also allow for the possibility of a few undiscovered gas accumulations deep in the basin of sizes volumetrically similar to the assessed undiscovered oil accumulations in the AU.

All assessment results and supporting documentation for the Lower Bakersfield Arch Assessment Unit of the San Joaquin Basin Province are available in files c100402.pdf (data form for conventional assessment unit), d100402.pdf (summary of discovery history), em100402.pdf (probabilistic estimates), g100402.pdf (graphs of exploration and discovery data for grown volumes), and k100402.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

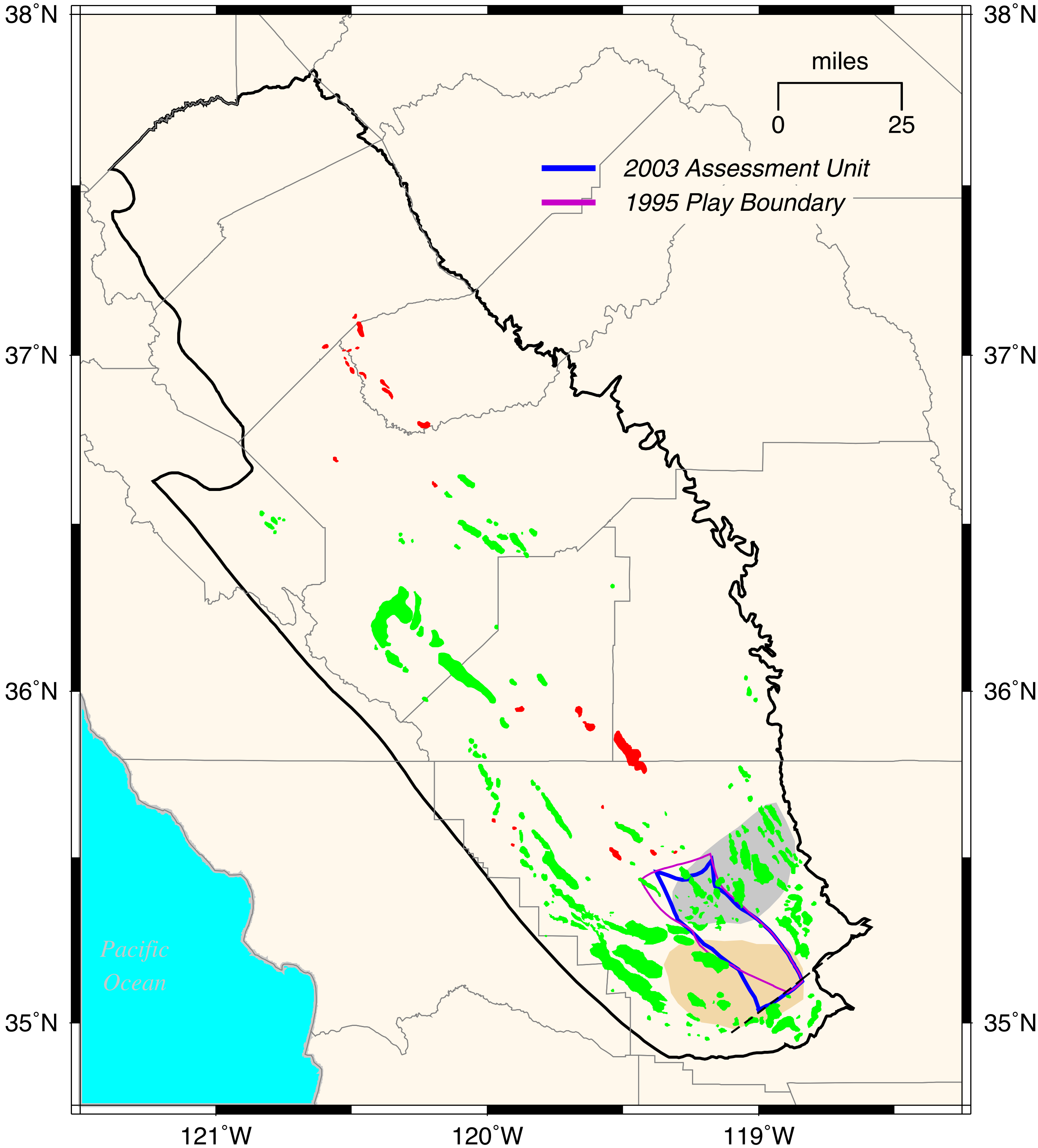


Figure 14.1. Map of the San Joaquin Basin, illustrating San Joaquin Basin Province boundary (bold line), county boundaries (thin gray line), Lower Bakersfield Arch Assessment Unit boundary (blue line), play boundary from previous USGS assessment (purple line), and oil (green) and gas (red) fields in the province. Gray shading shows the location of the Bakersfield Arch, which is mapped on the basement surface in a three-dimensional geologic model of the basin (Hosford Scheirer, this volume, chapter 7), and tan shading indicates the location of the Maricopa deep, which is mapped on the top of the Monterey Formation in the basin model. In figures 14.1 and 14.2, dashed line indicates surface and subsurface traces of the White Wolf Fault, as modeled by Bawden (2001).

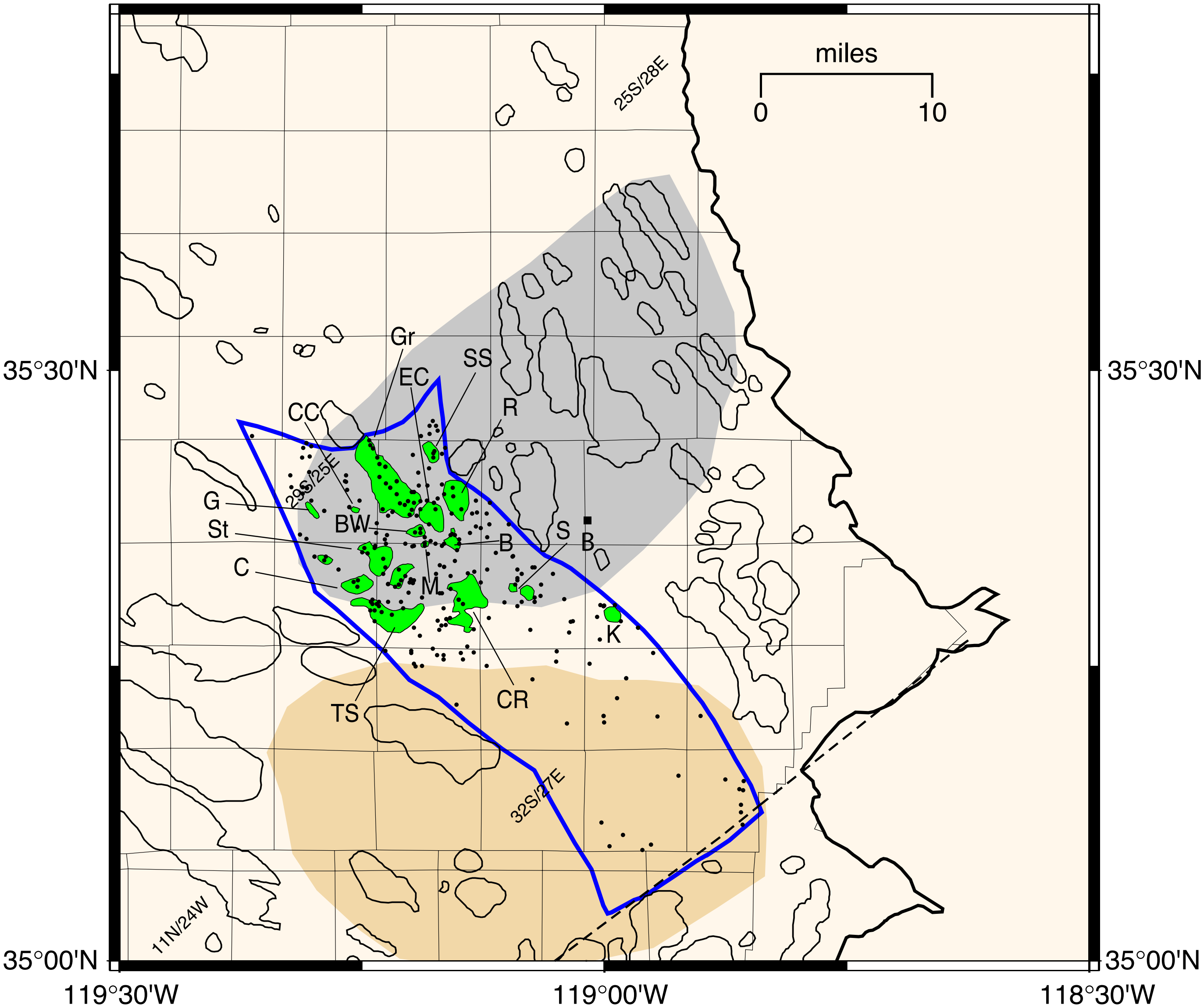


Figure 14.2. Detailed map of the Lower Bakersfield Arch Assessment Unit (AU). The blue line indicates the geographic limit of the AU. Oil fields in the AU are colored green. Fields outside the AU are outlined in black. Filled circles represent 280 exploratory wells drilled for petroleum within the AU between 1923 and 2000. Well locations are from the California Department of Conservation, Division of Oil, Gas, and Geothermal Resources, and are available in databases at ftp://ftp.consrv.ca.gov/pub/oil/maps/dist4. 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 Bakersfield Arch and tan shading indicates the location of the Maricopa deep. City of Bakersfield (B) denoted with filled square. Oil field labels are: B=Bellevue, BW=Bellevue West, CC=Calders Corner, C=Canal, CR=Canfield Ranch, EC=English Colony, G=Goosloo, Gr=Greeley, K=Kernsumner, M=McClung, R=Rosedale, SS=Seventh Standard, S=Stockdale, St=Strand, and TS=Ten Section.

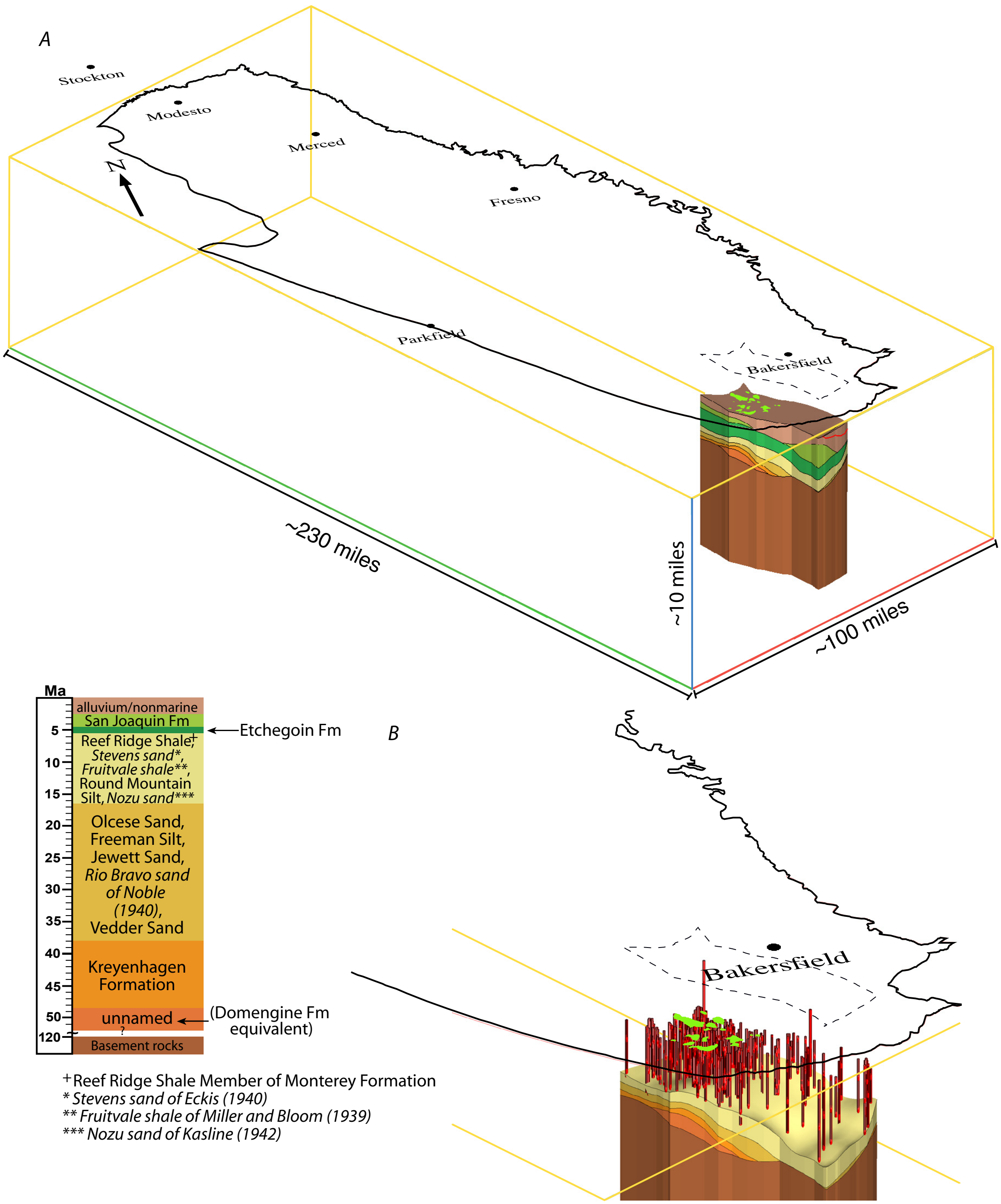


Figure 14.3. *A*, Three-dimensional stratigraphy model of the Lower Bakersfield Arch AU extracted from the EarthVision® model of the basin by Hosford Scheirer (this volume, chapter 7). The bounding polygonal block illustrates the model space within which the EarthVision® model is constructed. The major stratigraphic units of the AU are listed; see figure 14.4 for stratigraphic relationships between the units. Formation names in italics are informal. Note that Eocene-aged rocks rest directly on basement, indicating the absence of Cretaceous rocks on and south of the Bakersfield Arch. Oil fields (green) 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 15° west of south at a 30° inclination angle. Vertical exaggeration is 4. Fm, Formation. *B*, Same as above, but with alluvium, San Joaquin, and Etchegoin Formations stripped away. View is of the top of the Monterey Formation. The relative low area at the southern end of the assessment unit is the Maricopa deep. Wildcat wells (red vertical lines) are more densely spaced north of the Maricopa deep. EarthVision is a registered trademark (Marca Registrada) of Dynamic Graphics, Inc., Alameda, Calif.

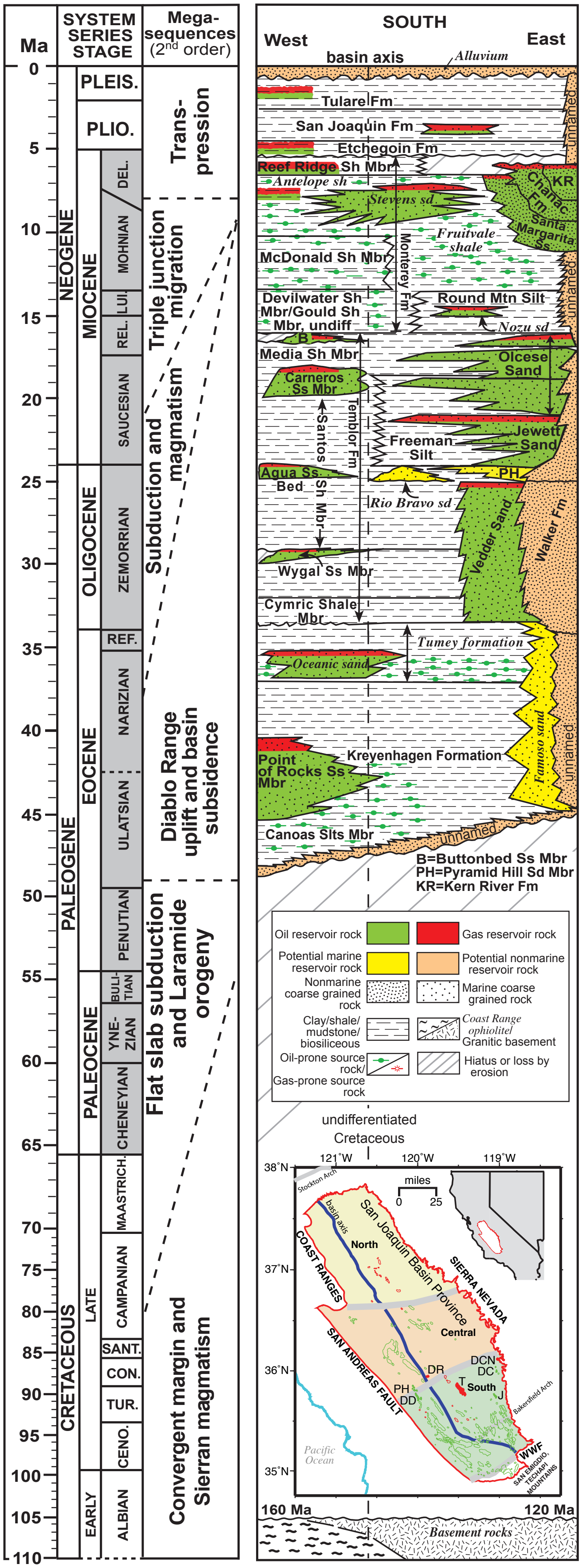


Figure 14.4. Generalized stratigraphic column for the southern San Joaquin Basin, showing hydrocarbon reservoir rocks and potential hydrocarbon source rocks. See Hosford Scheirer and Magoon (this volume, chapter 5) for complete explanation of the figure. Formation names in italics are informal and are defined as follows: Antelope shale of Graham and Williams (1985), Stevens sand of Eckis (1940), Fruitvale shale of Miller and Bloom (1939), Nozu sand of Kasline (1942), Rio Bravo sand of Noble (1940), Oceanic sand of McMasters (1948), Tumey formation of Atwill (1935), and Famoso sand of Edwards (1943).

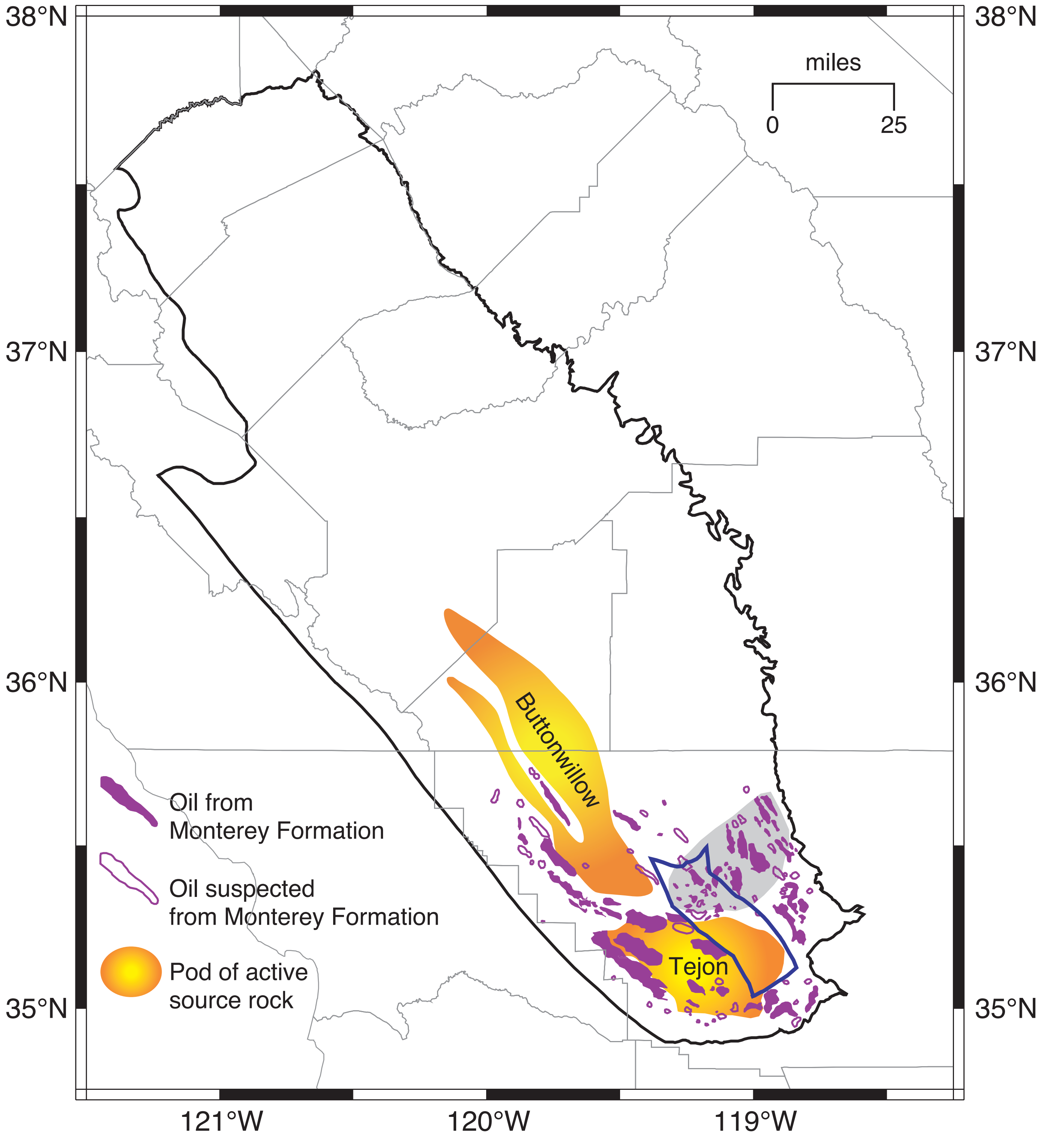


Figure 14.5. Location of Lower Bakersfield Arch AU (blue line) with respect to the pods of active source rock of the Miocene Total Petroleum System as mapped by Peters, Magoon, Lampe, and others (this volume, chapter 12). The bold line is the San Joaquin Basin Province boundary and thin gray lines are county boundaries. Gray shading shows the location of the Bakersfield Arch. See Magoon and others (this volume, chapter 8) for details of oil field assignment to petroleum systems based on geochemical analyses.

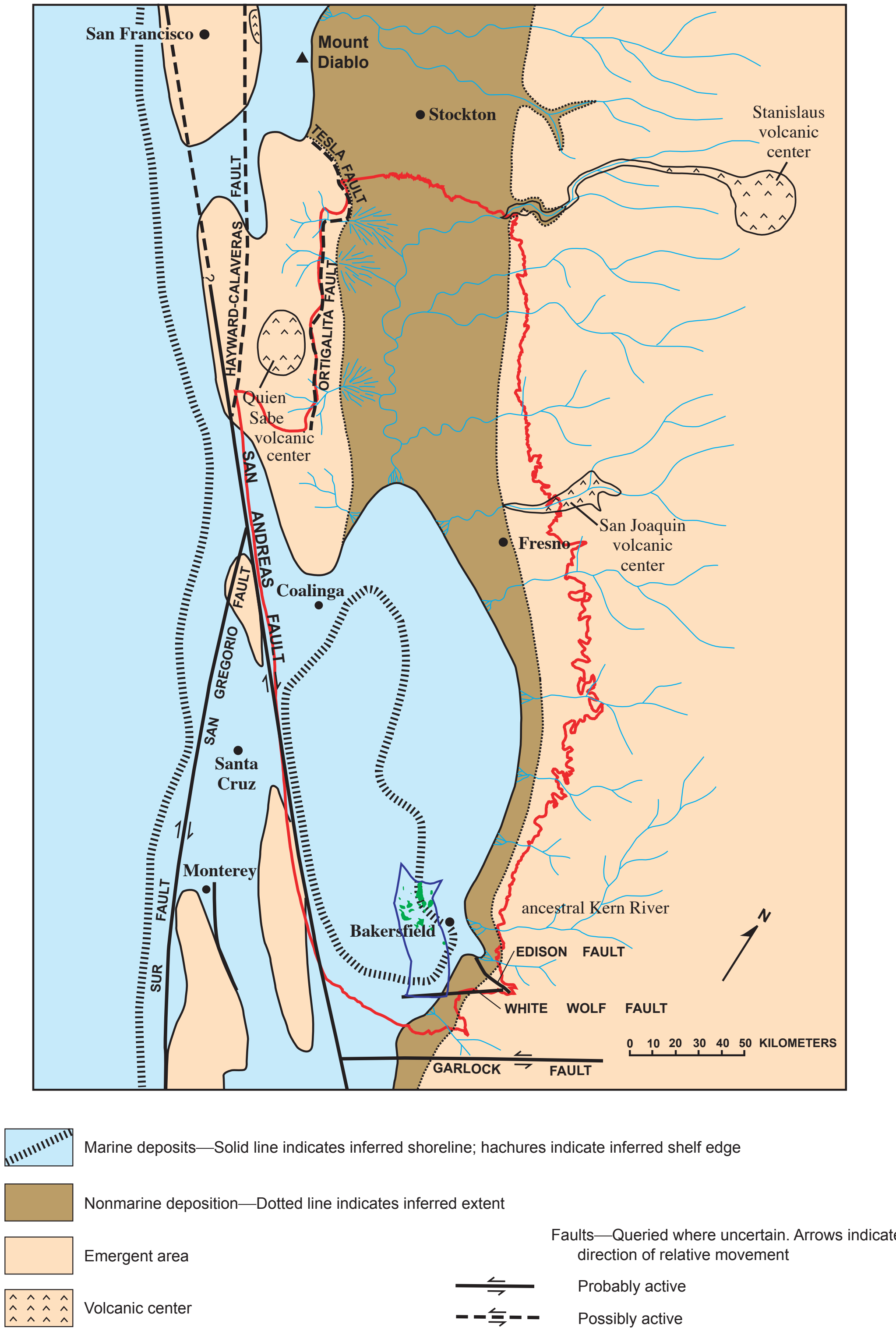


Figure 14.6. Paleogeography of the San Joaquin Basin (red outline) in the late Miocene, between 10 and 9 Ma. The Lower Bakersfield Arch AU (blue line) and known oil fields (green) are superimposed for reference. Figure modified from Bartow (1991).

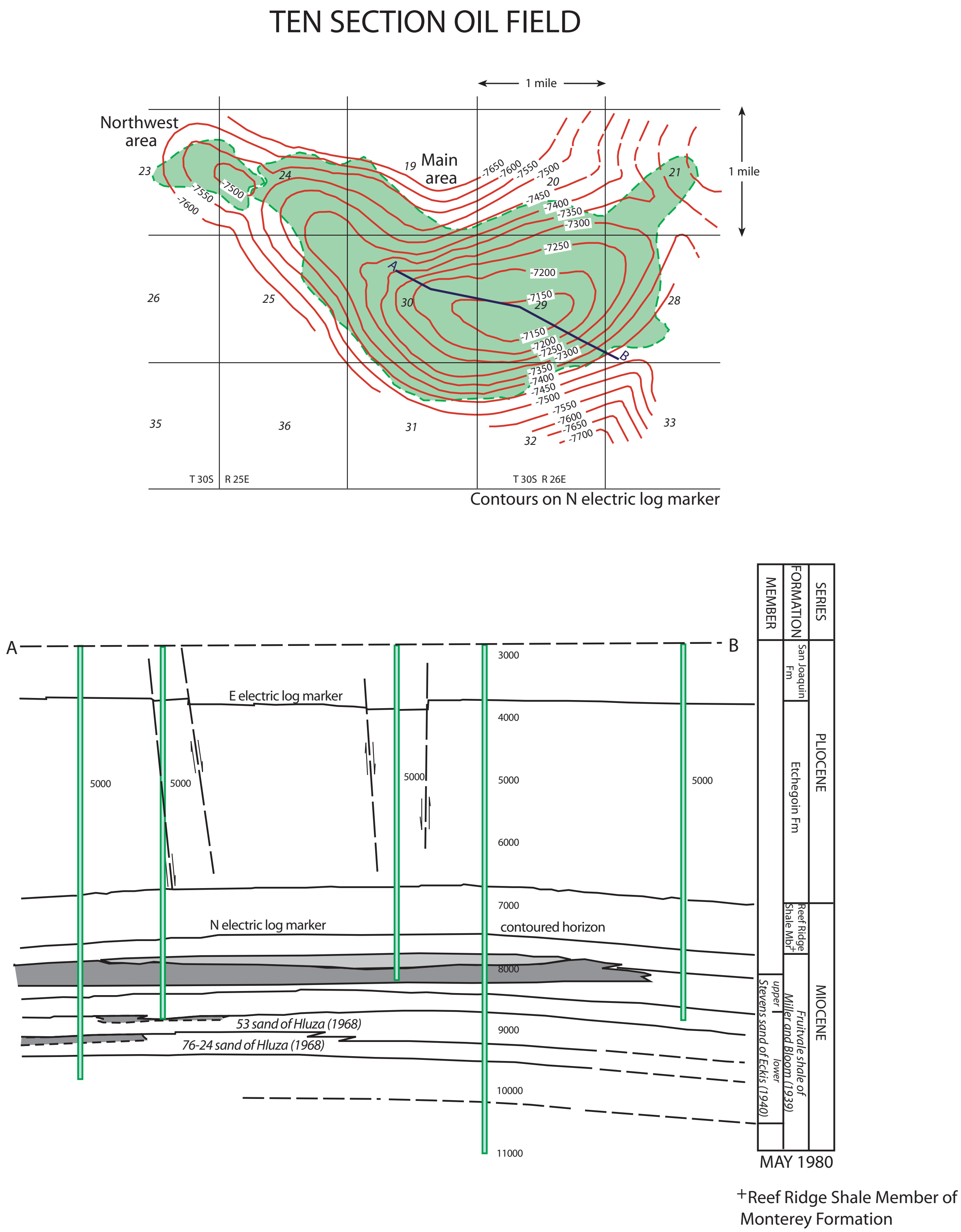


Figure 14.7. Figure of Ten Section oil field. Structure contours drawn on the N electric log marker within the Monterey Formation reveal an arcuate anticline that measures about 4 miles long and 1.5 miles across at its widest point. Green shading (underlying township-range grid) denotes reported 1998 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 53 sand of Hluza (1968) and the 76-24 sand of Hluza (1968). Township-range grid in figures 14.7 and 14.8 is relative to the Mount Diablo baseline and meridian; one mile by one mile sections within the township-range grid are numbered in italics. See figure 14.2 for location of field. Figure redrafted from CDOGGR (1998). Fm, Formation; Mbr, Member.

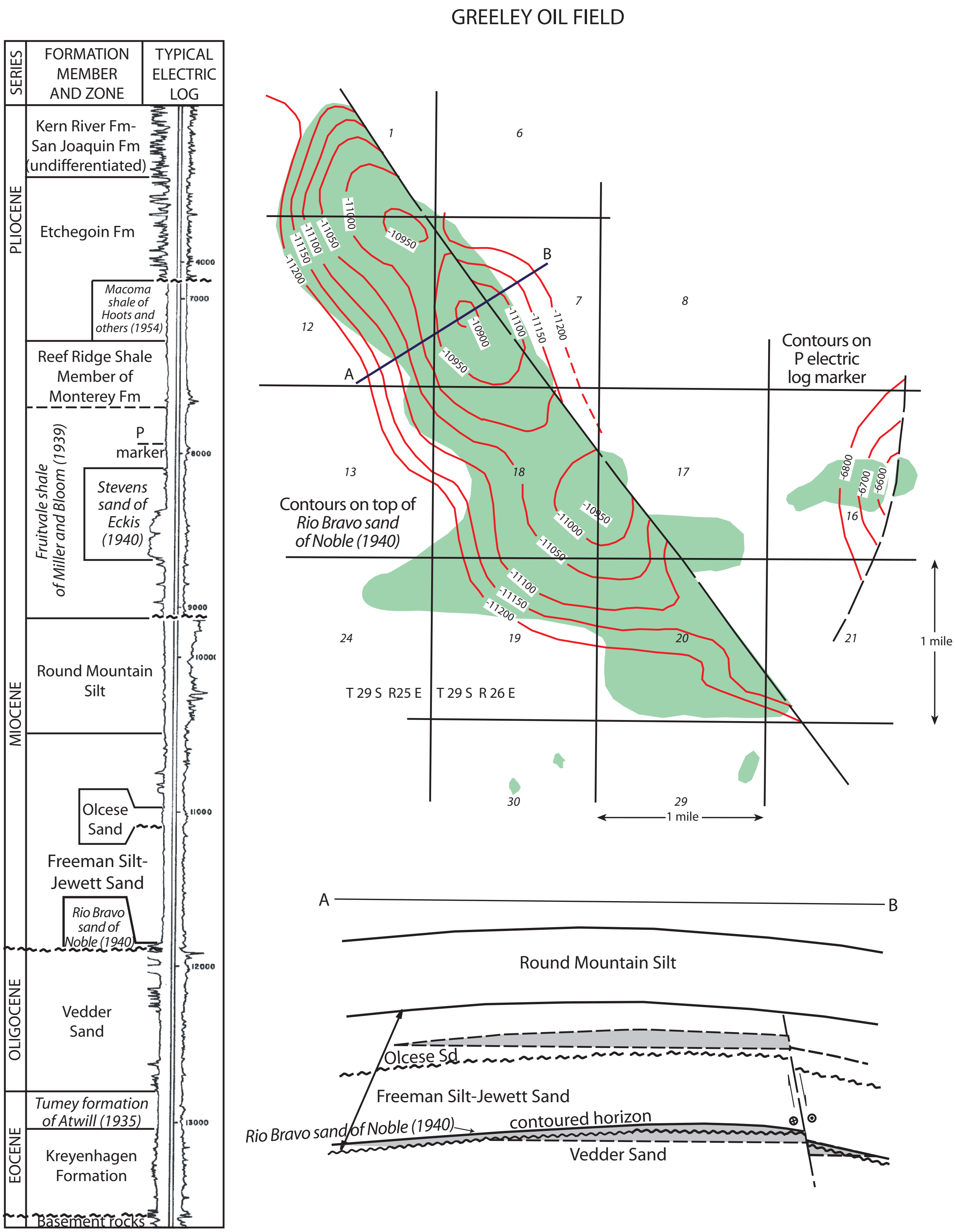


Figure 14.8. Figure of Greeley oil field, illustrating productive horizons below the Stevens sand. The large-offset Greeley fault confines up-dip production in the Olcese Sand, Rio Bravo sand of Noble (1940), and Vedder Sand pools. Green shading (underlying township-range grid) denotes reported 1998 limits of productive sand units within the field. All depths are in feet. Formations in italics denote informal geologic names. See figure 14.2 for location of field. Figure redrafted from CDOGGR (1998). Fm, Formation; Sd, Sand.

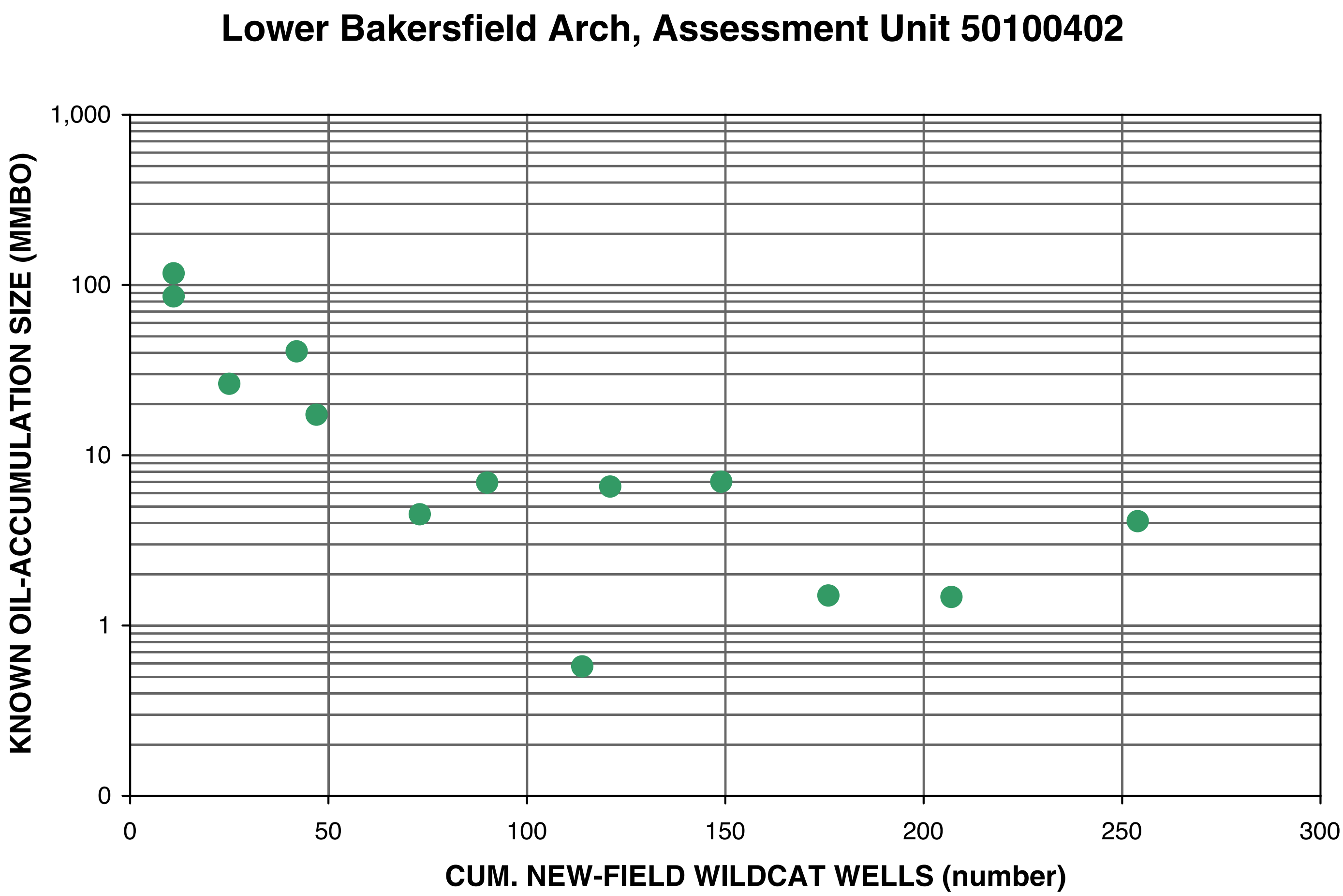


Figure 14.9. Cumulative number of new-field wildcat wells versus oil accumulation size in the Lower Bakersfield Arch AU. Figure is excerpted from data file k100402.pdf (see Klett and Le, this volume, chapter 28, for explanation of data file).

50100402
Lower Bakersfield Arch
Monte Carlo Results

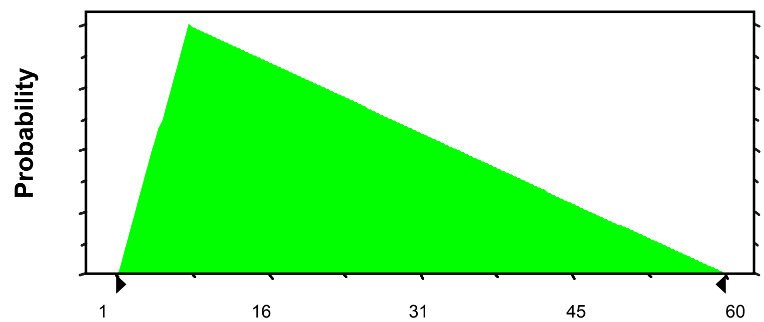
Assumptions

Assumption: Number of Oil Fields

Triangular distribution with parameters:

Minimum	1
Likeliest	8
Maximum	60

Selected range is from 1 to 60



Assumption: Sizes of Oil Fields

Lognormal distribution with parameters:		Shifted parameters
Mean	2.85	3.35
Standard Deviation	4.59	4.59

Selected range is from 0.00 to 49.50 0.50 to 50.00

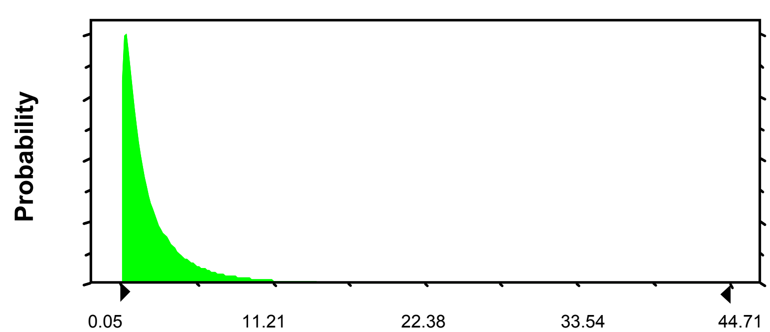


Figure 14.10. Probabilistic estimates of the number and size of undiscovered oil fields in the Lower Bakersfield Arch AU. Figure is excerpted from data file em100402.pdf (see Charpentier and Klett, this volume, chapter 26, for details of the calculation and Klett and Le, this volume, chapter 28, for explanation of data file).