Appendix H

Horizontal Well Drilling History in CA

In California, horizontal wells are used with and without well stimulation. This appendix discusses the historic application of horizontal wells without well stimulation, followed by an assessment of recent horizontal well installation activity. Historic and recent stimulation of horizontal wells is discussed in Section 3.2 regarding hydraulic fracturing. The following is a review of the use of horizontal wells in California.

Historical Horizontal Well Utilization

The first horizontal-well-drilling technology was developed in the 1920s, but the development of the technology led to limited use until the mid-1980s, followed by a rapid increase through the 1990s, when they became common (Ellis et al., 2000). Many thousands of horizontal wells had been installed in the United States by the mid-1990s (Joshi and Ding, 1996).

Modern methods of horizontal well drilling, as described in Section 2.2.2, have a number of applications in oil production (Ellis et al., 2000); in the shale oil and gas basins elsewhere in the country, their use is principally to allow production from relatively thin, impermeable shales. However, in California, the applications are more varied. They can have greater contact area with the petroleum-containing reservoir in near-horizontal layered geologic systems. Horizontal wells can also more readily intersect more natural fractures in the reservoir that may conduct oil, owing not only to their intersecting more of the reservoir than a vertical well, but also because fractures are typically perpendicular to rock strata, and so are nearly vertical in near-horizontal strata.

Horizontal wells can parallel water-oil or oil-gas contacts, and so can be positioned along their length to produce more oil, without drawing in water or gas, than is possible from a vertical well. Due to their orientation parallel to geologic strata, horizontal wells can improve sweep efficiency during secondary or tertiary oil recovery, which involves the injection of other fluids, such as steam, to mobilize oil to a production well. A horizontal well also provides for more uniform injection to a particular stratum. On the production side, a horizontal well provides a more thorough interception of the oil mobilized by the injection. Vertical wells are more readily bypassed by mobilized oil due to variation in the permeability of the reservoir rock. Similar to being better positioned to intercept oil mobilized by injection, horizontal wells are also better positioned to intercept oil draining by gravity through a reservoir.

An example of a thin reservoir development in California is the installation of a horizontal well in a Stevens Sand layer of the Yowlumne field in the southern San Joaquin Basin, which was a layer too thin to be developed economically using vertical wells. It was completed in 1991 at a true depth of over 3,400 m (11,200 ft) with a 687 m (2,252 ft) lateral. The well tripled the production rate from the previous vertical wells in the reservoir (Marino and Shultz, 1992).

The use of horizontal wells to improve the efficiency of steam injection for oil recovery began in the early 1990s. Steam injection reduces the viscosity of oil, allowing it to flow more readily to production wells. For example, in 1990 and 1991, three horizontal wells were installed by Shell Western Exploration and Production in 45° dipping (tilted) units with a long history of steam injection in the Midway Sunset field in the San Joaquin Basin. Two of the wells were installed with 121 m (400 ft) sloping laterals. These wells produced two to three times more oil as nearby vertical wells, but cost two to three times more, and so did not provide an economic benefit. The third well, with a longer horizontal lateral of 213 m (700 ft), produced six times more oil than nearby vertical wells and so was more economically successful (Carpenter and Dazet, 1992).

Shell Western Exploration and Production also installed horizontal wells in a shallow, tilted (dipping) geologic bed in the Coalinga field in the San Joaquin Basin in the early 1990s. Steam injection with oil production via vertical wells started in this zone in the late 1980s. The horizontal wells were installed in the same reservoir but deeper along the tilted bed. The wells were initially operated with steam cycling. This process entails injecting steam for a period, then closing the well to let the steam continue to heat the oil and reservoir, then opening the well and producing oil. However, the increase in production resulting from steam cycling was lower than expected. Vertical wells for continuous steam injection were subsequently installed shallower along the tilted bed from the horizontal wells. This resulted in a large sustained production rate that justified the horizontal wells, which led to considering further opportunities for installing horizontal wells in the Coalinga field (Huff, 1995).

By the late 1990s, horizontal well installation projects for production of shallow oil, using vertical steam injectors, involved tens of wells each. Nearly 100 horizontal wells were installed in shallow sands containing heavy (viscous) oil in the Cymric and McKittrick fields in the San Joaquin Basin from the late 1990s to early 2000s. These wells were installed in association with vertical wells that injected steam to reduce the viscosity of the oil by heating, allowing it to flow to the horizontal wells. The wells were installed in phases, allowing optimization with each phase that reduced the cost per well by 45% by the last phase (Cline and Basham, 2002). By the late 2000s and early 2010s, drilling programs in reservoirs with steam injection included as many as hundreds of wells. For instance, over 400 horizontal wells were installed in the Kern River field in the San Joaquin Basin between 2007 and 2013, targeting zones identified with low oil recovery to date. These wells provided a quarter of the field’s daily production (McNaboe and Shotts, 2013).

The third application of horizontal wells in California is for more efficient production of oil by gravity drainage. A prominent example of this is the installation of horizontal wells in a steeply dipping (60° from horizontal) sandstone reservoir in the Elk Hills field by Bechtel Petroleum Operations. Pressure in the formation was maintained by injecting natural gas updip in the reservoir. The position of the gas-oil contact moved deeper as oil production proceeded. Production from vertical wells in the oil zone was reduced to limit the amount of overlying gas they drew in, which then had to be re-injected. The wells were also reconfigured periodically to move the top of the interval from which they produced to greater depths (Mut et al., 1996).

The first horizontal well was installed in this steeply dipping sandstone reservoir in the Elk Hills field in 1988; the second in 1990. The wells' laterals (horizontal sections) were installed 12 m (40 ft) above the oil-water contact and about 76 m (250 ft) downdip of the gas-oil contact. This allowed production rates multiple times that from the adjacent vertical wells without drawing in the overlying gas or water from below. Production was also more constant over time compared to the typically declining rates from the vertical wells (Gangle et al., 1991); production from one of the first two wells remained constant for at least five years (Gangle et al., 1991). Given the successful production from these wells, another 16 had been installed by early 1995 (Mut et al., 1996).

Recent Horizontal Well Installation

The GIS data files made available by DOGGR with attributes of oil, gas, and geothermal wells in California (DOGGR, 2014a) include the county and field in which the well is located, the date drilling was initiated, and whether the well was vertical (listed as "not directional" in the file), directional, horizontal, or had an unknown path. Review of a sample of recent well records available from DOGGR for directionally drilled wells indicates they are typically near-vertical in the reservoir, with the directional drilling employed primarily to offset (shift) where the well encounters the reservoir relative to the point from which it is drilled. This is typical if the locations suitable for drilling are smaller than the extent of its oil resource.

Table H-1 shows the number of wells with a commencement date in 2012 or 2013 in DOGGR's GIS well data file and the number of these listed as horizontal. The percentage of all wells that are horizontal is relatively small. A higher percentage of these are in Kern County than wells in general.

A small percentage of recently installed wells in California are horizontal. All but three of these wells, more than 99% of the total, were installed in pre-existing fields as defined by DOGGR. The three outside pre-existing fields were in Kern County. The vast majority of all horizontal wells were installed are in Kern County. Outside of Kern County, 11 horizontal wells were installed in Fresno County, all in the Coalinga field; and nine in Monterey County, all in the San Ardo field. Three fields in Ventura County and two fields in Los Angeles County each had one or two horizontal wells installed.

Table H-1. ***Number of all wells and horizontal wells whose installation was listed as commencing in 2012 and 2013 (DOGGR, 2014b).***

All wells					Horizontal wells			
	With path type							
#	In California		In Kern County		#	% of wells with path type	% in Kern County	% in pre-existing fields
	#	%	#	%				
5,143	4,384	85	4,297	84	308	7	92	99

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Appendix I

Procedure for Searching Well Records for Indications of Hydraulic Fracturing

Well records are publicly available from the California Department of Oil, Gas, and Geothermal Resources (DOGGR) in the form of scans without searchable text (DOGGR, undated a). Through application of optical character recognition software, DOGGR provided versions of scanned records with searchable text for wells with first production or injection after 2001 (Bill Winkler, DOGGR, personnel communication).

Due to the large number of wells in Kern County, a sample of records was chosen for application of character recognition and subsequent searching. To define the sample proportion, the proportion of all records indicating hydraulic fracturing was presumed to be 20%. Given this presumption, the sample proportion for Kern County was selected to provide 95% confidence that the estimated proportion was within 2% of the actual proportion, using a finite population correction factor.

For some other counties, such as Fresno, digital records were available for all the wells. For the remaining counties, digital records were not available for all wells. Like for Kern County, this resulted in searching a sample of records for these counties. For some of them, such as Los Angeles and Orange counties, the proportion of wells with previously available digitized records was too small to provide a sufficiently constrained estimate of the proportion of wells hydraulically fractured. DOGGR scanned and provided additional records for these counties.

Searching the well record set provided by DOGGR resulted in data regarding the number of wells hydraulically fractured over time. Records potentially indicating that a well was hydraulically fractured were identified using the search term “frac.” The space after the term avoided occurrences of the term “fracture,” which appears in the template information on some forms, and consequently the term is not correlated with wells that have been hydraulically fractured.

Records containing “frac” were reviewed to determine if hydraulic fracturing indeed occurred. The term “frac” was found to correctly identify more records of hydraulic fracturing than other potential terms, such as “fracture,” “stimulation,” “stage,” and “frack.” The few records containing the latter term also all included the term “frac.”

For Kern County, 90% of all the well records containing the term “frac” were confirmed as indicating hydraulic fracturing had occurred. In the other 10% of records, the term was used for other purposes, such as to describe geologic materials or to refer to the fracture gradient (the minimum fluid pressure per depth that will fracture the rock in a particular location). For the rest of the state, 63% of the records containing “frac” were confirmed as indicating hydraulic fracturing had taken place, and the term was used for other purposes in the other 37% of records. These percentages are based on weighting the result for each county by the estimated number of records containing “frac” in that county. For individual counties with at least five records containing “frac,” the percentage confirmed as indicating hydraulic fracturing ranged from 13% (Santa Barbara County) to 73% (Solano County).

In some records, the term “frac” was found to also indicate a Frac-Pack was completed. As described previously, placement of a Frac-Pack occurs above the fracturing pressure, and results in a fracture (the “frac”) propagated from the well filled with introduced granular material (the “pack”). The purpose of a Frac-Pack is to bypass formation damage resulting from drilling and/or control production of granular material from the formation.

“HRGP,” standing for “high rate gravel pack,” was identified in records for a number of wells in Los Angeles County. This is an alternate term for a Frac-Pack. The Los Angeles County records were searched for this term with the result that 16 in addition to those containing the term “frac” were identified. Review confirmed each of these records indicated a fracturing operation had occurred. All the records regarded wells in the Inglewood field. Subsequently, all of the well records were searched for “HRGP.” Only one additional record not also containing the term “frac” was identified. This regarded a well in Kern County.

For records indicating hydraulic fracturing occurred, the operation was assigned to the date of the well’s first production, or first injection if first production was not available. For hydraulically fractured wells with first production and injection, the fracturing date in almost all the records is closer to the first production date.

Reference

DOGGR (Division of Oil, Gas and Geothermal Resources) (undateda). OWRS – Search Oil and Gas Well Records. Available at http://owr.conservation.ca.gov/WellSearch/WellSearch.aspx

Appendix J

Number of Well Records Searched for Indication of Hydraulic Fracturing

The following tables list the number of well first produced or injected from 2002 through September 2013, the number and % of these wells whose records were searched for reports of hydraulic fracturing (HF), and the number and percent of records that contained reports of hydraulic fracturing. The first table lists basins and the second counties with at least one well with first production or injection during this time period.

Table K-1 lists the estimated number of well records indicating hydraulic fracturing by sedimentary basin. Table K-2 lists the estimated number of well records indicating hydraulic fracturing by county.

Table J-1. ***Annual average total number of well records, and total number and percent of well records identified as indicating hydraulic fracturing by basin and for the state for wells with first production or injection from 2002 to 2013.***

Basin	2002-2006					2007-2011					2012-2013				
	New wells	Searched		HF recorded		New wells	Searched		HF recorded		New wells	Searched		HF recorded	
		#	%	#	%		#	%	#	%		#	%	#	%
Cuyama	21	2	10%	0	0%	11	1	9%	0	0%	1	0	0%	-	-
Eel River	9	9	100%	0	0%	2	2	100%	0	0%	0	-	-	-	-
Hollister-Sargent	0	-	-	-	-	8	4	50%	0	0%	0	-	-	-	-
Los Angeles	661	528	80%	153	29%	639	503	79%	75	15%	428	331	77%	32	10%
onshore	457	341	75%	106	31%	431	317	74%	34	11%	246	176	72%	14	8%
offshore	204	187	92%	47	25%	208	186	89%	41	22%	182	155	85%	18	12%
Sacramento	458	455	99%	15	3%	545	534	98%	59	11%	28	22	79%	0	0%
Salinas	156	18	12%	3	17%	405	121	30%	0	0%	118	7	6%	0	0%
San Joaquin	13,355	2,318	17%	591	25%	13,372	2,377	18%	523	22%	5,681	1,266	22%	372	29%
Santa Barbara-Ventura	130	126	97%	12	10%	347	339	98%	65	19%	154	149	97%	28	19%
Santa Maria	126	126	100%	12	10%	344	337	98%	65	19%	147	142	97%	28	20%
Santa Barbara-Ventura	4	0	0%	-	-	3	2	67%	0	0%	7	7	100%	0	0%
California	14,865	3,490	23%	775	22%	15,520	4,012	26%	724	18%	6,543	1,814	28%	432	24%

Table J-2. *Annual average total number of well records, and total number and percent of well records identified as indicating hydraulic fracturing by county and for the state for wells with first production or injection from 2002 to 2013.*

County	2002-2006					2007-2011					2012-2013				
	New wells	Searched		HF recorded		New wells	Searched		HF recorded		New wells	Searched		HF recorded	
		#	%	#	%		#	%	#	%		#	%	#	%
Alameda	1	1	100%	0	0%	0	0	-	0	-	0	0	-	0	-
Butte	6	6	100%	0	0%	9	7	78%	0	0%	0	0	-	0	-
Colusa	61	61	100%	1	2%	114	109	96%	10	9%	16	10	63%	0	0%
Contra Costa	5	5	100%	1	20%	8	8	100%	0	0%	0	0	-	0	-
Fresno	463	463	100%	2	0%	664	664	100%	4	1%	166	166	100%	3	2%
Glenn	63	63	100%	2	3%	125	124	99%	11	9%	4	4	100%	0	0%
Humboldt	9	9	100%	0	0%	2	2	100%	0	0%	0	0	-	0	-
Kern	12,821	1,785	14%	589	33%	12,655	1,663	13%	516	31%	5,506	1,093	20%	369	34%
Kings	11	11	100%	0	0%	10	10	100%	2	20%	3	2	67%	0	0%
Los Angeles	697	588	84%	157	27%	659	549	83%	64	12%	434	341	79%	26	8%
Madera	7	7	100%	0	0%	16	16	100%	0	0%	1	1	100%	0	0%
Merced	1	1	100%	0	0%	1	1	100%	0	0%	0	0	-	0	-
Monterey	156	18	12%	3	17%	405	121	30%	0	0%	118	7	6%	0	0%
Orange	50	26	52%	2	8%	56	30	54%	13	43%	18	14	78%	6	43%
Sacramento	73	72	99%	6	8%	46	45	98%	4	9%	5	5	100%	0	0%
San Benito	1	1	100%	0	0%	1	1	100%	0	0%	0	0	-	0	-
San Joaquin	43	43	100%	0	0%	13	11	85%	1	9%	3	3	100%	0	0%
San Luis Obispo	45	17	38%	0	0%	17	6	35%	0	0%	20	0	0%	-	-
Santa Barbara	55	18	33%	1	6%	185	125	68%	2	2%	113	38	34%	0	0%
Santa Clara	0	0	-	0	-	7	3	43%	0	0%	0	0	-	0	-
Solano	72	71	99%	4	6%	53	53	100%	10	19%	1	1	100%	0	0%
Stanislaus	2	2	100%	0	0%	0	0	-	0	-	0	0	-	0	-
Sutter	66	66	100%	1	2%	161	161	100%	24	15%	0	0	-	0	-
Tehama	77	77	100%	0	0%	19	19	100%	0	0%	2	2	100%	0	0%
Tulare	7	7	100%	0	0%	13	12	92%	0	0%	2	1	50%	0	0%
Ventura	40	40	100%	6	15%	271	264	97%	63	24%	130	125	96%	28	22%
Yolo	32	31	97%	0	0%	10	8	80%	0	0%	1	1	100%	0	0%
Yuba	1	1	100%	0	0%	0	0	-	0	-	0	0	-	0	-
California	14,865	3,490	23%	775	22%	15,520	4,012	26%	724	18%	6,543	1,814	28%	432	24%

Appendix K

Estimated Number of Well Records Indicating Hydraulic Fracturing By Geographic Area

Table K-1 lists the estimated number of well records indicating hydraulic fracturing by sedimentary basin. Table K-2 lists the estimated number of well records indicating hydraulic fracturing by county.

For geographic areas with more than zero wells fractured during a time period, the 95% confidence bounds were calculated using a logit transform. For geographic areas with zero wells fractured during a time period, the 95% confidence bounds were calculated using the rule of three. The positive confidence increment was taken as the theoretical maximum if it were less than either the logit or rule of three results. The theoretical maximum is calculated by assuming all the wells with unavailable records were fractured.

Table K-1. *Annual average number of wells with first production or injection from 2002 to 2013 by basin. Estimated annual average rate of wells fractured, percent of all wells fractured, and 95% confidence interval (CI) for the fracturing rate based on searching well records. No fracturing rate is shown if less than one eighth of the well records were available for searching. "NA" for the percentage fractured indicates no wells had first injection or production in the time period. No CI is shown if no rate was estimated or all the well records were searched. Analysis of more recent data from various sources indicates actual hydraulic fracturing rates may be up to twice as high.*

Basin	2002-2006	2007-2011	2012-2013									
	New wells	Frac. wells	% frac	95% CI	New wells	Frac. wells	% frac	95% CI	New wells	Frac. wells	% frac	95% CI
Cuyama	4.2	-	-	-	2.2	-	-	-	0.6	-	-	-
Eel River	1.8	0.0	0%	-	0.4	0.0	0%	-	0.0	0.0	NA	-
Hollister-Sargent	0.0	0.0	NA	-	1.6	0.0	0%	0.0-0.2	0.0	0.0	NA	-
Sonoma-Livermore	0.2	0.0	0%	-	0.0	0.0	NA	-	0.0	0.0	NA	-
Los Angeles	132	38.3	29%	36.0-40.6	128	19	15%	17.3-21.0	245	23.6	10%	20.2-27.6
onshore	91.4	28.4	31%	26.2-30.7	86.2	9.2	11%	7.8-10.9	140.6	11.2	8%	8.5-14.6
offshore	40.8	10.3	25%	9.5-11.0	41.6	9.2	22%	8.4-10.0	104.0	12.1	12%	10.3-14.3
Sacramento	91.6	3.0	3%	-	109	11.9	11%	11.9-11.9	16.0	0.0	0%	0.0-0.1
Salinas	31.2	-	-	-	81.0	0.0	0%	0.0-0.0	67.4	-	-	-
San Joaquin	2,671	847	32%	795-899	2,674	787	29%	735-841	3,246	1,064	33%	986-1,146
Santa Maria	15	0.5	3%	0.2-2.0	36.8	0.6	2%	0.4-1.2	74.3	0.0	0%	0.0-0.0
Santa Barbara-Ventura	26.0	2.5	10%	2.4-2.7	69.4	13.3	19%	13.0-13.8	88.0	16.5	19%	16.0-17.6
California	2,973	895	30%	837-961	3,104	832	27%	778-891	3,739	1,104	30%	1,022-1,192

Table K-2. *Annual average number of wells with first production or injection from 2002 to 2013 by county. Estimated annual average rate, percent, and 95% confidence interval (CI) for the rate of wells fractured based on searching well records. No fracturing rate is shown if less than one eighth of the well records were available for searching. NA" for the percentage fractured indicates no wells had first injection or production in the time period. No CI is shown if no rate was estimated or all the well records were searched. Analysis of more recent data from various sources indicates actual rates may be up to twice as high.*

County	2002-2006				2007-2011				2012-2013			
	New wells	Frac. wells	% frac.	95% CI	New wells	Frac. wells	% frac.	95% CI	New wells	Frac. wells	% frac.	95% CI
Alameda	0.2	0.0	0%	-	0.0	0.0	NA	-	0.0	0.0	NA	-
Butte	1.2	0.0	0%	-	1.8	0.0	0%	0.0-0.1	0.0	0.0	NA	-
Colusa	12	0.2	2%	-	22.8	2.1	9%	2.0-2.4	9.1	0.0	0%	0.0-0.2
Contra Costa	1.0	0.2	20%	-	1.6	0.0	0%	-	0.0	0.0	NA	-
Fresno	92.6	0.4	0%	-	133	0.8	1%	-	94.9	1.7	2%	1.7-1.7
Kern	2,564	846	33%	795-899	2,531	785	31%	734-839	3,146	1,062	34%	985-1,143
Kings	2.2	0.0	0%	-	2.0	0.4	20%	0.4-0.4	1.7	0.0	0%	0.0-0.6
Los Angeles	139	37.2	27%	35.3-39.2	132	15.4	12%	14.0-16.9	248	18.9	8%	15.9-22.4
Madera	1.4	0.0	0%	-	3.2	0.0	0%	-	0.6	0.0	0%	-
Merced	0.2	0.0	0%	-	0.2	0.0	0%	-	0.0	0.0	NA	-
Monterey	31.2	-	-	-	81.0	0.0	0%	-	67.4	-	-	-
Orange	10	0.8	8%	0.4-1.9	11.2	4.9	43%	3.5-6.3	10	4.4	43%	3.4-5.7
Sacramento	15	1.2	8%	1.2-1.3	9	0.8	9%	0.8-0.9	2.9	0.0	0%	-
San Benito	0.2	0.0	0%	-	0.2	0.0	0%	-	0.0	0.0	NA	-
San Joaquin	8.6	0.0	0%	-	2.6	0.2	9%	0.2-0.5	1.7	0.0	0%	-
San Luis Obispo	9.0	0.0	0%	-	3.4	0.0	0%	0.0-0.1	11.4	-	-	-
Santa Barbara	11	0.6	6%	0.2-2.8	37.0	0.6	2%	0.4-1.3	64.6	0.0	0%	-
Santa Clara	0.0	0.0	NA	-	1.4	0.0	0%	0.0-0.2	0.0	0.0	NA	-
Solano	14	0.8	6%	0.8-0.9	11	2.0	19%	2.0-2.0	0.6	0.0	0%	-
Stanislaus	0.4	0.0	0%	-	0.0	0.0	NA	-	0.0	0.0	NA	-
Sutter	13	0.2	2%	-	32.2	4.8	15%	4.8-4.8	0.0	0.0	NA	-
Tehama	15	0.0	0%	-	3.8	0.0	0%	-	1.1	0.0	0%	-
Tulare	1.4	0.0	0%	-	2.6	0.0	0%	0.0-0.1	1.1	0.0	0%	0.0-0.6
Ventura	8.0	1.2	15%	-	54.2	12.9	24%	12.6-13.4	74.3	16.6	22%	16.0-17.7
Yolo	6.4	0.0	0%	-	2.0	0.0	0%	0.0-0.1	0.6	0.0	0%	-
Yuba	0.2	0.0	0%	-	0.0	0.0	NA	-	0.0	0.0	NA	-
California	2,973	895	30%	837-961	3,104	832	27%	778-891	3,739	1,104	30%	1,022-1,192

Appendix L

Well-Record Result Data Set

The data listing the API number for the wells considered in the well record search are provided in both Excel and tab-delimited text format. These wells have a first production date between 2002 and near the end of 2013, or a first injection date if no first production date, which is also listed, along with the basin, county, field, and area where that well is located, and the pool it was open to on that date. Whether the record for a well was searched, if the record indicated hydraulic fracturing occurred, and if the hydraulic fracturing consisted of a frac-pack is also listed.

The first production and injection date source file provided by the California Department of Oil, Gas, and Geothermal Resources has more than one record for some wells. The start dates are specific to the combination of a well and pool, so if a well is recompleted in a new pool it will have an additional start date. The data in this appendix include only the first occurrence of a well's production and injection dates, and the pool for that date. The full data can be found at http://ccst.us/publications/WST.

Appendix M

Integrated hydraulic fracturing data set regarding occurrence, location, date, and depth

Data regarding the occurrence, location, date and depth of hydraulic fracturing was integrated from the following data sources:

1. Well stimulation disclosures to the California Division of Oil, Gas, and Geothermal Resources (DOGGR),

2. South Coast Air Quality Management District (SCAQMD) well work data,

3. FracFocus,

4. FracFocus data compiled by SkyTruth,

5. Well record search results combined with first production or injection date (described above),

6. Central Valley Regional Water Quality Control Board (CVRWQCB) well work data, and

7. DOGGR geographic information system (GIS) well layer.

Each of these sources is described in the section 3.5 of the associated report. The data are provided in both Excel and tab-delimited text formats. The tables include all the data from all the sources. The first columns contain the most accurate version of each datum from among all the sources in the authors' judgment and a code indicating the source of that datum. The data source codes are as follows:

AW = DOGGR's AllWells GIS layer
CR = Hydraulic fracturing disclosures (completion reports) provided to DOGGR
CV = CVRWQCB data set
FF = FracFocus
FI = First injection
FP = First production
SC = SCAQMD data set
WR = Well record search

Some of the data sources contain more than one record for a well, such as DOGGR's AllWells GIS layer. This appendix lists the data from the first record for each well with regard to occurrence and location, and the minimum value for date and depth. The full data can be found at http://ccst.us/publications/WST.

Appendix N

Pools with Production Predominantly Facilitated By Hydraulic Fracturing

This appendix contains two lists of pools for which more than half the wells starting production from 2002 through late 2013 are estimated to be hydraulically fractured. The first list ("non-GS") regards oil and gas production pools. The second list ("GS") regards gas storage pools. The lists provide the following for each pool:

- The number of wells entering production during the time period
- The number of these wells for which records were received
- The fraction of wells with records received
- The number of records indicating hydraulic fracturing
- The fraction of records indicating hydraulic fracturing
- The fraction of such records adjusted for underreporting,
- Oil, gas, and water production from 2002 through May 2014
- The oil, gas, and water production multiplied by the fraction of records indicating hydraulic fracturing adjusted for underreporting
- Average oil and gas production per well per day
- The gas-oil ratio

The underreporting adjustment was made by taking the minimum of one or 1.63 times the fraction of records indicating hydraulic fracturing. The underreporting adjustment factor is equal to 150, which is the estimated average number of well fractured per month statewide, divided by 92, which is the estimated average number of records indicating fracturing statewide (shown on Figure 3-10 and discussed in related text).

The oil, gas, and water production were summed from sum by pool data available through the California Department of Oil, Gas, and Geothermal Resources online production and injection portal (http://opi.consrv.ca.gov/opi/opi.dll). The full data can be found at http://ccst.us/publications/WST.

Appendix O

Water Volume Per Stimulation Event

The available data regarding the volume of water used per stimulation were aggregated from FracFocus, CVRWQCB well work, SCAQMD well work, and the well stimulation disclosures. For some wells, multiple values were available. If the volume was different and the dates sufficiently different, these were judged to be refracturing operations and were included. If the volume or date was the same, these were judged to be two records regarding the same operation. Judgment was used in selecting which data to include. The full data can be found at http://ccst.us/publications/WST.

Appendix P

California Oil Fields and Source Rocks

This appendix provides support for the fraction of known oil reservoirs in California that have source rocks in the Monterey Formation. The table below lists large California oil fields along with the associated basin, discovery date, cumulative production, reserves, source rock name, source rock age, source rock status relative to the Monterey Formation, and indicates the references for the information.

Field Name	Basin	Discovered	Cum Prod	Reserves	Known oil	SourceRock Name	SR Age	Monterey-equivalent	Reference
Midway-Sunset	San Joaquin	1894	2,981	498	3,479	Antelope Sh	Miocene	Yes	1
Wilmington	Los Angeles	1932	2,701	283	2,984	Nodular Sh	Miocene	Yes	2,3
Kern River	San Joaquin	1899	2,064	569	2,633	Antelope Sh	Miocene	Yes	1
Belridge South	San Joaquin	1911	1,564	483	2,047	McLure Sh	Miocene	Yes	1
Elk Hills	San Joaquin	1911	1,330	62	1,392	Antelope Sh	Miocene	Yes	1
Huntington Beach	Los Angeles	1920	1,133	32	1,165			Yes	2,3
Ventura	Santa Barbara-Ventura	1919	999	106	1,105	Monterey Formation	Miocene	Yes	5
Long Beach	Los Angeles	1921	944	2	946	Nodular Sh	Miocene	Yes	2,3
Coalinga	San Joaquin	1890	929	89	1,018	Kreyenhagen Sh	Eocene	No	1
Buena Vista	San Joaquin	1909	670	5	675	Antelope Sh	Miocene	Yes	1
Santa Fe Springs	Los Angeles	1919	629	5	634	Miocene Undifferentiated	Miocene	Yes	2,3
Cymric	San Joaquin	1909	515	79	594	McLure Sh		Yes	1
Coalinga East Ext	San Joaquin	1938	504	0	504	Kreyenhagen Sh	Eocene	No	1
San Ardo	Salinas	1947	498	35	533	Monterey Formation	Miocene	Yes	7
Kettleman North Dome	San Joaquin	1928	459	2	461	Kreyenhagen Sh, Tumey Sh	Eocene	No	1
Brea-Olinda	Los Angeles	1880	413	18	431	Miocene Undifferentiated	Miocene	Yes	2,3
Lost Hills	San Joaquin	1910	403	124	527	McLure Sh	Miocene	Yes	1
Inglewood	Los Angeles	1924	399	30	429	Miocene Undifferentiated	Miocene	Yes	2,3
McKittrick	San Joaquin	1896	311	14	325	Kreyenhagen Sh?	Eocene	No	1
Cat Canyon	Cat Canyon	1908	303	2	305	Monterey Formation	Miocene	Yes	8

Field Name	Basin	Discovered	Cum Prod	Reserves	Known oil	SourceRock Name	SR Age	Monterey-equivalent	Reference
Mount Poso	San Joaquin	1926	300	6	306	Antelope Sh	Miocene	Yes	1
Hondo Offshore	Santa Barbara-Ventura	1969	286	31	317	Monterey Formation	Miocene	Yes	8
Dominguez	Los Angeles	1923	274	52	326	Nodular Shale	Miocene	Yes	2,3
Dos Cuadras	Santa Barbara-Ventura	1968	263	2	265	Monterey Formation	Miocene	Yes	8
Coyote West	Los Angeles	1909	253	0	253			Yes	2,3
Torrance	Los Angeles	1922	226	5	231	Nodular Sh	Miocene	Yes	2,3
Cuyama South	Cuyama	1949	255	4	259	Vacqueros	Oligocene	No	4
Seal Beach	Los Angeles	1924	215	6	221	Nodular Sh	Miocene	Yes	2,3
Kern Front	San Joaquin	1912	215	18	233	Antelope Sh	Miocene	Yes	1
Santa Maria Valley	Santa Maria	1934	207	1	208	Monterey Formation	Miocene	Yes	
Montebello	Los Angeles	1917	205	6	211	Undifferentiated Miocene shales	Miocene	Yes	2,3
Richfield	Los Angeles	1919	203	3	206	Undifferentiated Miocene shales	Miocene	Yes	2,3
Orcutt	Santa Maria	1901	181	12	193	Monterey Formation	Miocene	Yes	8
Point Arguello Offshore	Santa Maria	1981	179	29	208	Monterey Formation	Miocene	Yes	6
Coles Levee North	San Joaquin	1938	165	1	166	Antelope Sh	Miocene	Yes	1
Rincon	Santa Barbara-Ventura	1927	163	3	166	Monterey Formation	Miocene	Yes	5
South Mountain	Santa Barbara-Ventura	1916	159	6	165	Monterey Formation	Miocene	Yes	
Edison	San Joaquin	1928	150	6	156	Antelope Sh	Miocene	Yes	1
Beverly Hills	Los Angeles	1900	150	9	159			Yes	2,3
Belridge North	San Joaquin	1912	147	17	164	Kreyenhagen Sh?	Eocene	No	1
Pescado Offshore	Santa Barbara-Ventura	1970	132	15	147	Monterey Formation	Miocene	Yes	8
Fruitvale	San Joaquin	1928	126	9	135	Antelope Sh	Miocene	Yes	1
Rio Bravo	San Joaquin	1937	118	1	119	Antelope Sh	Miocene	Yes	1
San Miguelito	Santa Barbara-Ventura	1931	118	7	125	Monterey Formation	Miocene	Yes	5
Coyote East	Los Angeles	1909	116	4	120			Yes	2,3
Greeley	San Joaquin	1936	116	1	117	Antelope Sh	Miocene	Yes	1
Round Mountain	San Joaquin	1947	115	7	122	Antelope Sh	Miocene	Yes	1
Yowlumne	San Joaquin	1974	111	2	113	Antelope Sh	Miocene	Yes	1
Carpinteria Off-shore	Santa Barbara-Ventura	1966	107	2	109	Monterey Formation	Miocene	Yes	8

Field Name	Basin	Discovered	Cum Prod	Reserves	Known oil	SourceRock Name	SR Age	Monterey-equivalent	Reference
Elwood	Santa Barbara-Ventura	1928	106	0	106	Monterey Formation	Miocene	Yes	8
Beta Offshore	Los Angeles	1976	91	16	107	Undifferentiated Miocene shale	Miocene	Yes	2,3
Point Pedernales Offshore	Santa Maria	1983	86	20	106	Monterey Formation	Miocene	Yes	8

Discovery date, cumulative production and reserves from CDOGGR AR 2009

Known oil is the sum of cumulative production and reserves, all in millions of barrels.

If field known oil is assigned to likely principal reservoir oil source rock non-Monterey is about 9.74% of total oil in fields larger than 100 MMBO

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Appendix Q

Unit Conversion Table

1	Barrel	=	0.158987	Cubic Meters (m^3)
1	Cubic Foot (ft^3)	=	0.02831685	Cubic Meters (m^3)
1	Cubic Mile (mi^3)	=	4.16818	Cubic Kilometers (km^3)
1	Foot (ft)	=	0.3048	Meters (m)
1	Inch (in)	=	2.54	Centimeters (cm)
1	Gallon (gal)	=	0.00378541	Cubic Meters (m^3)
1	Acre-foot	=	1,233.4	Cubic Meters (m^3)
1	Miles (mi)	=	1.609344	Kilometers (km)
1	Square Mile (mi^2)	=	2.589988	Square Kilometers (km^2)
1	Nautical Mile	=	1.852	Kilometers (km)
1	Millidarcy (md)	=	9.87 x 10-16	Square meters (m^2)
1	Pound per Square Inch (psi)	=	6.89476 x 10-6	Gigapascals (GPa)