# Supporting Information

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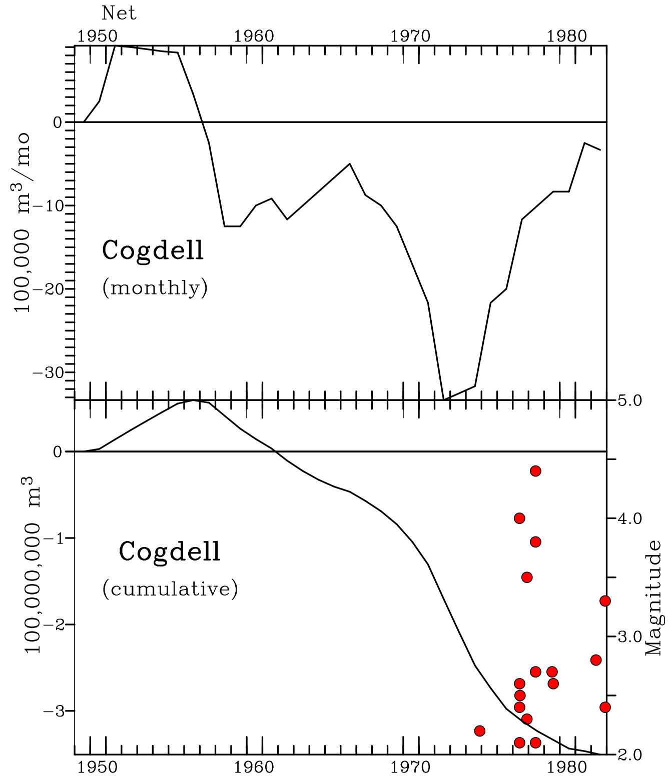


**Fig. S1.** Monthly rates (*Upper*) and cumulative volumes (*Lower*) of liquid extracted at the Cogdell field for 1949–1982 as reported by Davis and Pennington (1). Rates and volumes plotted are oil plus water extracted minus water injected. Red circles are Cogdell earthquakes as reported by the National Earthquake Information Center (NEIC), the International Seismological Center (ISC), and Davis (2) from inspection of seismograms recorded at Lubbock, TX.

1. Davis SD, Pennington WD (1989) Induced seismic deformation in the Cogdell oil field of west Texas. *Bull Seismol Soc Am* 79:1477–1495.
2. Davis SD (1985) Investigations of natural and induced seismicity in the Texas Panhandle. MS thesis (Univ Texas Austin, Austin, TX), p 230.

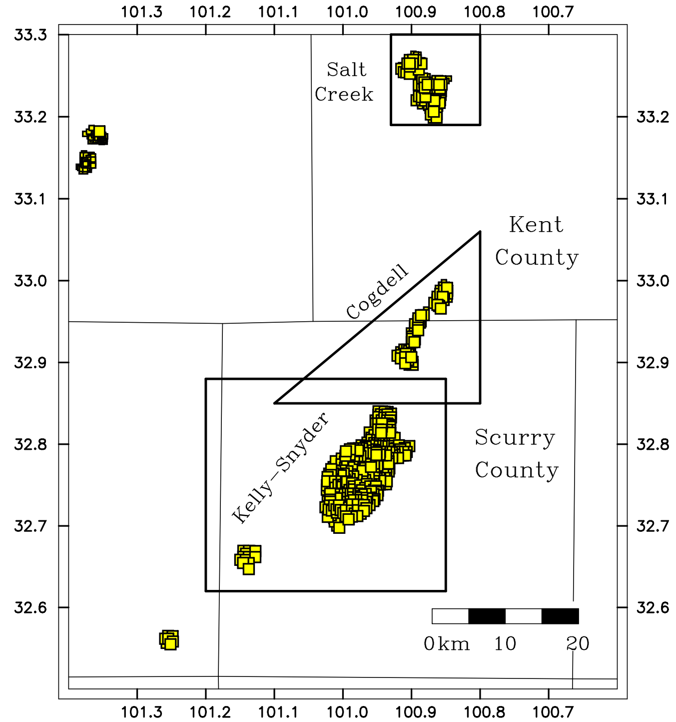


**Fig. S2.** Map showing gas injection wells active since 2004 (yellow squares) and polygons surrounding areas where extraction and injection were summed to construct Figs. 4 and 5 (Cogdell), Figs. S5 and S6 (Kelly–Snyder), and Figs. S7 and S8 (Salt Creek).

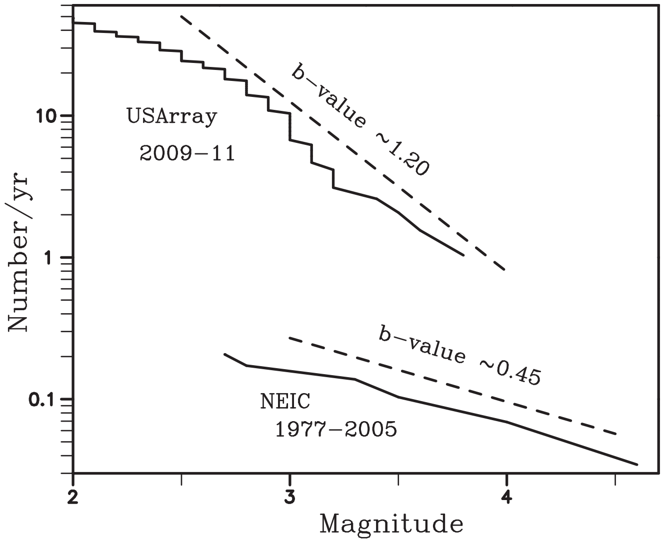


**Fig. S3.** Magnitude–frequency distribution of earthquakes as reported for 1977–2005 by the NEIC, and for 2009–2011 from the combined NEIC-ISC-Array Network Facility (ANF) catalogs. The data available to and procedures used by the NEIC and ANF are considerably different during the two periods of interest, and thus a precise comparison of magnitudes may not be meaningful. Nevertheless, the two groups have significantly different b values, possibly suggesting the events are generated by a different physical process. The plotted data for 1977–2005 do not include earthquakes reported by Harding (1) unless they also appeared in the NEIC catalog.

1. Harding ST (1981) Induced Cogdell Canyon Reef oil field. *Summaries of Technical Reports,* Vol. IX (US Department of the Interior, Menlo Park, CA), pp 452–455.

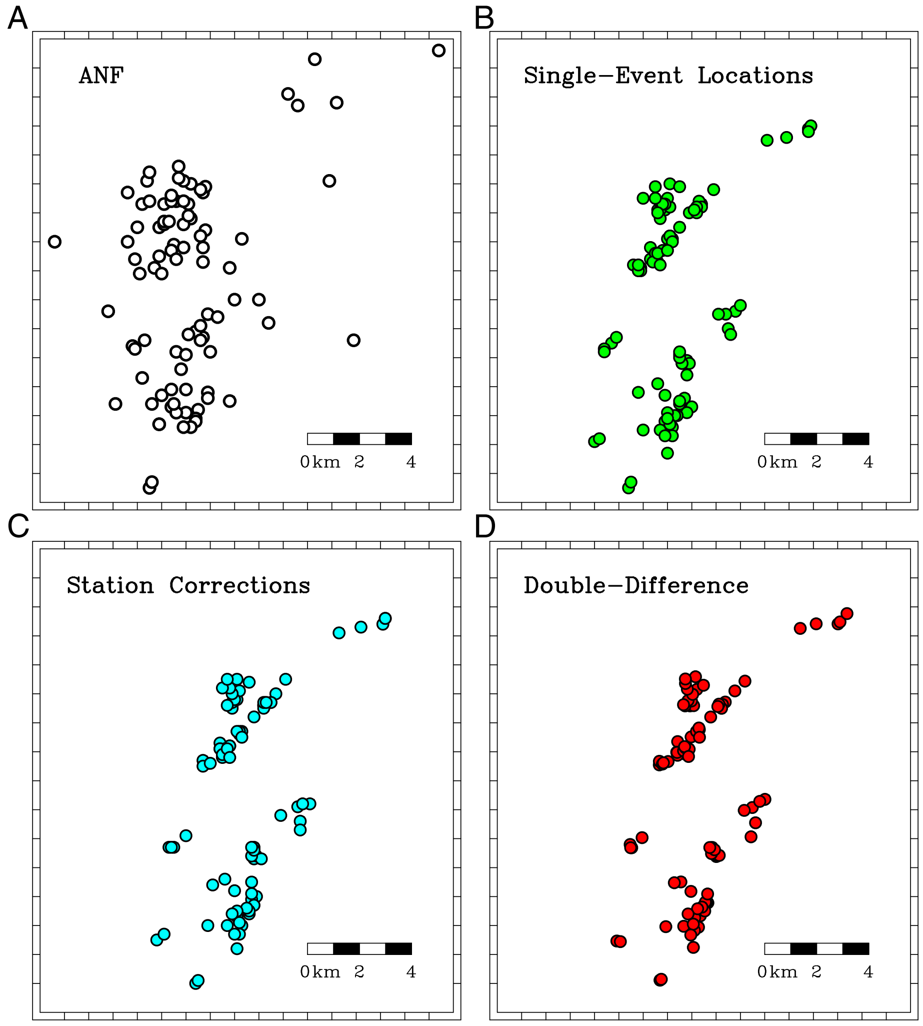


**Fig. S4.** Maps showing Cogdell-area epicenters (circles) determined using different methods. Earthquakes are 90 well-recorded events occurring between March 2009 and December 2010. (*A*) Unrelocated epicenters in the ANF catalog; (*B*) Single-event locations located from primary (P) and secondary (S) phases at the six stations in Table S1; (*C*) Locations determined using same arrivals and the station corrections in Table S1; (*D*) Relocations determined using the double-difference method (1) (Table S3).

1. Waldhauser F, Ellsworth WL (2000) A double-difference earthquake location algorithm: Method and application to the northern Hayward Fault, California. *Bull Seismol Soc Am* 90: 1353–1368.

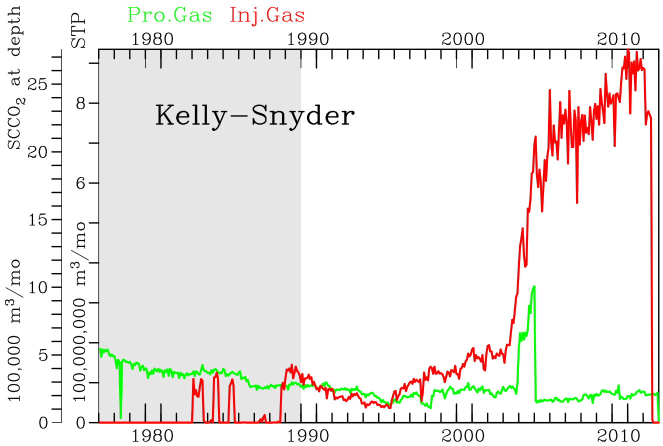


**Fig. S5.** For the Kelly–Snyder field, monthly volumes of natural gas produced (green line) and gas injected (red line) from 1977 to 2012 (red circles). Volumes on left axes are as reported by Texas Railroad Commission (RRC) for gas at surface at standard temperature and pressure (STP), and for $CO_2$ at 200 bars and 75 °C (supercritical $CO_2$, $SCCO_2$, at depth). Volumes at depth are highly approximate because the pressure–temperature effect differs for natural gas and $CO_2$, and because injected gas is often mixed with water and the physical properties of the mixture changes after injection. Gas volume data are from RRC and IHS digital database for the region labeled "Kelly–Snyder" in Fig. S2. Gas volume data before 1990 (gray area) are incomplete (see *Materials and Methods*).

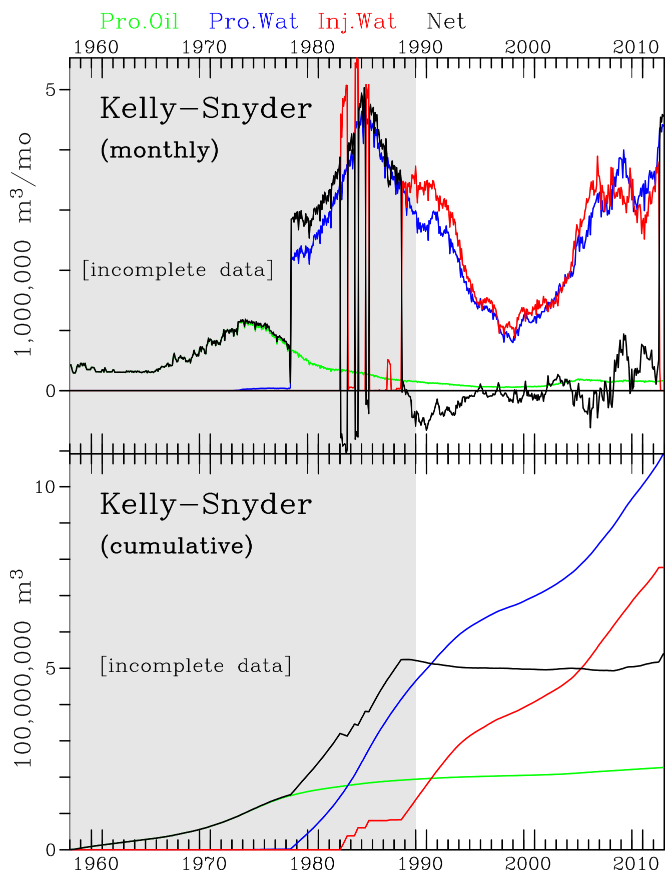


**Fig. S6.** For the Kelly–Snyder field, monthly (*Upper*) and cumulative (*Lower*) volumes of oil produced (green line), water produced (blue line), water injected (red line), and net extracted volume (black line, oil + water produced minus water injected). Volume data are from RRC and IHS digital database for the region labeled "Kelly–Snyder" in Fig. S2; data before 1990 (gray area) are incomplete (see *Materials and Methods*).

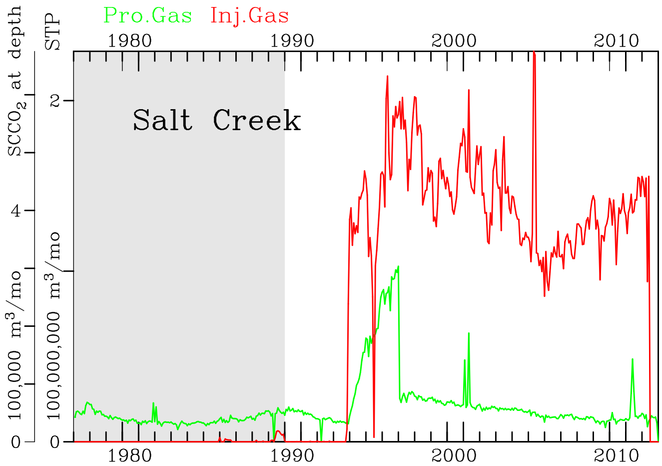


**Fig. S7.** For the Salt Creek field, monthly volumes of natural gas produced (green line) and gas injected (red line) from 1977 to 2012 (red circles). Volumes on left axes are as reported by RRC for gas at surface at STP, and for $CO_2$ at 200 bars and 75 °C ($SCCO_2$ at depth). Volumes at depth are highly approximate because the pressure–temperature effect differs for natural gas and $CO_2$, and because injected gas is often mixed with water and the physical properties of the mixture changes after injection. Gas volume data are from RRC and IHS digital database for the region labeled "Salt Creek" in Fig. S2. Gas volume data before 1990 (gray area) are incomplete (see *Materials and Methods*).

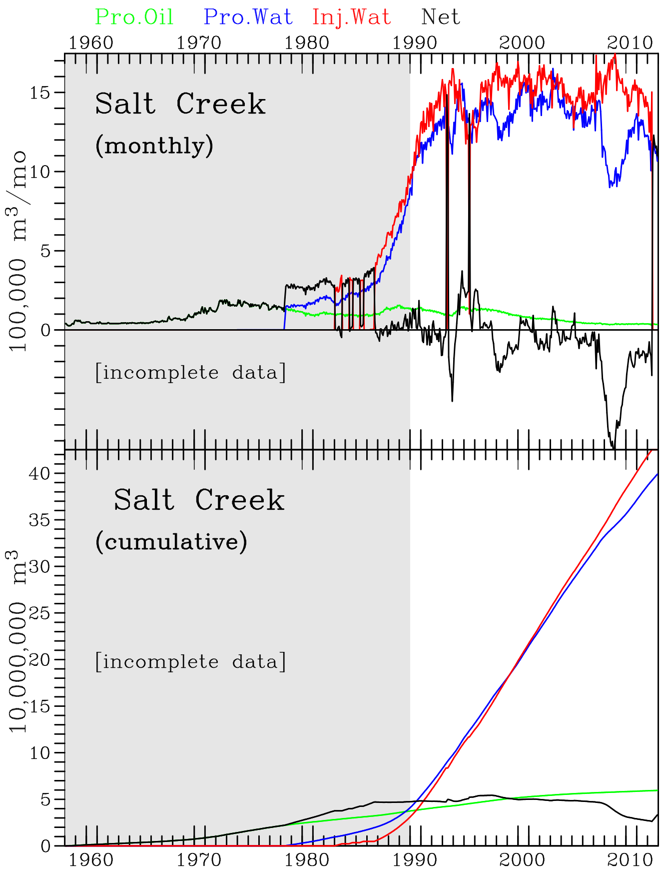


**Fig. S8.** For the Salt Creek field, monthly (*Upper*) and cumulative (*Lower*) volumes of oil produced (green line), water produced (blue line), water injected (red line), and net volume extracted (black line, oil + water produced minus water injected). Volume data are from RRC and IHS digital database for the region labeled "Salt Creek" in Fig. S2; data before 1990 (gray area) are incomplete (see *Materials and Methods*).

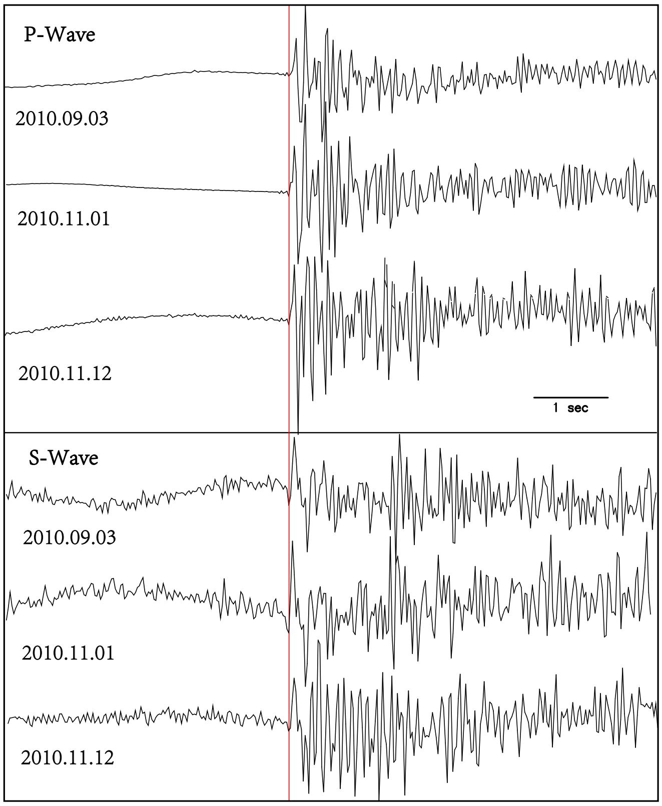


**Fig. S9.** Example P and S phases plotted to ensure we picked the same features so as to improve relative locations. Red line indicates the phase arrival picked. Labels indicate year, month, and day events occurred.

**Table S1. Seismograph stations used in this investigation**

| Station | Start time | End time | Latitude, ° | Longitude, ° | Correction, s |
|---|---|---|---|---|---|
| 129A | 01/31/09 | 12/7/10 | 32.6309 | −101.8662 | +0.125 |
| 130A | 03/12/09 | 02/9/11 | 32.5961 | −100.9652 | −0.010 |
| 131A | 03/14/09 | 02/9/11 | 32.6737 | −100.3888 | +0.210 |
| Z29A | 01/29/09 | 12/4/10 | 33.2595 | −101.7062 | −0.278 |
| Z30A | 03/10/09 | 02/6/11 | 33.2861 | −101.1282 | −0.107 |
| Z31A | 3/17/09 | 2/8/11 | 33.3183 | −100.1435 | +0.063 |

Station corrections are used to determine locations in Fig. S4C, and were determined using a joint hypocenter determination method.

**Table S2. Focal mechanisms, locations, and moment magnitude ($M_W$) for Cogdell-area earthquakes as reported by the St. Louis group (1)**

| Latitude,° | Longitude,° | Date | Strike 1,° | Dip 1,° | Rake 1,° | Strike 2,° | Dip 2,° | Rake 2,° | $M_W$ |
|---|---|---|---|---|---|---|---|---|---|
| 33 | −100.7 | 1978/6/16 | 260 | 60 | −60 | 31 | 41 | −131 | 4.51 |
| 32.99 | −100.79 | 2010/8/8 | 203 | 61 | −132 | 85 | 50 | −40 | 3.37 |
| 32.95 | −100.81 | 2011/3/13 | 70 | 60 | −50 | 191 | 48 | −138 | 3.81 |
| 32.82 | −100.9 | 2011/9/11 | 207 | 85 | −160 | 115 | 70 | −5 | 4.41 |
| 32.84 | −100.88 | 2011/9/12 | 206 | 76 | −154 | 110 | 65 | −15 | 3.51 |

Table gives strike, dip, and rake of nodal planes 1 and 2.

1. Herrmann RB, Benz H, Ammon CJ (2011) Monitoring the earthquake source process in North America. *Bull Seismol Soc Am* 101:2609–2625.

**Table S3. Epicenters determined by relocation using the double-difference method (1) with focal depths fixed arbitrarily at 5 km**

| Year | mo | d | h | mi | s | Latitude,° | Longitude,° | Mag | rms |
|---|---|---|---|---|---|---|---|---|---|
| 2009 | 5 | 26 | 14 | 31 | 6.930 | 32.93369 | −100.90347 | 2.9 | 0.072 |
| 2009 | 6 | 29 | 4 | 33 | 0.280 | 32.87752 | −100.89502 | 1.8 | 0.068 |
| 2009 | 7 | 31 | 9 | 21 | 51.280 | 32.80895 | −100.92980 | 2.3 | 0.081 |
| 2009 | 7 | 31 | 18 | 39 | 28.940 | 32.93098 | −100.90223 | 3.6 | 0.086 |
| 2009 | 8 | 12 | 14 | 48 | 39.390 | 32.91095 | −100.87277 | 2.0 | 0.090 |
| 2009 | 8 | 25 | 19 | 45 | 13.840 | 32.87746 | −100.89560 | 3.0 | 0.065 |
| 2009 | 8 | 26 | 2 | 1 | 51.130 | 32.87560 | −100.89650 | 2.4 | 0.085 |
| 2009 | 8 | 28 | 23 | 14 | 19.960 | 32.87261 | −100.89848 | 2.4 | 0.062 |
| 2009 | 9 | 1 | 10 | 36 | 55.950 | 32.93701 | −100.89541 | 2.4 | 0.075 |
| 2009 | 10 | 11 | 4 | 10 | 54.350 | 32.92989 | −100.90093 | 2.0 | 0.089 |
| 2009 | 10 | 16 | 23 | 50 | 15.240 | 32.90931 | −100.87753 | 3.5 | 0.073 |
| 2009 | 11 | 15 | 18 | 41 | 30.640 | 32.87471 | −100.89629 | 2.3 | 0.065 |
| 2009 | 11 | 26 | 15 | 20 | 38.470 | 32.91125 | −100.87443 | 2.0 | 0.086 |
| 2009 | 12 | 28 | 11 | 56 | 7.330 | 32.93594 | −100.89720 | 2.0 | 0.108 |
| 2010 | 1 | 5 | 13 | 36 | 11.380 | 32.93739 | −100.89561 | 2.1 | 0.071 |
| 2010 | 1 | 8 | 6 | 17 | 42.860 | 32.94754 | −100.88601 | 2.1 | 0.049 |
| 2010 | 1 | 8 | 21 | 27 | 8.080 | 32.94738 | −100.88595 | 2.6 | 0.086 |
| 2010 | 1 | 27 | 4 | 59 | 32.390 | 32.87156 | −100.90045 | 3.1 | 0.105 |
| 2010 | 1 | 27 | 6 | 25 | 43.950 | 32.86911 | −100.90491 | 2.9 | 0.082 |
| 2010 | 2 | 6 | 5 | 4 | 8.870 | 32.93069 | −100.90382 | 2.3 | 0.163 |
| 2010 | 2 | 10 | 2 | 51 | 41.660 | 32.88150 | −100.90250 | 2.4 | 0.074 |
| 2010 | 2 | 13 | 11 | 21 | 23.130 | 32.86150 | −100.90096 | 2.5 | 0.080 |
| 2010 | 3 | 22 | 13 | 42 | 51.490 | 32.89176 | −100.89473 | 2.1 | 0.070 |
| 2010 | 3 | 24 | 5 | 2 | 9.520 | 32.89643 | −100.92702 | 1.9 | 0.046 |
| 2010 | 3 | 24 | 20 | 50 | 4.880 | 32.89239 | −100.89441 | 2.7 | 0.067 |
| 2010 | 3 | 28 | 21 | 7 | 23.360 | 32.95127 | −100.88199 | 2.7 | 0.076 |
| 2010 | 3 | 30 | 6 | 18 | 1.820 | 32.86898 | −100.91271 | 2.2 | 0.080 |
| 2010 | 4 | 3 | 13 | 8 | 48.470 | 32.92860 | −100.90295 | 2.8 | 0.102 |
| 2010 | 4 | 9 | 21 | 15 | 59.900 | 32.93103 | −100.90353 | 2.2 | 0.094 |
| 2010 | 4 | 11 | 19 | 56 | 36.680 | 32.92944 | −100.90271 | 3.2 | 0.088 |
| 2010 | 4 | 12 | 0 | 20 | 5.340 | 32.93182 | −100.89978 | 2.8 | 0.076 |
| 2010 | 5 | 1 | 10 | 20 | 50.190 | 32.86531 | −100.93324 | 1.8 | 0.152 |
| 2010 | 5 | 1 | 10 | 46 | 39.220 | 32.86644 | −100.92968 | 2.9 | 0.097 |
| 2010 | 5 | 8 | 5 | 7 | 10.030 | 32.93771 | −100.89642 | 1.9 | 0.118 |
| 2010 | 5 | 15 | 10 | 43 | 1.820 | 32.92684 | −100.90781 | 2.3 | 0.147 |
| 2010 | 6 | 5 | 3 | 31 | 17.860 | 32.86855 | −100.89926 | 1.9 | 0.073 |
| 2010 | 6 | 5 | 4 | 6 | 51.710 | 32.94828 | −100.88364 | 2.7 | 0.097 |
| 2010 | 6 | 10 | 9 | 28 | 4.660 | 32.92624 | −100.90977 | 1.8 | 0.090 |
| 2010 | 6 | 23 | 0 | 39 | 7.550 | 32.89208 | −100.89223 | 2.5 | 0.071 |
| 2010 | 6 | 23 | 18 | 34 | 11.960 | 32.90010 | −100.92205 | 2.2 | 0.096 |
| 2010 | 6 | 25 | 17 | 45 | 58.180 | 32.94785 | −100.89964 | 3.0 | 0.068 |
| 2010 | 6 | 25 | 20 | 17 | 23.840 | 32.94730 | −100.89836 | 2.2 | 0.092 |
| 2010 | 6 | 25 | 23 | 14 | 54.080 | 32.94660 | −100.89754 | 2.4 | 0.089 |
| 2010 | 7 | 11 | 8 | 34 | 56.430 | 32.88440 | −100.90612 | 2.5 | 0.069 |
| 2010 | 7 | 17 | 2 | 44 | 35.390 | 32.90715 | −100.88365 | 1.8 | 0.061 |
| 2010 | 7 | 20 | 17 | 12 | 28.680 | 32.90445 | −100.87633 | 3.0 | 0.075 |
| 2010 | 7 | 22 | 4 | 44 | 0.060 | 32.94817 | −100.89915 | 2.9 | 0.094 |
| 2010 | 7 | 22 | 23 | 28 | 5.800 | 32.93533 | −100.89507 | 2.9 | 0.083 |
| 2010 | 7 | 25 | 0 | 41 | 23.380 | 32.94630 | −100.88605 | 2.5 | 0.080 |
| 2010 | 7 | 28 | 11 | 49 | 57.680 | 32.89631 | −100.92844 | 1.9 | 0.081 |
| 2010 | 7 | 29 | 12 | 19 | 19.910 | 32.88315 | −100.91032 | 2.8 | 0.080 |
| 2010 | 8 | 6 | 6 | 39 | 45.000 | 32.93178 | −100.89928 | 3.2 | 0.085 |
| 2010 | 8 | 8 | 1 | 12 | 38.130 | 32.87533 | −100.89779 | 3.4 | 0.078 |
| 2010 | 8 | 8 | 2 | 10 | 7.490 | 32.87357 | −100.90027 | 2.0 | 0.171 |
| 2010 | 8 | 8 | 7 | 31 | 9.000 | 32.86706 | −100.90028 | 2.8 | 0.077 |
| 2010 | 8 | 8 | 11 | 47 | 18.150 | 32.87078 | −100.90039 | 2.7 | 0.086 |
| 2010 | 8 | 10 | 19 | 56 | 23.560 | 32.93225 | −100.89944 | 2.1 | 0.127 |
| 2010 | 8 | 11 | 3 | 6 | 59.110 | 32.87365 | −100.90312 | 2.4 | 0.069 |
| 2010 | 8 | 11 | 8 | 7 | 30.160 | 32.84985 | −100.91677 | 2.7 | 0.081 |
| 2010 | 8 | 11 | 8 | 51 | 14.340 | 32.85085 | −100.91650 | 2.2 | 0.086 |
| 2010 | 8 | 13 | 15 | 3 | 15.370 | 32.94770 | −100.88596 | 2.4 | 0.100 |
| 2010 | 8 | 14 | 8 | 27 | 31.030 | 32.86646 | −100.90155 | 1.7 | 0.074 |

**Table S3. Cont.**

| Year | mo | d | h | mi | s | Latitude,° | Longitude,° | Mag | rms |
|---|---|---|---|---|---|---|---|---|---|
| 2010 | 8 | 14 | 10 | 49 | 3.690 | 32.94912 | −100.89742 | 2.1 | 0.092 |
| 2010 | 8 | 14 | 19 | 49 | 29.520 | 32.95174 | −100.89634 | 2.3 | 0.070 |
| 2010 | 8 | 15 | 12 | 55 | 43.840 | 32.95568 | −100.87695 | 1.7 | 0.073 |
| 2010 | 8 | 22 | 0 | 27 | 22.340 | 32.88015 | −100.89494 | 2.0 | 0.072 |
| 2010 | 8 | 25 | 2 | 5 | 14.220 | 32.94224 | −100.89045 | 2.8 | 0.080 |
| 2010 | 8 | 28 | 13 | 35 | 31.980 | 32.89254 | −100.89574 | 2.1 | 0.068 |
| 2010 | 8 | 29 | 5 | 34 | 20.250 | 32.97548 | −100.83881 | 1.9 | 0.068 |
| 2010 | 8 | 29 | 12 | 48 | 36.920 | 32.94930 | −100.89818 | 2.6 | 0.066 |
| 2010 | 8 | 31 | 6 | 11 | 41.170 | 32.94822 | −100.90033 | 2.1 | 0.132 |
| 2010 | 8 | 31 | 15 | 56 | 5.310 | 32.92727 | −100.91029 | 2.8 | 0.091 |
| 2010 | 9 | 1 | 10 | 58 | 24.040 | 32.89584 | −100.89478 | 1.9 | 0.066 |
| 2010 | 9 | 1 | 11 | 29 | 40.330 | 32.89452 | −100.89502 | 1.9 | 0.096 |
| 2010 | 9 | 1 | 16 | 53 | 58.730 | 32.94772 | −100.88591 | 2.6 | 0.089 |
| 2010 | 9 | 3 | 3 | 34 | 47.430 | 32.97729 | −100.83728 | 2.5 | 0.067 |
| 2010 | 9 | 30 | 3 | 44 | 24.260 | 32.95070 | −100.89815 | 2.4 | 0.066 |
| 2010 | 10 | 2 | 20 | 37 | 49.460 | 32.95337 | −100.89901 | 2.6 | 0.090 |
| 2010 | 10 | 9 | 7 | 42 | 26.650 | 32.95378 | −100.90072 | 3.1 | 0.097 |
| 2010 | 10 | 9 | 9 | 13 | 0.820 | 32.95631 | −100.89751 | 2.0 | 0.100 |
| 2010 | 10 | 9 | 15 | 51 | 56.600 | 32.95666 | −100.90025 | 2.1 | 0.113 |
| 2010 | 10 | 10 | 8 | 20 | 0.680 | 32.90051 | −100.87720 | 2.7 | 0.076 |
| 2010 | 10 | 10 | 10 | 27 | 48.970 | 32.97366 | −100.84705 | 2.1 | 0.103 |
| 2010 | 10 | 12 | 7 | 59 | 32.690 | 32.89605 | −100.92686 | 1.9 | 0.072 |
| 2010 | 10 | 17 | 2 | 9 | 16.110 | 32.92612 | −100.90992 | 2.1 | 0.138 |
| 2010 | 10 | 26 | 6 | 56 | 28.940 | 32.92793 | −100.89966 | 3.1 | 0.108 |
| 2010 | 11 | 1 | 9 | 10 | 57.400 | 32.97683 | −100.83755 | 2.8 | 0.068 |
| 2010 | 11 | 10 | 11 | 6 | 26.620 | 32.95483 | −100.89198 | 2.1 | 0.145 |
| 2010 | 11 | 12 | 22 | 17 | 54.280 | 32.97174 | −100.85622 | 2.5 | 0.103 |
| 2010 | 11 | 14 | 0 | 40 | 24.760 | 32.89586 | −100.89577 | 1.8 | 0.105 |
| 2010 | 12 | 7 | 22 | 35 | 44.480 | 32.92649 | −100.90888 | 2.5 | 0.042 |

Mag, magnitude; rms, rms residual.

1. Waldhauser F, Ellsworth WL (2000) A double-difference earthquake location algorithm: Method and application to the northern Hayward Fault, California. *Bull Seismol Soc Am* 90: 1353–1368.