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Monitoring CO_2 Emissions in Tree-Kill Areas near the Resurgent Dome at Long Valley Caldera, California

Scientific Investigation Report 2011-5038

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COVER
Dead trees and thermal ground at Basalt Canyon, Long Valley Caldera, California. (USGS photograph by Deborah Bergfeld, June 2006.)

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By Deborah Bergfeld and William C. Evans

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U.S. Geological Survey, Reston, Virginia: 2011

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Suggested citation:
Bergfeld, Deborah, and Evans, W.C., 2011, Monitoring CO_2 emissions in tree kill areas near the resurgent dome at Long Valley Caldera, California: U.S. Geological Survey Scientific Investigations Report 2011-5038, 22 p.

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Monitoring CO_2 Emissions in Tree-Kill Areas near the Resurgent Dome at Long Valley Caldera, California

By Deborah Bergfeld and William C. Evans

Abstract

We report results of yearly measurements of the diffuse CO_2 flux and shallow soil temperatures collected since 2006 across two sets of tree-kill areas at Long Valley Caldera, California. These data provide background information about CO_2 discharge during a period with moderate seismicity, but little to no deformation. The tree kills are located at long-recognized areas of weak thermal fluid upflow, but have expanded in recent years, possibly in response to geothermal fluid production at Casa Diablo. The amount of CO_2 discharged from the older kill area at Basalt Canyon is fairly constant and is around 3–5 tonnes of CO_2 per day from an area of about 15,000 m^2. The presence of isobutane in gas samples from sites in and around Basalt Canyon suggests that geothermal fluid production directly effects fluid upflow in the region close to the power plant. The average fluxes at Shady Rest are lower than average fluxes at Basalt Canyon, but the area affected by fluid upflow is larger. Total CO_2 discharged from the central portion of the kill area at Shady Rest has been variable, ranging from 6 to11 tonnes per day across 61,000 m^2. Gas collected at Shady Rest contains no detectable isobutane to link emissions chemically to geothermal fluid production, but two samples from 2009-10 have detectable H_2S and suggest an increasing geothermal character of emitted gas. The appearance of this gas at the surface may signal increased drawdown of water levels near the geothermal productions wells.

Introduction

Localized areas of elevated CO_2 flux and elevated soil temperatures on or around the resurgent dome at Long Valley Caldera, California, are identified by stressed, dying, and dead vegetation (fig.1). Our early work (Bergfeld and others, 2006) indicated that about 8.7 metric tonnes of CO_2 per day (t/d) were emitted from these kill zones, with the highest discharge occurring in areas within a few km of the Casa Diablo geothermal power plant, and that most of the kill zones developed as a response to changing conditions in the shallow hydrothermal system.

This report presents results from 2006–2010 CO_2-flux surveys of two of the largest tree-kill zones and chemical data on gas collected between 1989 and 2010 in and around several of the tree-kill zones. The flux measurements provide baseline data from a time when seismicity has waned and deformation of the resurgent dome has leveled off (http://volcanoes.usgs.gov/lvo/activity/index.php, last accessed December 15, 2010). Because of this, changes in the size of kill zones, increases in soil temperatures or steam discharge, and changes in CO_2 emissions most likely reflect the response of the shallow hydrothermal system to geothermal fluid production at the Casa Diablo power plant. Results from diffuse CO_2-flux and soil-temperature measurements collected under these conditions allow a better understanding of the shallow system and will improve our ability to detect changes in the fluxes of CO_2 and heat associated with magmatic unrest.

Field Locations

Our field studies since 2006 have focused on two main kill zones, herein referred to as Basalt Canyon and Shady Rest. The grid at Basalt Canyon and at Shady Rest are partly composed of measurement sites from the BC, BCE, and SR grids of Bergfeld and others, 2006. The outline of present-day measurement grids are irregular, and the footprints of the grids have varied with time as we encompassed more areas of thermal fluid upflow, or as new areas of kill developed.

The Basalt Canyon grid is about 1.6 km due west of the Casa Diablo power plant (fig. 1) and is sited along a localized SW-NE trending fault (Bergfeld and others, 2006). The grid consists primarily of tree-kill with a zone of live grass in the northeast section. The volcanic rocks in Basalt Canyon include Quaternary rhyolites and basalts (Bailey, 1989). During June 2010, the measurement grid covered about 23,000 m^2 and had 88 measurement sites (table 1). Gas samples occasionally are collected from thermal and nonthermal sites within the grid and from a nearby gas vent, known as Basalt Fumarole (Sorey and others, 1998), that is ~100 m west of the grid boundary.

The Shady Rest grid is about 3.4 km northwest of the Casa Diablo power plant (fig. 1) and, as of June 2010, had 129 measurement sites and covered about 100,000 m^2 (table 1).

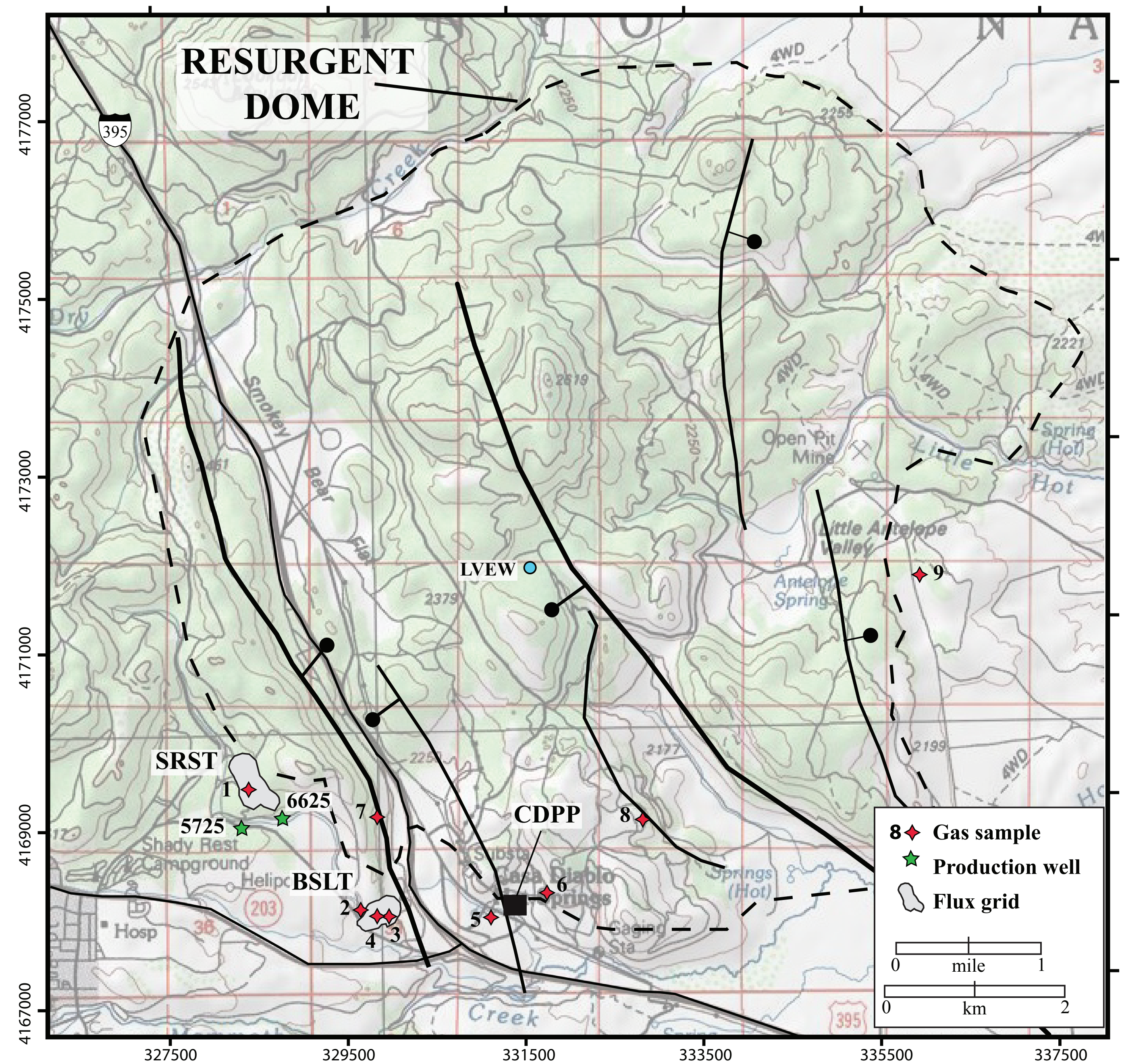

Figure 1. Map showing the resurgent dome, gas sample locations in kill zones, and the 5725 and 6625 production wells. Gray areas labeled BSLT (Basalt Canyon) and SRST (Shady Rest) show the extent of the flux grids. CDPP, Casa Diablo power plant; LVEW, Long Valley Exploration well. Locations where gas samples were collected are identified by a map number that is given in table 2.

Table 1. Summary statistics of flux data collected at Basalt Canyon and Shady Rest from 2006-2010, Long Valley Caldera, California.

[Weighted mean (*W*) and sequential Gaussian simulation (*S*) results given. Values in parentheses indicate the data did not satisfy the lognormal assumption, and are estimates calculated from weighted flux values using the arithmetically-derived mean]

Date	# of sites	Grid area m^2	Maximum flux $gm^{-2}d^{-1}$	Mean flux (*W*) $gm^{-2}d^{-1}$	Discharge (*W*) $t\ d^{-1}$	Range (*W*) $t\ d^{-1}$	Mean flux (*S*) $gm^{-2}d^{-1}$	Discharge (*S*) $t\ d^{-1}$	Range (*S*) $t\ d^{-1}$	Δ means (%)
ALL BASALT CANYON										
06/2006	64	15,200	2,589	291	4.4	4-6	334	5.1	2-9	14
09/2006	62	15,125	2,602	273	4.1	3-6	330	5.0	2-9	19
06/2007	80	21,825	2,111	162	3.5	3-5	200	4.4	1-8	21
06/2008	83	20,600	3,151	237	4.9	4-7	261	5.4	2-10	10
07/2009	85	26,375	1,693	162	4.3	3-6	243	6.4	2-13	40
06/2010	88	23,125	1,700	162	3.7	3-5	192	4.4	2-10	17
BASALT CANYON CORE SITES										
06 2006	60	14,800	2,589	283	4.2	3-6	333	4.9	2-8	16
09/2006	59	14,800	2,602	289	4.3	3-7	320	4.7	1-9	10
06/2007	60	14,800	2,111	205	3.0	2-4	255	3.8	<1-8	22
06/2008	60	14,800	3,151	258	3.8	3-6	364	5.4	2-9	34
07/2009	53	14,800	1,581	196	2.9	2-4	247	3.7	1-8	23
06/2010	61	14,800	1,327	182	2.7	2-4	190	2.8	<1-7	4
ALL SHADY REST										
09/2006	81	61,000	867	121	7.4	6-10	147	9.0	5-12	20
06/2007	90	68,175	1,290	179	12.2	10-16	216	14.7	9-22	19
05/2008	105	77,575	898	93	7.2	6-9	126	9.8	6-13	30
07/2009	106	78,950	1,465	128 (113)	10.1 (8.9)	8-13	146	11.5	8-15	13 (25)
06/2010	129	98,800	1,332	99	9.8	8-12	142	14.0	9-20	36
SHADY REST CORE SITES										
09/2006	77	61,000	820	112	6.8	5-9	135	8.2	5-12	18
06/2007	77	61,000	1,290	181	11.1	9-14	231	14.1	9-19	24
05/2008	77	61,000	898	102	6.2	5-8	121	7.4	4-11	17
07/2009	77	61,000	1,465	144	8.8	7-11	168	10.2	6-15	15
06/2010	77	61,000	492	111	6.8	5-9	121	7.4	5-10	9

The most recent area of tree kill is focused in the northeast and east portions of the grid. The center of the grid is comprised of mostly bare ground that is surrounded by live vegetation consisting of a mix of grass, brush, and widely spaced pine trees. Volcanic rocks include the same Quaternary-aged rhyolite found at Basalt Canyon (Bailey, 1989). The measurement grid includes a sub-boiling-temperature gas vent, commonly known as the Shady Rest fumarole, that is sampled routinely for gas. Two recently drilled geothermal production wells went online in summer 2006 and are about 0.5 km to the south of the grid (fig. 1).

Methods

Field Methods

The grids were established using pace and compass methods. Physical constraints imposed by dead trees, rock outcrops, steep topography, and roads are such that spacing between measurement sites is irregular. Locations are recorded using a Garmin® GPS, and each site is marked with flagging in an effort to measure the flux at the same spot during subsequent visits. Our goal is to measure flux at each site during each field visit, but sites sometimes are missed, and some sites have been abandoned. It typically requires two days to complete the flux measurements for each grid. In 2006 we made two sets of flux measurements at both grids. In subsequent years we made one set of measurements.

The CO_2-flux measurements were made using a West Systems flux meter, equipped with a LI-COR® 820 infrared CO_2 analyzer and an accumulation chamber. Detailed explanations about measurement techniques and methods for determining flux values are presented in Lewicki and others (2005) and Bergfeld and others (2006). Our protocol includes field calibration of the analyzer using CO_2-free air and a gas standard containing 1,000 ppm CO_2. At Basalt Canyon we use a 6-L accumulation chamber, which provides sufficient volume to compensate for the high fluxes without saturating the capacity of the CO_2 analyzer. At Shady Rest, the flux at most sites can be measured by using a 2.7-L chamber. Our laboratory tests using the large and small chambers show that measured fluxes underestimate the actual flux by about 7 percent and 10 percent, respectively. Soil temperatures are measured adjacent to the accumulation chamber coincident with each flux measurement. The target depth for soil-temperature measurements through 2008 was 10 cm. In 2009–10 soil temperatures were measured at 20 cm.

Gas samples are collected into evacuated glass bottles by inserting a stainless steel tube into the ground at an area of gas discharge. In some cases sample sites consist of a crack in the bedrock, and at other sites the collection tube is driven into the soil. Tygon® tubing is used to connect the stainless steel tube to the sample bottle. The collection apparatus is then purged of air, and the collection bottle is opened until gas stops flowing into the bottle.

Data Reporting

The CO_2 flux is reported as grams of CO_2 per square meter per day (g/m^2/d). Total CO_2 discharged from each grid is determined by multiplying the mean flux for all the sites by the grid area. CO_2 discharge is reported in units of metric tonnes of CO_2 emitted per day (t/d). The discharge is not corrected for biogenic CO_2 contributions, nor for the systematic under-estimation of flux revealed in laboratory testing. Many studies of diffuse CO_2 flux in volcanic and geothermal environments have shown that flux data are skewed positively with lognormal distributions (Bergfeld and others, 2001; Chiodini and others, 1998, 2001; Cardellini and others, 2003; Lewicki and others, 2005). Statistical analysis of the flux data from both Basalt Canyon and Shady Rest supports this premise (figs. 2 and 3; note that figs. 2 through 13 are at the back of this report); therefore, calculations of the mean CO_2 flux were determined by using methods that are appropriate for lognormal datasets. For this report we calculated the mean CO_2 flux by using two methods, and the difference in the results is reported as the absolute difference in the mean values divided by the average mean and expressed as a percent (table 1).

The weighted method (*W*) uses minimum variance estimator equations to determine mean flux values. To avoid any bias related to the irregular site spacing, a weighting factor is applied to each measured flux value. Weighting factors are calculated by inputting site location coordinates and measured flux values into the DECLUS module of the GSLIB geostatistical software package (Deutsch and Journel, 1998). Once calculated, the weighted flux data are log-transformed and are tested for a lognormal distribution using D'Agostino's test (Gilbert, 1987), as described in Bergfeld and others (2006). All but one of the weighted datasets satisfies the hypothesis of a lognormal distribution. The log-transformed weighted flux values are used to calculate the mean and 95-percent confidence interval about the mean by using minimum variance estimator equations given in Gilbert (1987) as presented in the appendix of Bergfeld and others (2006). The resulting means, and lower and upper limits from the confidence interval, are back-transformed, and those results are multiplied by the grid area to provide estimates of the total CO_2 discharge for the grid.

The sequential Gaussian simulation method (sGs) for estimating the means for each dataset also uses log-transformed flux values. The method produces multiple equiprobable outcomes of the spatial distribution of the flux over a 5 m^2 grid cell using the sgsim module of the GSLIB program (Deutsch and Journel, 1998), following methods outlined in Cardellini and other (2003) and Lewicki and others (2005). The sGs-technique is superior to using kriging to estimate flux at unsampled locations because it honors the measured flux values (Cardellini and others, 2003). The mean flux is determined from the summation of 1,000 simulations, and results are used to produce contour plots of the flux. Differences in results from the replicate simulations yield a 95-percent upper and lower boundary on the determined discharge and provide a measurement of uncertainty.

The summary statistics for each site visit are given in table 1 and include results for a subset of locations herein defined as "core sites," where measurements have been made on at least 80 percent of the site visits. Because the footprint of the core sites is static, the data are used for temporal comparisons of CO_2 emissions. Basalt Canyon and Shady Rest grids contain 61 and 77 core sites, respectively. At Shady Rest the full contingency of core sites was not established until September 2006. Flux data from the small grid at Shady Rest in June 2006 are not presented.

Results

Basalt Canyon Tree Kills, Soil Temperatures, and CO_2 Emissions

The kill zone at Basalt Canyon is a mixture of old and recent tree kills. The core sites are in the central portion of the grid and are characterized by long-dead, downed and standing trees that are stripped of their bark and are breaking apart. Many of these kills occurred during the mid-1990s and were associated with early power-plant operations at Casa Diablo (Bergfeld and others, 2006). New tree kills include large, mature pines and are found mostly in the northeast part of the grid. These new tree kills are recent enough that the bark is intact and brown needles and pine cones often are attached. The new kills are adjacent to what appears to be healthy forest. Shallow soil temperatures in this part of the grid are up to 50°C (fig. 4). Changes in soil temperature effect different tree species in varying ways (Pregitzer and others, 2000) and may induce stress that would contribute to increased mortality rates; however, at the time of this writing, the exact cause of tree death is not known.

Sites with the highest soil temperatures are clustered in the central section of the Basalt Canyon grid (fig. 4), and are located both along the bottom of the canyon, as well as along the western slope. The highest soil temperature measured at 10 cm was 92.9°C during the July 2007 site visit. Soil at steaming ground sites has low permeability, has been altered to clay, and commonly is encrusted with sulfur-bearing minerals. Steam tends to discharge at discrete points, such as the surface exposures of tree-root tunnels.

Plots of soil temperature versus CO_2 flux at Basalt Canyon show considerable scatter (fig. 5), and correlation coefficients (R) from linear regression of the data are ≤ 0.4 for all years. The low R-values reflect both the presence of high-temperature sites with moderate flux and sites with normal soil temperatures that have high CO_2 fluxes. There appears to be no difference in correlations between flux and temperatures whether the temperatures are measured at 10 cm or 20 cm.

During this investigation the maximum flux for each set of measurements at Basalt Canyon was between about 1,700 to 3,100 $g/m^2/d$ (table 1). Comparison of contour plots of the diffuse CO_2 flux from different years shows that although the intensity of the flux at an individual site may change from year to year, the general pattern across the grid is fairly static (fig. 6). The areas around the two gas-sampling sites often have the largest CO_2 fluxes and are separated from each other by a zone of lower flux sites. The CO_2 fluxes at the non-core sites in the east were lower than the CO_2 fluxes from core sites in the center of the grid (fig. 7).

The raw and weighted flux data for all years for the core sites and the full grid at Basalt Canyon pass D'Agostino's test as having a lognormal distribution. For most years the two methods of estimating the mean flux agree within 25 percent, with slightly higher means and larger confidence intervals estimated using the sGs method (table 1). Summary statistics for the flux data from core sites show that mean fluxes were between about 200–300 $g/m^2/d$. The upper and lower bounds on discharge estimates for all years overlap (fig. 8), and comparison of the flux maps from core sites suggests that emissions were fairly constant during the course of this investigation (fig. 6). Total CO_2 discharge from Basalt Canyon core sites is about 3–5 t/d.

Shady Rest Tree Kills, Soil Temperatures, and CO_2 Emissions

The core sites at Shady Rest are centered on an area of mostly bare ground with some scattered grass, brush, and individual trees. The full grid includes more forested areas along the boundary. Most observed kills are of recent age and are clustered in two groups on the east side of the grid (fig. 9). As compared with Basalt Canyon, the Shady Rest kill areas have fewer old decayed trees, although this may be a function of easy access and firewood scavenging.

Soil-temperature measurements at 10 cm show that, in general, Shady Rest sites are cooler than sites at Basalt Canyon (figs. 4 and 9). In winter, snow will accumulate later and melt sooner from sites around the Shady Rest fumarole, but unlike Basalt Canyon, there are no large patches of steaming ground. We have observed steam issuing only from a few point-source locations at Shady Rest. The highest soil temperature at a grid site was 75.0°C. Plots of soil temperature and CO_2 flux show the data are positively correlated with correlation coefficients around 0.7 for most years (fig. 10).

In general, Shady Rest sites with the highest fluxes are oriented along a north-south trend that incorporates the location of the Shady Rest fumarole (figs. 11 and 12). The maximum flux from each set of measurements was between about 850 and 1,500 $g/m^2/d$ (table 1) and was obtained at one of two sites in the north near one of the areas of recent tree kills. In 2009 we discovered a discrete patch of slightly thermal ground with some recent tree kills ~200 m southeast of the main grid boundary. In 2010 the area was incorporated into the Shady Rest grid. The new sites have moderately high fluxes, up to ~300 $g/m^2/d$, and are aligned along a southeast trend in line with the 6625 geothermal production well (fig. 12*E*).

Table 2. Sample locations, gas chemistry in volume percent and permil (‰) carbon isotope values of samples collected on or around the resurgent dome, Long Valley Caldera, California.

[Sites are characterized as discrete gas vents (V), steaming ground (SG), and nonthermal (NT). n-C_4H_{10} and i-C_4H_{10} are normal- and iso-butane. Basalt Canyon Extended grid site 24 (BCE 24), Basalt fumarole (BF), Casa Diablo fumarole (CDF), Casa Diablo north (CDN), Chris' hot spot (CHS), Fumarole Valley (FV); Isha fumarole (ISHA), Shady Rest fumarole (SRF), Teapot (TPT), not analyzed (na), not recorded (nr). Datum for the UTM coordinates is referenced to WGS84 zone 1]

Location	Date	Temp. (C)	Map #	Type	Easting (m)	Northing (m)	CO_2	He	H_2	Ar
							-----------volume percent-----------			
Basalt Canyon Area										
CHS	12/06/95	91.0	3	SG	329974	4168152	98.6	0.001	0.024	0.020
CHS	09/29/99	nr	3	SG	329974	4168152	98.1	0.001	0.039	0.023
Near CHS	06/08/10	91.5	3 *	SG	329977	4168147	98.8	0.002	0.022	0.012
BCE 24	07/26/04	32.5	4	NT	329872	4168129	84.2	0.001	0.001	0.143
BF	07/31/90	nr	2	V	329698	4168166	96.8	0.006	0.003	0.039
BF	11/01/95	92	2	V	329698	4168166	97.4	0.005	0.021	0.032
BF	08/03/96	nr	2	V	329698	4168166	97.4	0.004	0.010	0.031
BF	06/16/97	nr	2	V	329698	4168166	97.5	0.003	0.013	0.035
BF	01/01/98	nr	2	V	329698	4168166	96.9	0.003	0.009	0.032
BF	07/26/04	91.0	2	V	329698	4168166	97.4	0.004	0.026	0.029
BF	07/14/06	92.0	2	V	329698	4168166	97.6	0.005	0.006	0.027
Shady Rest										
SRF	09/25/96	90	1	V	328427	4169615	81.4	0.004	0.029	0.159
SRF	06/19/97	nr	1	V	328427	4169615	69.1	0.003	0.011	0.276
SRF	06/06/02	89.6	1	V	328427	4169615	85.1	0.004	0.009	0.130
SRF	07/14/06	91.0	1	V	328427	4169615	85.9	0.005	0.002	0.132
SRF	06/22/09	79.2	1	V	328427	4169615	70.9	0.004	0.035	0.271
SRF	09/08/10	87.9	1	V	328427	4169615	63.5	0.002	0.037	0.343
Other Kill Areas										
CDN	02/12/03	92.7	5	SG	331005	4167986	92.9	0.001	0.055	0.069
CDF	09/18/02	nr	6	V	331758	4168378	96.7	0.002	0.245	0.050
CDF	07/14/06	94.1	6	V	331758	4168378	97.6	0.001	0.065	0.031
TPT	03/25/04	86.0	7	SG	329860	4169286	73.5	0.004	0.057	0.239
FV	06/09/99	nr	8	V	332894	4169428	69.3	0.001	0.027	0.306
FV	Sept. 1999	nr	8	V	332894	4169428	98.4	0.002	0.014	0.018
FV	10/13/06	nr	8	V	332894	4169428	98.1	0.003	0.021	0.025
ISHA	10/24/89	nr	9	SG	336024	4171860	53.6	0.003	0.008	0.489
ISHA	11/13/03	32.8	9	SG	336024	4171860	36.4	0.004	0.001	0.612

*Near site 3 on figure 1.

O_2	N_2	CH_4	C_2H_6	H_2S	C_3H_8	n-C_4H_{10}	i-C_4H_{10}	$\delta^{13}C$-CO_2	N_2/Ar	N_2/O_2
volume percent								(‰)		
Basalt Canyon Area										
0.05	1.0	0.060	0.001	0.193	<0.0005	<0.0005	0.003	na	52	19
0.10	1.5	0.056	<0.0002	0.204	<0.0005	0.003	0.003	–4.0	65	15
0.03	0.8	0.037	<0.0002	0.364	<0.0005	<0.0005	na	–4.1	65	28
2.7	13.0	0.001	<0.0002	<0.0005	<0.0005	<0.0005	<0.0005	–3.4	91	5
0.04	2.9	0.124	<0.0002	0.090	na	na	na	–3.8	76	78
0.06	2.1	0.116	0.001	0.169	<0.0005	<0.0005	0.006	–4.0	67	34
0.11	2.2	0.112	0.001	0.203	<0.0005	<0.0005	0.007	–3.9	69	20
0.02	2.1	0.108	0.001	0.207	<0.0005	<0.0005	0.008	na	60	127
0.15	2.6	0.106	0.000	0.204	<0.0005	<0.0005	0.008	na	80	17
0.06	2.1	0.102	0.000	0.227	<0.0005	<0.0005	0.015	–4.1	75	37
0.02	2.0	0.101	0.001	0.226	<0.0005	<0.0005	0.015	–3.9	74	81
Shady Rest										
3.0	15.0	0.027	<0.0002	<0.0005	<0.0005	<0.0005	<0.0005	–3.9	97	5
5.7	25.0	0.023	<0.0002	<0.0005	<0.0005	<0.0005	<0.0005	na	90	4
2.7	12.0	0.059	<0.0002	<0.0005	<0.0005	<0.0005	<0.0005	–3.7	92	4
2.4	12.0	0.062	0.000	<0.0005	<0.0005	<0.0005	<0.0005	–4.4	87	5
5.7	23.0	0.049	0.002	0.019	<0.0005	<0.0005	<0.0005	na	85	4
7.2	29.0	0.044	<0.0002	0.030	<0.0005	<0.0005	<0.0005	–3.7	84	4
Other Kill Areas										
1.3	5.6	0.031	0.001	0.083	<0.0005	<0.0005	0.009	–4.6	80	4
0.07	2.5	0.041	<0.0002	0.332	0.001	0.001	0.058	–6.9	51	37
0.04	1.7	0.026	<0.0002	0.427	<0.0005	<0.0005	0.035	–5.7	56	45
5.1	21.0	0.046	<0.0002	<0.0005	<0.0005	<0.0005	0.007	–4.4	88	4
5.6	25.0	0.048	0.000	<0.0005	<0.0005	<0.0005	0.020	na	81	4
0.05	1.4	0.063	0.001	0.050	<0.0005	0.001	0.030	–5.4	79	31
0.07	1.5	0.062	<0.0002	0.231	0.001	0.001	0.079	na	58	20
8.5	37.0	0.030	<0.0002	<0.0005	<0.0005	<0.0005	<0.0005	na	77	4
12.0	51.0	0.037	<0.0002	<0.0005	<0.0005	<0.0005	<0.0005	–5.1	83	4

All but one of the flux datasets from Shady Rest pass D'Agostino's test as having a lognormal distribution. The test was negative for the full grid from 2009, and we calculated the simple arithmetic mean of the weighted flux values (shown in the parentheses in table 1), as well as the mean, by using the minimum variance estimator. For all datasets the mean flux determinations from the sGs method are higher, and the confidence intervals are larger, than those derived from the weighted-flux values (table 1). Differences in the means derived from the two methods are ≤36 percent and generally are better than 25 percent.

Estimates of the total CO_2 emissions from Shady Rest core sites in 2006, 2008, 2009, and 2010 are similar, and the ranges in the discharge estimates for these 4 sets of measurements overlap (fig. 13). The results indicate about 6–9 tonnes of a CO_2 per day (7–10 from sGs) discharged from the central portion of the grid (table 1). The discharge estimate (11–14 t/d) and the contour plot from the 2007 measurements stand out as having higher emissions than in other years (figs. 11 and 13).

Gas Chemistry from Sites on or Around the Resurgent Dome

Table 2 gives analyses of gas samples collected from discrete gas vents (V), steaming ground (SG) sites, and a nonthermal (NT) high flux (500–900 $g/m^2/d$) site in the Basalt Canyon grid. The gas compositions are dominated by CO_2, but gas from many sites contains significant amounts of atmospheric components (Ar, N_2 and O_2). H_2S is a component in the gas from thermal sites around Basalt Canyon, as well as other sites near the Casa Diablo power plant, but until recently was not detected at the Shady Rest fumarole. CH_4 is detectable in all gas samples, irrespective of location. The carbon isotope composition of CO_2 collected at nine locations is between –6.9 and –3.4 permil. The $\delta^{13}C$ values of CO_2 from sites around Basalt Canyon and Shady Rest are indistinguishable and range from –4.4 to –3.4 permil. These values are similar, but slightly higher than the $\delta^{13}C$ composition of CO_2 from Mammoth Mountain fumarole (–5.5 to –4.5 permil, Sorey and others, 1998). Isobutane ($i\text{-}C_4H_{10}$), the working fluid used at the Casa Diablo power plant, is detected at numerous thermal sites, but has not been found in gas from the Shady Rest fumarole.

Summary

Comparison of the Two Areas

In a visual sense, the kill areas at Basalt Canyon and Shady Rest are distinct. The prominent tree and brush kills in the center of Basalt Canyon have been the focus points for steam and gas upflow for decades, and many of the old logs and stumps are coated with a layer of sulfur. The kill area at Shady Rest contains more subtle features and stands out from its surroundings as unusual in that there is a large area of mostly bare ground. Both Basalt Canyon and Shady Rest are, however, similar in that development of new areas of tree kill is an ongoing phenomena.

The Basalt Canyon and Shady Rest study areas are located over thermal fluid upflow zones. Overall, the CO_2 fluxes are higher at Basalt Canyon than at Shady Rest, but the extent of discharge zone at Basalt Canyon is confined to a smaller area. At Shady Rest the CO_2 flux and soil temperatures are moderately-to-well correlated, indicating that CO_2 and steam are transported together. The correlation between flux and soil temperature at Basalt Canyon is poor. Sites with a low flux and high soil temperatures occur in areas of strong fluid upflow where alteration products, such as clays and mineral sublimates, occlude void spaces, decreasing permeability. The presence of low-temperature, high-flux sites at Basalt Canyon may reflect steam condensation in the subsurface.

During the course of this investigation, total CO_2 emissions from the Basalt Canyon core sites were constant. We estimate that about 3–5 tonnes of CO_2 per day discharge from the central core part of the grid. CO_2 emissions from the Shady Rest core sites were more variable and ranged from 6 to 14 t/d. The variability could be related to changes in the shallow hydrothermal system resulting from geothermal fluid production at the new wells. At present, we do not have the temporal data needed to fully assess this hypothesis, but the alignment of high CO_2 flux sites in the direction of the 6625 well (fig. 12) lends support to this idea.

The composition of gases collected from sites at Shady Rest and Basalt Canyon distinguishes gas across the two areas. While the carbon isotope composition of CO_2 indicates a common source of CO_2, other components, such as isobutane, and until recently H_2S, are distinct to thermal features around Basalt Canyon. All samples collected from the Shady Rest fumarole have entrained air, which tends to oxidize H_2S and may be part of the reason that it rarely is detected. The presence of H_2S in 2009-10 samples could, however, indicate a change in fluid chemistry related to production from the new wells. Isobutane, which is unaffected by the presence of air, has never been detected at Shady Rest.

Isobutane enters the thermal aquifer at Long Valley when occasional leaks in heat exchangers at the Casa Diablo power plant cause it to be injected along with spent geothermal fluids into deep parts of the geothermal reservoir (Evans and others, 2004). It has been detected in gas samples collected at Basalt Canyon since 1995 (table 2) and may have reached the area before that time. The purpose of injection is to provide pressure support in the geothermal reservoir and the presence of isobutane in gas samples at Basalt Canyon shows that volatiles from the injectate have reached the underlying area. The pressure support provided by the injectate would stabilize the depth of boiling in the reservoir and, consequently, would control the upflow of steam and CO_2, producing more constant CO_2 emissions.

The absence of isobutane at Shady Rest may be a function of distance from the injection wells and may indicate the shallow reservoir in the area lacks pressure support.

Without sufficient pressure support, the shallow hydrothermal system would respond to the 2006 onset of fluid production at the 5725 and 6625 wells. Variations in CO_2 emissions since that time may reflect adjustments in the shallow reservoir to the fluid production.

Further Work

Results of CO_2 flux mapping since 2006 provide a well-constrained estimate of diffuse CO_2 emissions at Basalt Canyon. As a tool for volcano monitoring, the baseline information needed is now available for comparison if, in the future, seismicity or deformation rates change. Barring such changes, continued study of CO_2 flux at Basalt Canyon provides only information on geothermal fluid upflow. Our understanding of baseline CO_2 emissions at Shady Rest also is well constrained, but drilling of a new production well west of Shady Rest commenced in late 2010. Additional study of the CO_2 fluxes, and a more in-depth study of soil temperatures, is warranted as the new well goes into production. Collection of gas samples at both sites should continue as part of future monitoring efforts at both sites.

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Figures 2–13

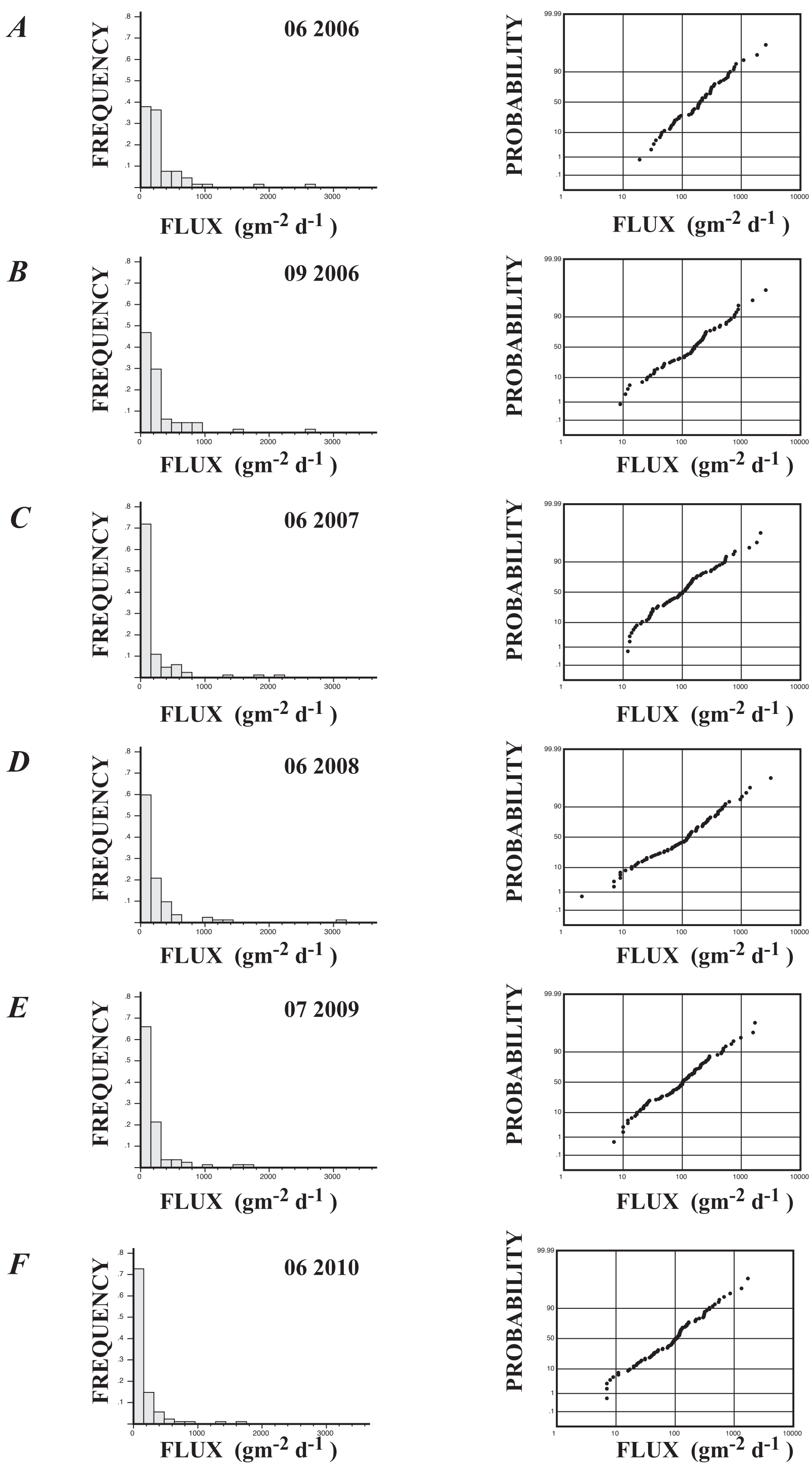


Figure 2. Histograms and cumulative probability plots showing flux values from the Basalt Canyon grid from the June 2006–June 2010 site visits. Flux data are positively skewed. Kinks in the probability plots indicate multiple populations of data, and linear trends within a population suggest a lognormal distribution.

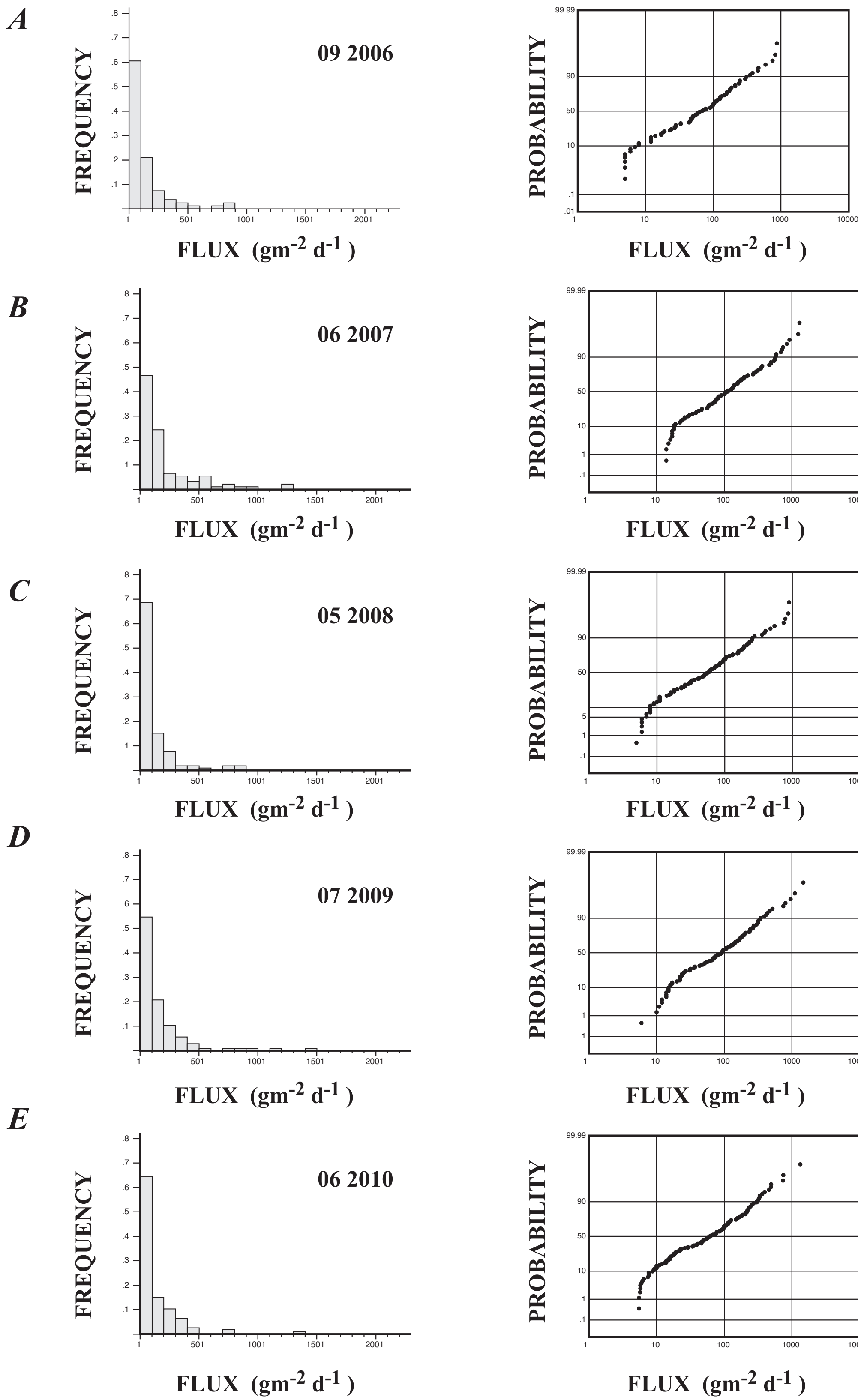


Figure 3. Histograms and cumulative probability plots showing flux values from the Shady Rest grid from the September 2006–June 2010 site visits. Flux data are positively skewed. Kinks in the probability plots indicate multiple populations of data, and linear trends within a population suggest a lognormal distribution.

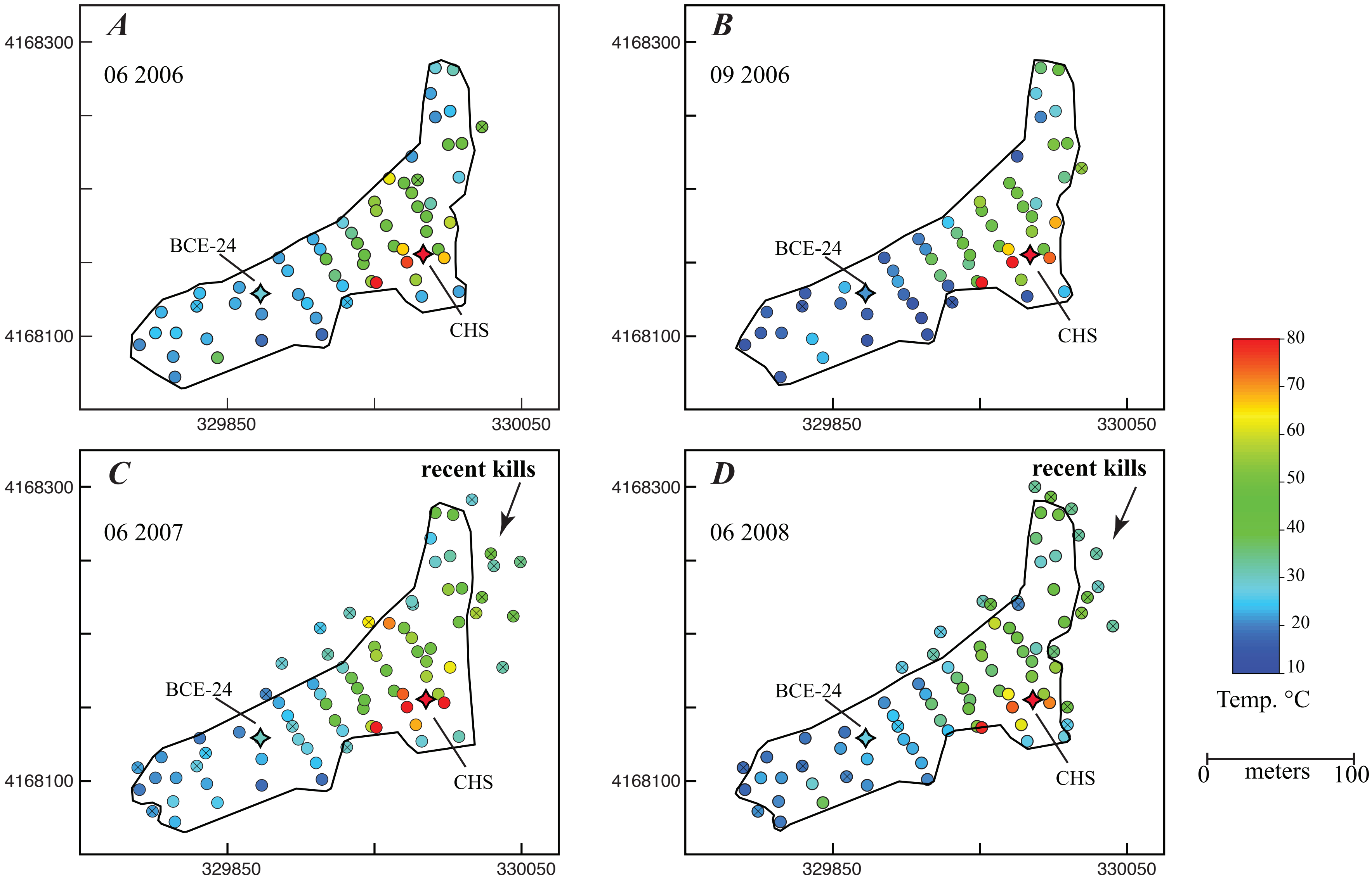


Figure 4. Map showing color-coded soil temperatures at 10 cm for the Basalt Canyon grid from the June 2006–June 2008 site visits. Star symbols are color-coded according to soil temperature and show the CHS and BCE-24 gas-sample locations. The heavy black line delineates the extent of the core sites. Circles marked with an "x" indicate that the location is not a designated core site. The black arrow in *C* and *D* shows the general location of the most recent tree kills.

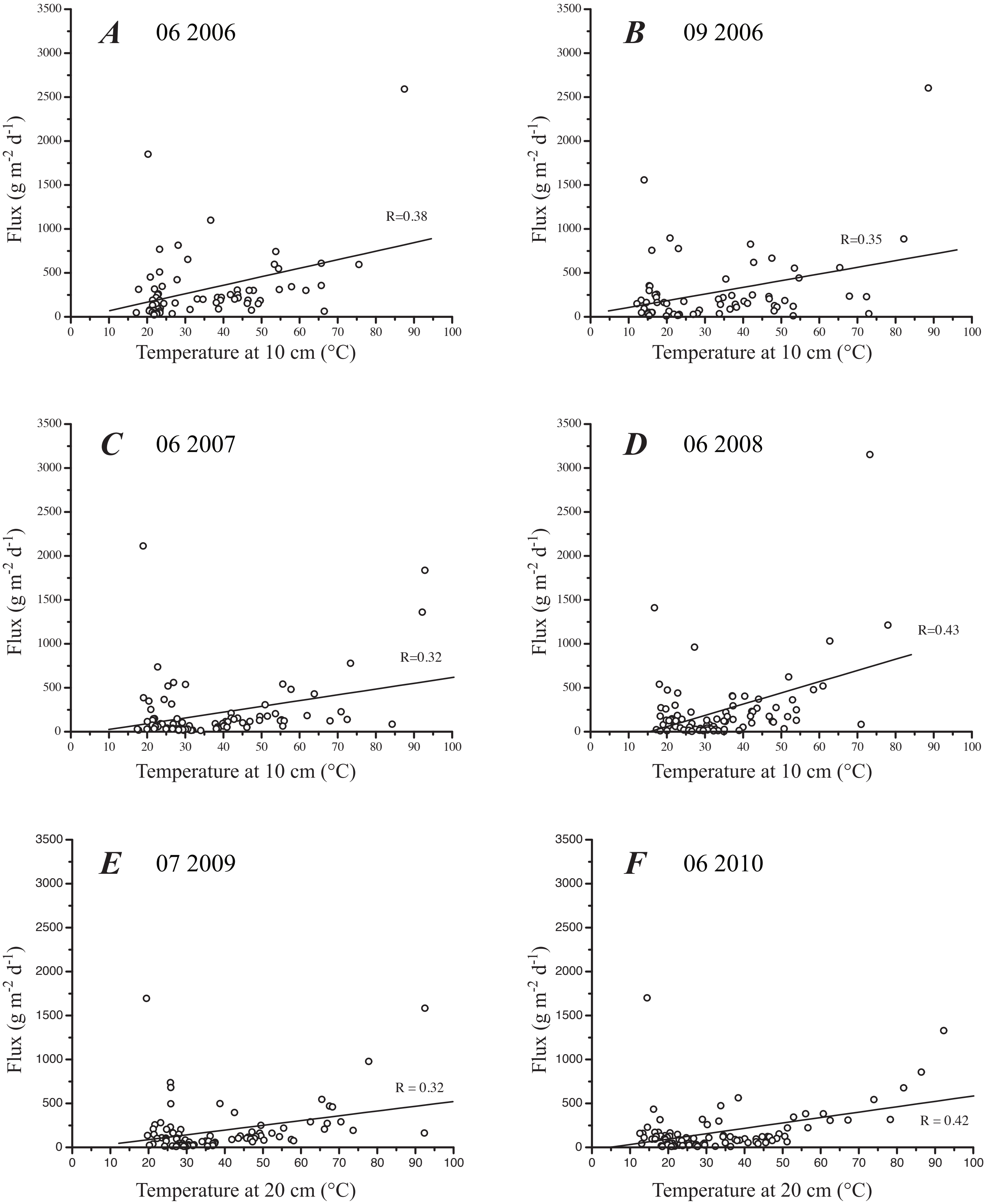


Figure 5. Scatter plots showing CO_2 flux versus soil temperature for the Basalt Canyon grid from June 2006–June 2008 at 10 cm and for July 2009–June 2010 at 20 cm. The R-values are the correlation coefficients calculated for linear regressions of the datasets.

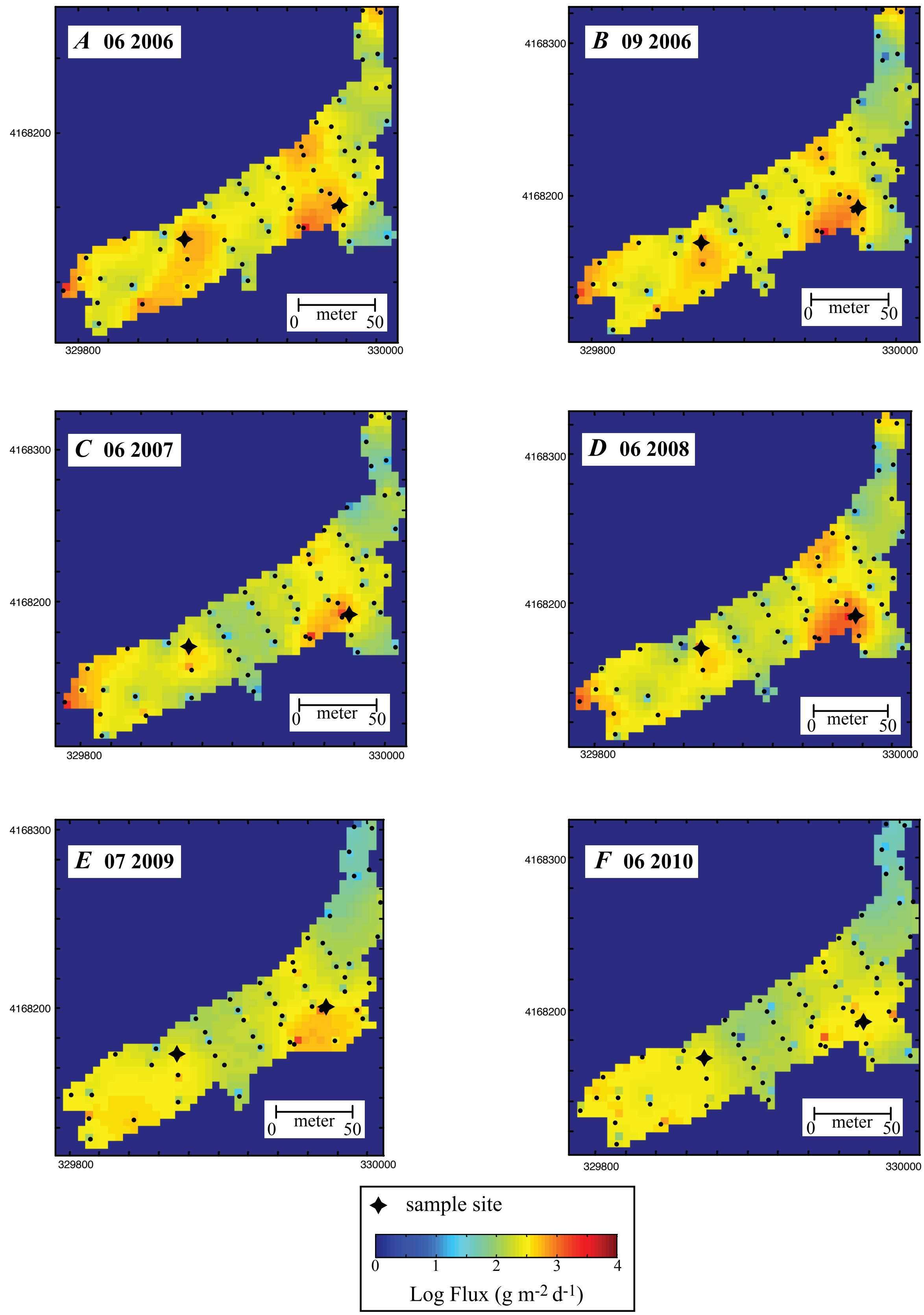
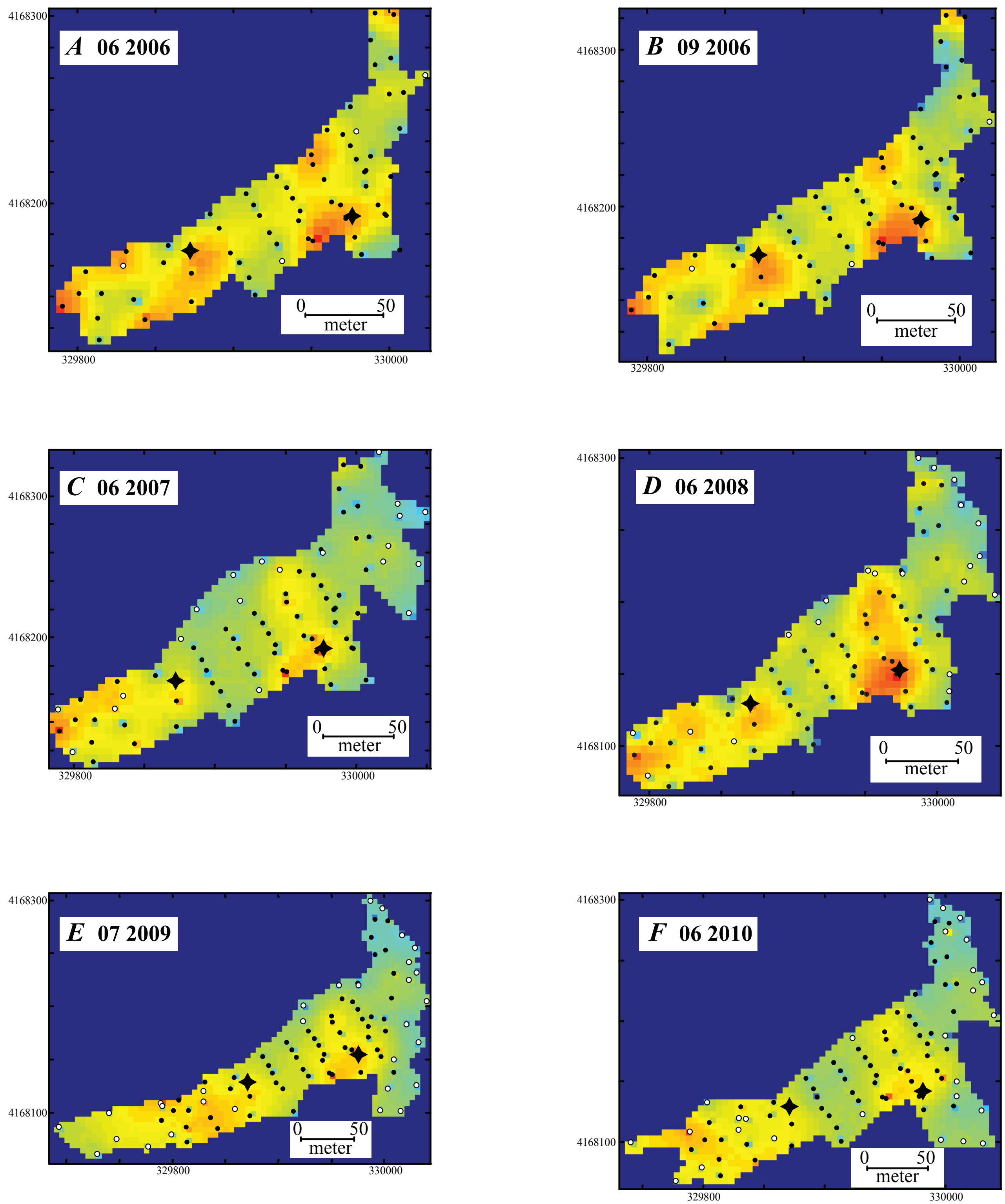


Figure 6. Contour plots from sGs calculations showing the diffuse CO_2 flux at core sites in the Basalt Canyon grid from the June 2006–June 2010 site visits. The black stars show the CHS (east) and BCE-24 (west) gas-sample locations.



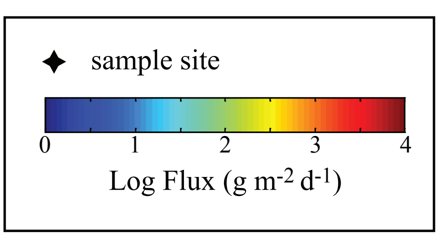


Figure 7. Contour plots from sGs calculations showing the diffuse CO_2 flux for all sites at the Basalt Canyon grid from the June 2006–June 2010 site visits. The white circles indicate a location is not a designated core site. The black stars show the CHS (east) and BCE-24 (west) gas-sample locations.

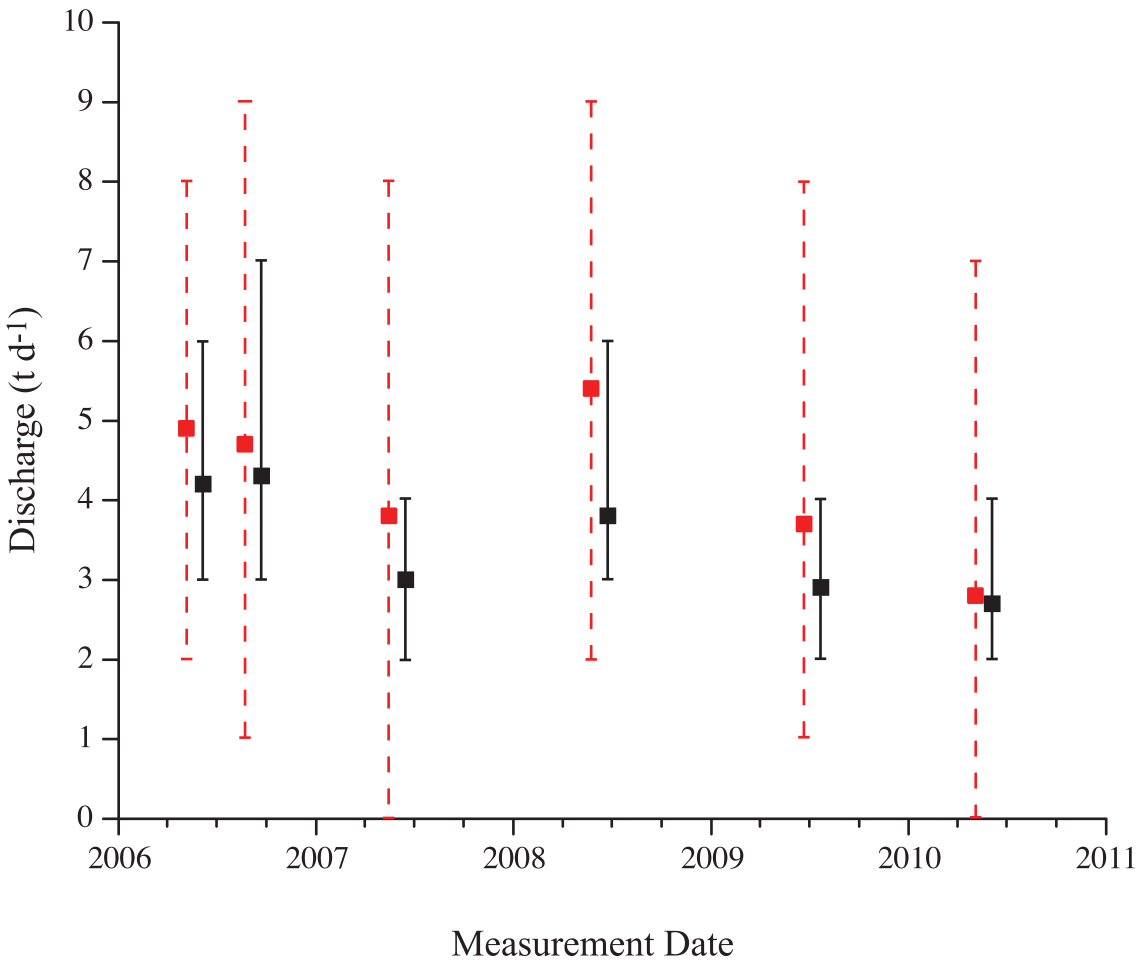


Figure 8. Plot showing the average CO_2 discharge from core sites at Basalt Canyon for 6 sets of measurements between June 2006 and June 2010. Error bars represent the range in emissions estimated for a 95-percent confidence interval. Black squares show average emissions calculated from minimum variance estimator equations. Red squares show average emissions based on sGs determinations and are offset slightly for clarity.

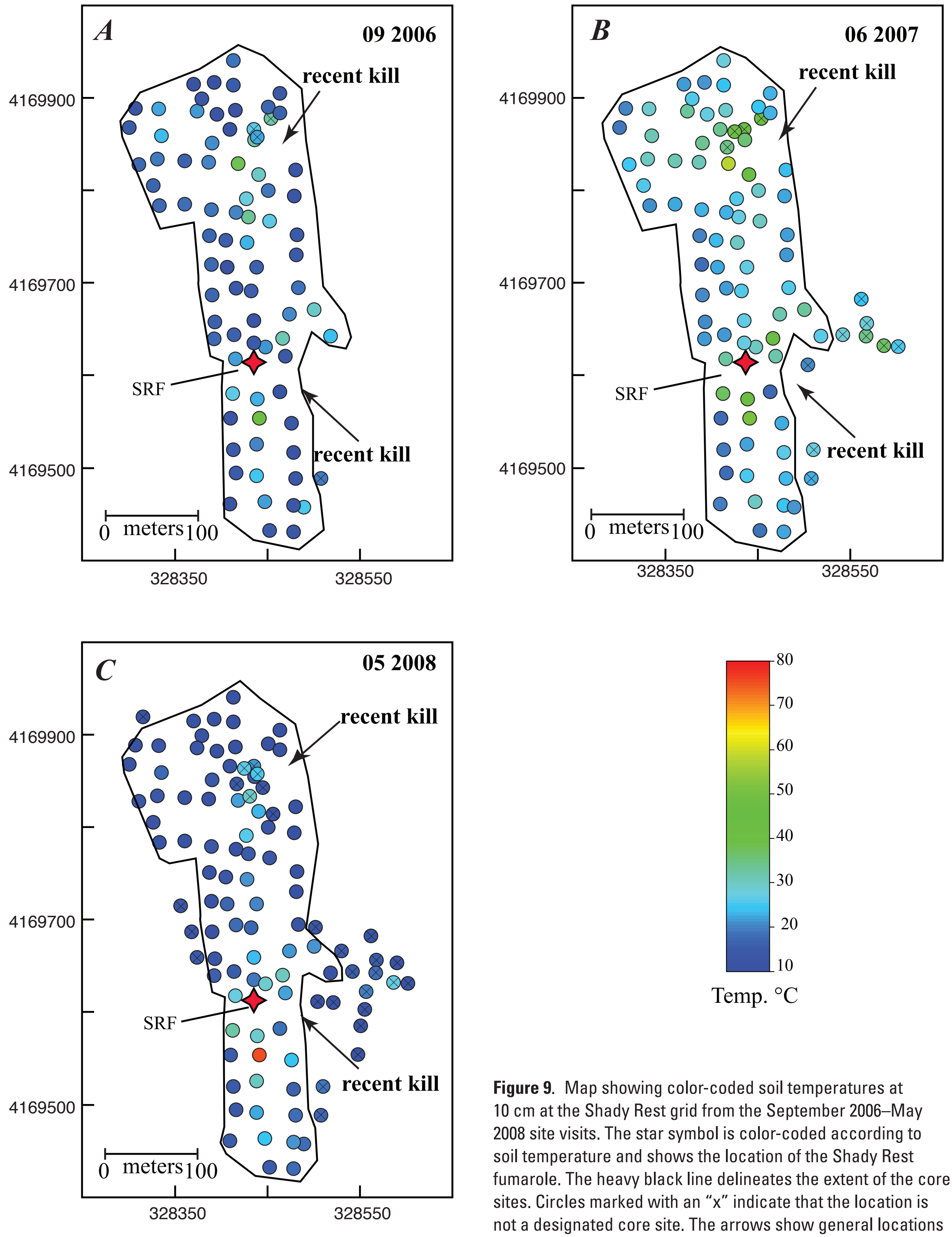


Figure 9. Map showing color-coded soil temperatures at 10 cm at the Shady Rest grid from the September 2006–May 2008 site visits. The star symbol is color-coded according to soil temperature and shows the location of the Shady Rest fumarole. The heavy black line delineates the extent of the core sites. Circles marked with an "x" indicate that the location is not a designated core site. The arrows show general locations of recent tree kills.

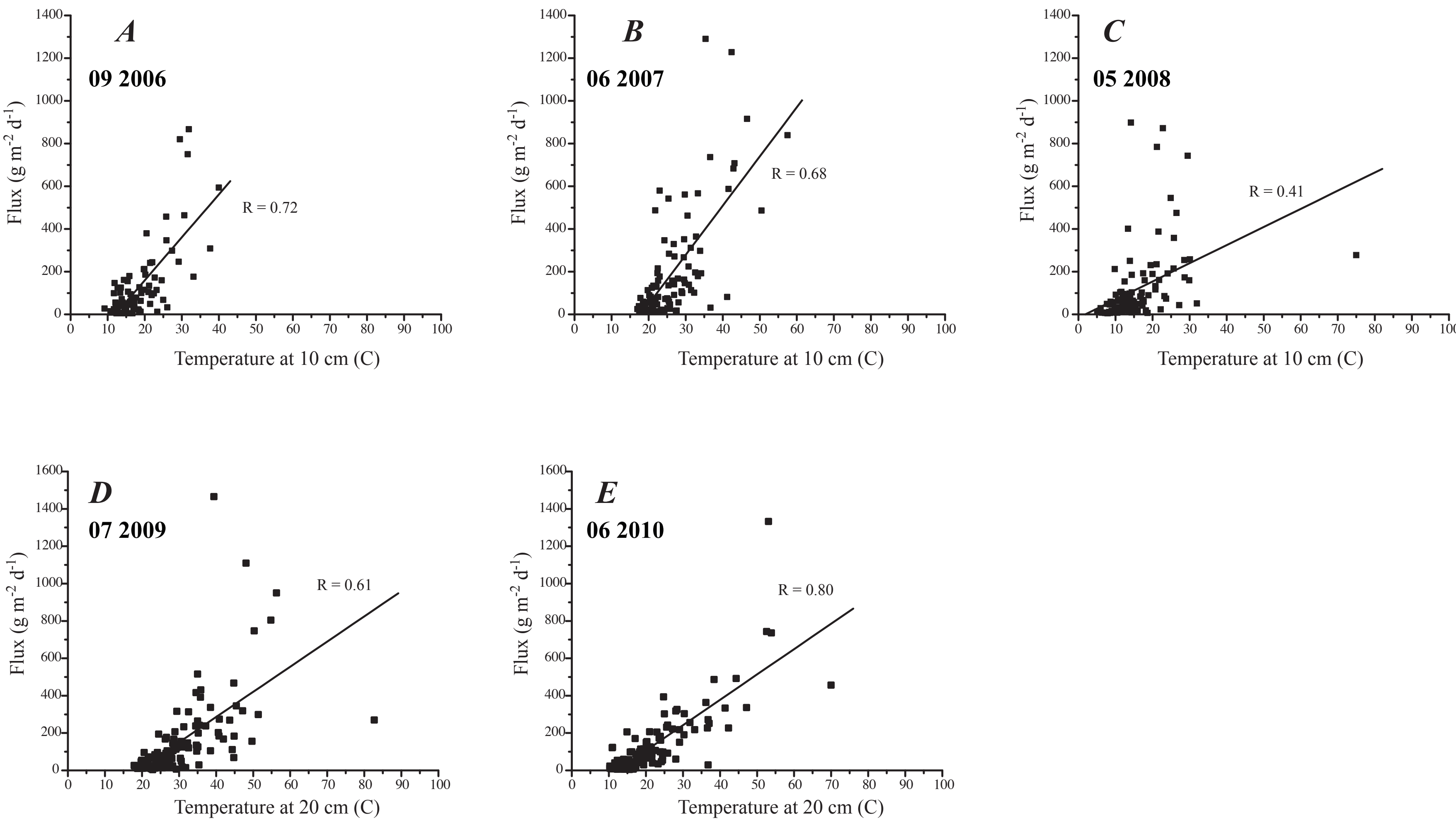


Figure 10. Scatter plots showing CO_2 flux versus soil temperature for the Shady Rest grid from September 2006–May 2008 at 10 cm and for July 2009–June 2010 at 20 cm. Note the larger scale for flux values (y-axis) from the 2009–10 data. The R-values are the correlation coefficients calculated for linear regressions of the datasets.

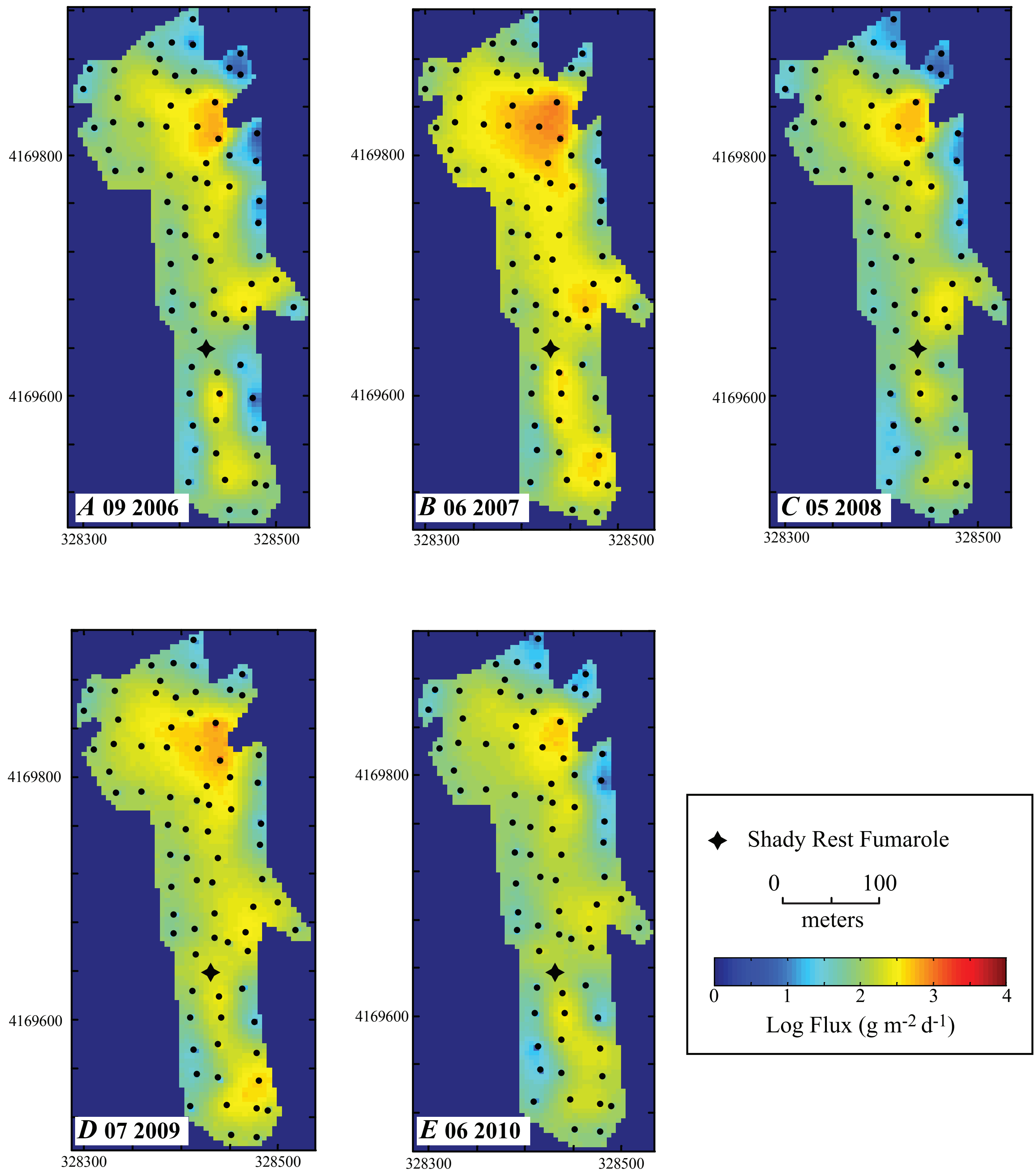


Figure 11. Contour plots from sGs calculations showing the diffuse CO_2 flux at core sites in the Shady Rest grid from the September 2006–June 2010. The black star shows the location for Shady Rest fumarole.

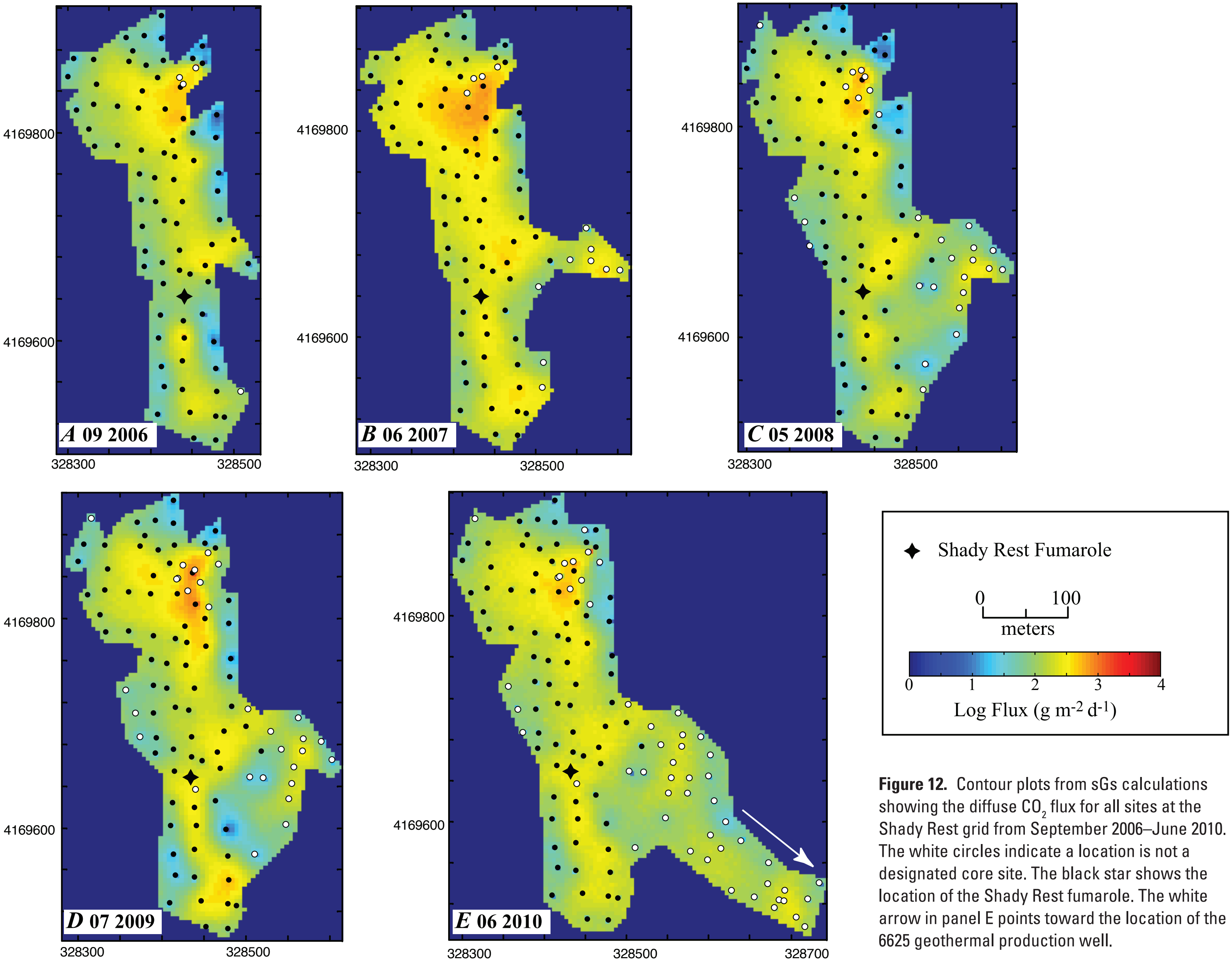


Figure 12. Contour plots from sGs calculations showing the diffuse CO_2 flux for all sites at the Shady Rest grid from September 2006–June 2010. The white circles indicate a location is not a designated core site. The black star shows the location of the Shady Rest fumarole. The white arrow in panel E points toward the location of the 6625 geothermal production well.

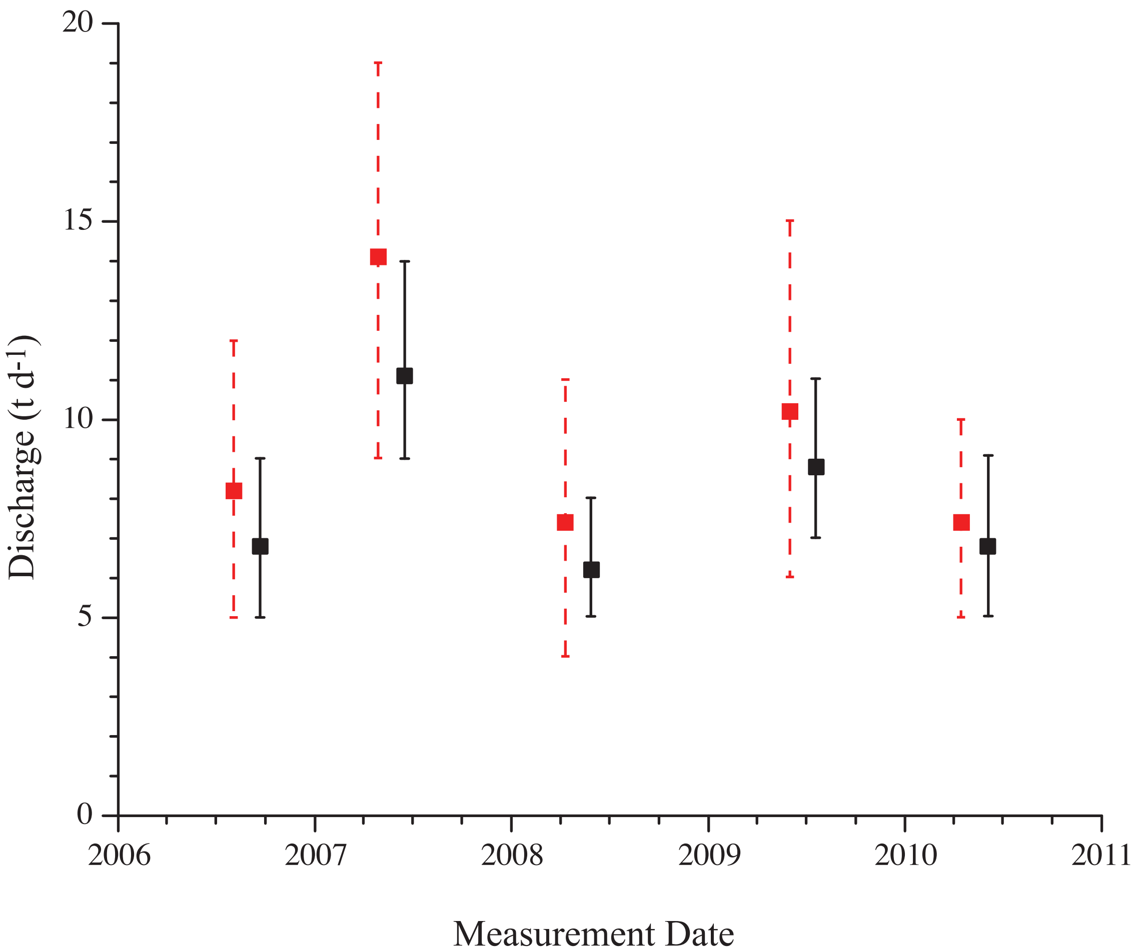


Figure 13. Plot showing the average CO_2 discharge from core sites at Shady Rest for five sets of measurements made between September 2006 and June 2010. Error bars represent the range in emissions estimated for a 95-percent confidence interval. Black squares show average emissions calculated from minimum variance estimator equations. Red squares show average emissions based on sGs determinations and are offset slightly for clarity.

Produced in the Western Region, Menlo Park, California
Manuscript approved for publication March 8, 2011
Text edited by Tracey Suzuki
Layout and design by Judy Weathers

Deborah Bergfeld and others—**Monitoring CO_2 Emissions near the Resurgent Dome at Long Valley Caldera, California**—Scientific Investigations Report 2011–5038