Geothermal Gases—Community Experiences, Perceptions, and Exposures in Northern California

Cindy H. Chiu, MPH, PhD
Epidemic Intelligence Service, Centers for Disease Control and Prevention
Health Studies Branch, National Center for Environmental Health

Matthew J. Lozier, MPH, PhD
Epidemic Intelligence Service, Centers for Disease Control and Prevention
Air Pollution and Respiratory Health Branch, National Center for Environmental Health

Tesfaye Bayleyegn, MD
Health Studies Branch, National Center for Environmental Health

Karen Tait, MD
Lake County Public Health Division

Tracy Barreau, REHS
Lori Copan, MPH, RPh
Rachel Roisman, MPH, MD
Rebecca Jackson, MPH
Svetlana Smorodinsky, MPH
Richard A. Kreutzer, MD
Division of Environmental and Occupational Disease Control
California Department of Public Health

Fuyuen Yip, MPH, PhD
Air Pollution and Respiratory Health Branch, National Center for Environmental Health

Amy Wolkin, MSPH, DrPH
Health Studies Branch, National Center for Environmental Health

Abstract **Lake County, California, is in a high geothermal-activity area. Over the past 30 years, the city of Clearlake has reported health effects and building evacuations related to geothermal venting. Previous investigations in Clearlake revealed hydrogen sulfide at levels known to cause health effects and methane at levels that can cause explosion risks. The authors conducted an investigation in multiple cities and towns in Lake County to understand better the risk of geothermal venting to the community. They conducted household surveys and outdoor air sampling of hydrogen sulfide and methane and found community members were aware of geothermal venting and some expressed concerns. The authors did not, however, find hydrogen sulfide above the California Environmental Protection Agency air quality standard of 30 parts per billion over one hour or methane above explosive thresholds. The authors recommend improving risk communication, continuing to monitor geothermal gas effects on the community, and using community reports and complaints to monitor and document geothermal venting incidents.**

Introduction

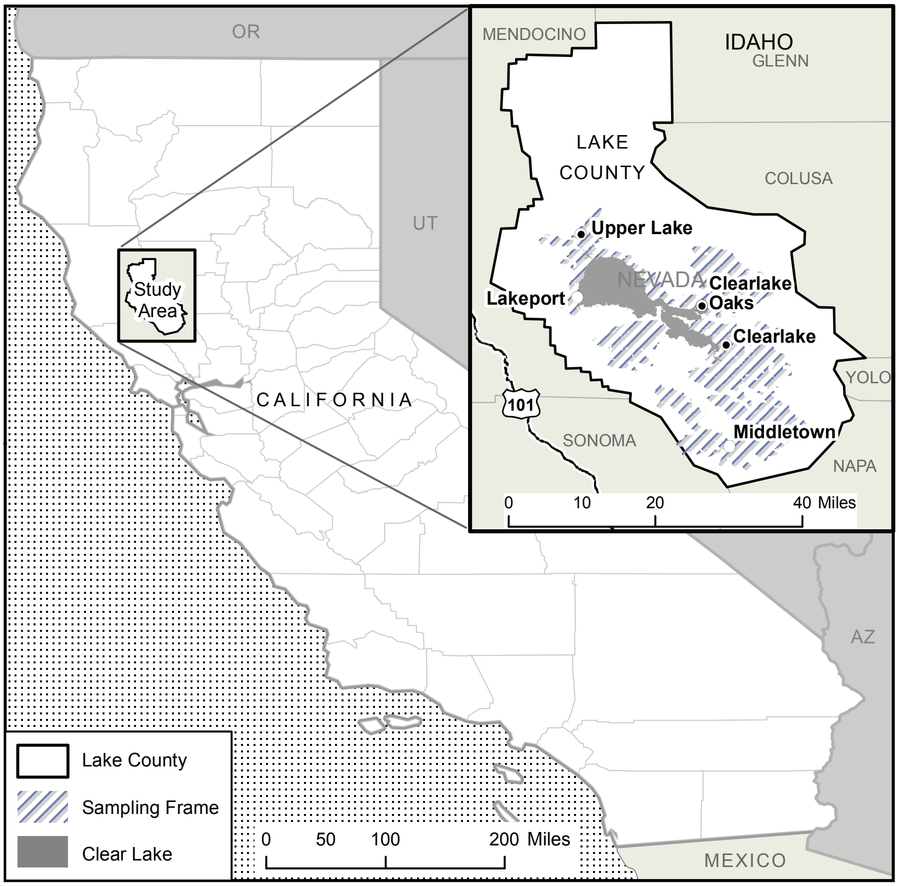
Lake County, California, is in north central California, north of San Francisco Bay. Lake County sits on tectonic plate conjunctions, generally described as areas where separate slabs of the earth's crust meet. Consequently, Lake County's population—currently at some 64,323 persons—has long been subjected to volcanic activity resulting from plate tectonics, or the movement of these giant slabs (U.S. Census Bureau, 2012; U.S. Geological Survey [USGS], 2004). Plate tectonics make Lake County vulnerable to a variety of environmental hazards, including earthquakes, volcanic eruptions, and geothermal venting. When a complex mixture of geothermal gases vents into the atmosphere from holes in the ground or diffuses through the soil, geothermal venting occurs. Gases such as hydrogen sulfide and methane release into the environment, which at high exposure levels can cause adverse health effects (both) and risk of explosion (methane) (Agency for Toxic Substances and Disease Registry [ATSDR], 2006; Etiope et al., 2006; International Programme on Chemical Safety, 2000a, 2000b; USGS, 2010). Hydrogen sulfide and methane can be summarized as follows:

- Hydrogen sulfide is a toxic gas with a characteristic rotten egg odor detected at 0.0005–0.3 parts per million (ppm), with olfactory fatigue at >100 ppm where continued exposure can temporarily disable the sense of smell (ATSDR, 2006). At 10–20 ppm, exposure can cause irritation to the eyes (World Health Organization [WHO], 2000); higher levels can cause headache, dizziness, and breathing difficulty. Exposure to extremely high levels (1,000–2,000 ppm) can result in immediate collapse and death (WHO, 2000).
- Methane is an odorless but highly flammable gas with risk of explosion at 5%–15% in air (International Programme on Chemical Safety, 2000b). At high levels, methane can also cause death through asphyxiation; however, explosion is likely to occur before reaching asphyxiation levels, making explosion risk the primary concern.

Most hydrogen sulfide health effects studies evaluated high-level occupational or accidental release exposures. One example is Poza Rica, Mexico, where in 1950, 22 people died and 320 people were hospitalized (McCabe & Clayton, 1952; National Institute for Occupational Safety and Health, 1977). More recent studies, however, suggest health

FIGURE 1

Sampling Frame for Household Survey Conducted in Lake County, California, During November 26–28, 2012



effects in communities chronically exposed to low environmental hydrogen sulfide levels (Bates, Garrett, Graham, & Read, 1997, 1998; Bates, Garrett, & Shoemack, 2002; Durand & Wilson, 2006; Hansell & Oppenheimer, 2004; Legator, Singleton, Morris, & Philips, 2001). In Rotorua, New Zealand, residents living in an area with hydrogen sulfide levels ≥ 1 ppm were at increased risk of hospitalization for nervous system and sense organ diseases compared with residents living where hydrogen sulfide exposure levels were < 50 parts per billion (ppb) (Bates et al., 2002; Horwell, Patterson, Gamble, & Allen, 2005). Compared with a control community, a Puna, Hawaii, community close to a geothermal plant with periodic releases of hydrogen sulfide ranging from 200 to 500 ppb showed a greater risk of diseases for all body systems, especially for central nervous system and respiratory system disorders (Legator et al., 2001). Other studies have demonstrated adverse health outcomes associated with hydrogen sulfide concentrations in the window between the odor and irritant thresholds (Jaakkola, Vilkka, Marttila, Jappinen, & Haahtela, 1990; Kilburn & Warshaw, 1995; Schiffman & Williams, 2005).

In Lake County's Clearlake area, researchers have identified several geothermal vents. Documentation of geothermal venting and its effects in this area began in the early 1990s, when a home was demolished because of persistent hydrogen sulfide intrusion (ground-level hydrogen sulfide detected at 150 ppm). In 2010, a vent was discovered in Clearlake with high levels of hydrogen sulfide (750–800 ppm) and methane (55%–58% lower explosive limit [LEL]) at the vent surface (Ecology and Environment, 2011). This vent was capped with a scrubber, a specialized equipment to capture and neutralize the vented hydrogen sulfide. In 2011 Lake County Health Services Department (LCHSD) recommended that a community-based organization vacate its building due to hydrogen sulfide and methane intrusion (hydrogen sulfide detected at 53 ppb; methane detected at 12% LEL) (Ecology and Environment, 2011; K. Tait, personal communication, August 16, 2013). In response to these reports and findings, California Department of Public Health (CDPH), Lake County Public Health Division (LCPHD), the U.S. Environmental Protection Agency (U.S. EPA), and the U.S. Geological Survey (USGS) over the years have conducted a series of air sampling investigations in Clearlake. Areas beyond the small Clearlake neighborhood, however, have been largely unexplored.

This investigation described the knowledge and risk perception of Lake County communities about geothermal venting and determined whether areas beyond Clearlake were experiencing geothermal venting. Our objectives were to determine 1) vulnerability to geothermal gas exposure among Lake County residents; 2) perceptions of and experiences with geothermal venting among Lake County residents; and 3) outdoor air levels of hydrogen sulfide and methane concentrations in residential areas to identify potential areas of Lake County geothermal venting.

Methods

During November 26–28, 2012, we conducted a cross-sectional household survey and air sampling in Lake County between 8:30 a.m. and 5:00 p.m. PST each day.

Sampling Frame

The sampling frame contained 26,730 housing units (2010 census) and included all census blocks within or adjacent to the following cities and towns in Lake County (Figure 1): Clearlake, Clearlake Oaks, Cobb, Hidden Valley Lake, Kelseyville, Lakeport, Lower Lake, Lucerne, Middletown, Nice, and Upper Lake. To select a representative sample of households to interview, we used a two-stage cluster sampling methodology (30 census blocks, seven households). The methodology was modified from the World Health Organization's Expanded Program on Immunization coverage survey methodology (Centers for Disease Control and Prevention [CDC], 2012). For the first stage of sampling, we selected 30 census blocks (clusters) within this sampling frame using probability-proportional-to-size. For the second stage of sampling, interview teams systematically selected seven households to interview from each of the 30 clusters.

Household Survey

The questionnaire included 12 closed-ended questions (e.g., multiple choice, yes/no) to collect information about household demographics, home characteristics, awareness, experiences, and concerns about geothermal venting. Fourteen two-person interview teams administered the survey, primarily consisting of CDPH, LCPHD, and Centers for Disease Control and Prevention (CDC) public health staff. The teams were trained on the overall purpose of the survey, the questionnaire, interview techniques, the household selection method, safety, and logistics. Participants who were at least 18 years of age and a household resident were eligible to participate in the study and were asked to respond to the questions on behalf of the entire household.

For questions about geothermal experiences in or around the home, and to assist recall, interview teams showed printed photos of "unusual corrosion on metal surfaces" and "bubbling in puddles." Interview teams also recorded observations of geothermal venting evidence outside the homes where interviews occurred. We assessed vulnerability to geothermal gas exposure, including age of household members and characteristics and age of housing structures that make homes more susceptible to vapor intrusion and gas accumulation (ATSDR, 2006; U.S. Environmental Protection Agency [U.S. EPA], 2002; Zummo & Karol, 1996).

Air Sampling

We conducted air sampling to measure outdoor levels of gaseous hydrogen sulfide and methane in the same clusters where we conducted the interviews. We focused on hydrogen sulfide and methane because previous air sampling in the area indicated outdoor levels of hydrogen sulfide and methane that may pose a health or safety threat. The air sampling teams conducted systematic air sampling in residential areas, in water meter boxes (buried, dry, enclosed chambers approximately 1' wide x 1.5' long x 0.75' deep), and in other public right-of-way areas outside systematically selected homes. In clusters with ≥50 homes, air sampling was conducted outside every 10th home. In clusters with <50 homes, air sampling was conducted outside at least five homes. At each selected home, the team took spot measurements of hydrogen sulfide levels in the water meter box associated with the home (where available), and at 6" and 30" above ground. Methane levels were only measured in the water meter box. Where water meter boxes were not available, methane was not measured, and hydrogen sulfide was measured at 6" and 30" above dirt or grass/gravel-covered surfaces free of pavement on public property in front of the selected house. Air sampling teams used a hydrogen sulfide analyzer to measure hydrogen sulfide levels (detection range = 3 ppb–50 ppm), and a combustible gas monitor to measure methane levels (detection range = 0%–100% LEL). All air sampling locations were geocoded using a GPS instrument (differential GPS accuracy = 3 m/10 ft.). For quality control, we calibrated instruments daily and we took duplicate measurements at the first location in each cluster.

TABLE 1

Demographics of Interviewed Households for Survey Conducted in Lake County, California, During November 26–28, 2012

Demographic	*n* (%) (*N* = 161)	Projected Number of Households (*N* = 26,730)	Weighted % (95% Confidence Interval)
Household size			
1	42 (26.1)	6,570	24.6 (16.0–33.1)
2 to 4	103 (64.0)	17,712	66.3 (57.2–75.3)
5 or more	15 (9.3)	2,321	8.7 (3.3–14.0)
Age distribution in households			
<2 years old	13 (8.1)	2,244	8.4 (3.1–13.7)
2–17 years old	41 (25.5)	7,018	26.3 (16.8–35.7)
18–64 years old	125 (77.6)	21,083	78.9 (70.9–86.8)
≥65 years old	57 (35.4)	9,169	34.3 (24.6–44.0)
Main language spoken			
English	153 (95.0)	25,396	95.0 (91.3–98.7)
Spanish	8 (5.0)	1,334	5.0 (1.3–8.7)
Type of home lived in			
Mobile home	41 (25.5)	7,383	27.6 (17.5–37.8)
Single family home	114 (70.8)	18,512	69.3 (59.4–79.1)
Duplex	5 (3.1)	709	2.7 (0.4–4.9)
Multi-unit complex	1 (0.6)	127	0.5 (0–1.5)

Note. Missing: household size (*n* = 1).

Data Analysis

We calculated the response rates and conducted unweighted and weighted analyses using SAS version 9.3 to account for the sampling probabilities of the interviewed households within each cluster. Unless otherwise stated, throughout this article the percentages represent unweighted percentages. For air sampling data analysis for each cluster, we used SAS version 9.3 to calculate the maximum, minimum, and median levels for the water meter box and at 6" and 30" above ground. We also mapped individual point measurements and used ArcGIS version 10.1 to look at the detected gases' geographical distribution.

We conducted stratified analysis to examine the survey responses among households in clusters with detectable hydrogen sulfide levels (≥80% of the individual measurements in the cluster were ≥3 ppb at the water meter box, 6", or 30") compared with clusters with undetectable levels. Univariate odds ratios

TABLE 2

Surveyed Cities and Towns With Detectable Levels and Undetectable Levels of Hydrogen Sulfide (H_2S) in Lake County, California, on November 26–28, 2012

Cities and Towns	Clusters *n*	Detectable H_2S levels* *n* (%)	Undetectable H_2S levels* *n* (%)	Unknown H_2S Levels+ (not measured) *n* (%)
City of Clearlake	8	1 (12.5)	7 (87.5)	–
Clearlake Oaks	6	4 (66.7)	2 (33.3)	–
Cobb	1	1 (100.0)	–	–
Hidden Valley Lake	2	–	2 (100.0)	–
Kelseyville	1	1 (100.0)	–	–
Lakeport	3	–	3 (100.0)	–
Lucerne	3	–	–	3 (100.0)
Middletown	1	–	1 (100.0)	–
Nice	3	–	2 (66.6)	1 (33.3)
Paradise Cove	1	1 (100.0)	–	–
Total number of clusters	29	8 (27.6)	17 (58.6)	4 (13.8)
Total number of surveys	161	53 (32.9)	86 (53.4)	22 (13.7)

*A cluster is defined as having detectable levels when ≥80 of the individual H_2S measurements in the cluster were ≥3 parts per billion (ppb) at the water meter box, 6", or 30" levels. Highest reading detected was 5 ppb.

+ No measurements were taken in four clusters due to weather conditions.

and 95% confidence intervals were calculated using SAS. Fisher's exact test was used to estimate odds ratio when cell size was ≤5.

Results

Interview teams conducted household surveys in 29 clusters in 9 of the 11 sampled Lake County cities and towns; no clusters were selected in Upper Lake and Lower Lake. One cluster was selected twice; therefore, 14 interviews were attempted in this cluster. Interview teams approached 514 houses, of which 261 (50.7%) answered the door. The teams completed 161 interviews for a completion rate of 76.7% (compared with the target of 210 interviews). Air sampling was conducted in 25 clusters from nine cities and towns in Lake County, including 427 hydrogen sulfide measurements at 173 locations, and 83 methane measurements at 83 locations.

Demographics of Surveyed Households

Table 1 shows the demographics of the interviewed households. The majority of the surveyed households had a household size of 2–4 persons (*n* = 103; 64.0%). Fifty-seven (35.4%) households had one or more persons 65 years or older, and 13 (8.1%) households had one or more persons younger than two years. Eight (5.0%) households spoke Spanish as their main language at home. The most common home types were single-family homes (*n* = 114; 70.8%) and mobile homes (*n* = 41; 25.5%).

Hydrogen Sulfide and Methane Levels in the Community

We conducted air sampling in 25 of the 29 clusters; weather conditions prohibited taking measurements in four clusters. All hydrogen sulfide measurements in water meter boxes were ≤1 ppb, and above ground median values (all 6" and 30" measurements) per cluster ranged from 0 to 4 ppb (minimum = 0 ppb; maximum = 5 ppb). All methane readings were 0% LEL, with the exception of two readings measured at 1% LEL. The maximum hydrogen sulfide and methane levels were both detected in Clearlake. Detectable levels of hydrogen sulfide were measured in eight (27.6%) clusters in Clearlake, Clearlake Oaks, Cobb, Kelseyville, and Paradise Cove (Table 2). Fifty-three (32.9%) surveys were conducted in clusters with detectable hydrogen sulfide levels.

Vulnerability to Geothermal Gas Exposure and Effects

Table 3 shows the vulnerability to geothermal gas exposure and effects among surveyed households. Of the 53 surveyed households living in clusters with detectable hydrogen sulfide levels, two (3.8%) had one or more children younger than two years, and 24 (45.3%) had at least one household member 65 years or older. Forty-one (25.5%) of the total surveyed households lived in mobile homes, five (12.2%) of which were located in a cluster with detectable hydrogen sulfide levels. Fifty-five (34.2%) lived in a home built on slab-on-grade, 25 (45.5%) of which were in a cluster with detectable hydrogen sulfide levels. Sixty-nine (42.9%) lived in a home with crawl space, 21 (30.4%) of which were in a cluster with detectable hydrogen sulfide levels. Sixty-seven (41.6%) of the surveyed households lived in homes built before 1980, 20 (29.8%) of which were in a cluster with detectable hydrogen sulfide levels.

Perceptions and Experiences of Geothermal Venting

After prompting about Mt. Konocti and geothermal venting in the area, 109 (67.7%) households interviewed said they were aware of hydrogen sulfide and methane coming up through the ground (Table 4). Fifty-eight (36%) households had at least one concern about potential health or environmental effects of geothermal venting: 55 (34.2%) about potential health effects on their family, 38 (23.6%) about potential health effects on their pets or livestock or both, and 33 (20.5%) concerning potential effects on their property. Thirty-three (20.5%) households reported ever having experienced geothermal venting in or around their homes; the most common reported experience was noticing a rotten egg smell at some time in the past (*n* = 23; 14.3%). No statistically significant differences were observed in geothermal venting perceptions and experiences for households living in clusters with detectable hydrogen sulfide levels compared with undetectable levels.

Discussion

Air Sampling Findings

We used spot air sampling in Lake County, California, to identify potential areas of concern for geothermal venting in residential areas.

TABLE **3**

Vulnerability to Geothermal Gas Exposure and Effect Among Surveyed Households for Survey Conducted in Lake County, California, During November 26–28, 2012

Characteristic	*n* (%) (*N* = 161)	Projected Number of Households (*N* = 26,730)	Weighted % (95% *CI*[a])	*n* (%) Detectable H_2S^a Levels* (*N* = 53)
Households with vulnerable age groups				
<2 years old	13 (8.1)	2,244	8.4 (3.1–13.7)	2 (3.8)
≥65 years old	57 (35.4)	9,169	34.3 (24.6–44.0)	24 (45.3)
Home characteristics vulnerable to vapor intrusion and gas accumulation				
Mobile home	41 (25.5)	7,383	27.6 (17.5–37.8)	5 (9.4)
Slab-on-grade foundation	55 (34.2)	9,252	34.6 (23.7–45.5)	25 (47.2)
Home with basement	5 (3.1)	636	2.4 (0.4–4.4)	2 (3.8)
Home with crawl space	69 (42.9)	11,806	44.2 (33.3–55.0)	21 (39.6)
Home age (year built)				
2000 or later	18 (11.2)	3,488	13.0 (4.8–21.3)	5 (9.4)
1980 to 1999	40 (24.8)	6,108	22.8 (12.8–32.9)	20 (37.7)
Before 1980	67 (41.6)	11,755	44.0 (31.9–56.1)	20 (37.7)

Note. Missing: slab-on-grade foundation (*n* = 4); home with basement (*n* = 4); home with crawl space (*n* = 4); home age (year built) (*n* = 5). Don't know: slab-on-grade foundation (*n* = 6); home with basement (*n* = 6); home with crawl space (*n* = 6); home age (year built) (*n* = 31).

[a]*CI* = confidence interval; H_2S = hydrogen sulfide.

*A cluster is defined as having detectable levels when ≥80 of the individual H_2S measurements in the cluster were ≥3 parts per billion (ppb) at the water meter box, 6", or 30" levels. Highest reading detected was 5 ppb; 22 household surveys were conducted in the four clusters where no measurements were taken.

Methane was virtually undetectable, and the hydrogen sulfide levels detected in the various cities and towns in Lake County were all ≤5 ppb, similar to ambient levels detected in Clearlake in a recent June 2012 LCPHD-CDPH investigation (K. Tait, personal communication, August 8, 2012). Hydrogen sulfide levels from natural sources usually range between 0.11 and 0.33 ppb, with hydrogen sulfide concentrations in urban areas generally <1 ppb (ATSDR, 2006). Although some measurements from this study were >1 ppb, all these outdoor measurements were well below the ambient California Environmental Protection Agency air quality standard of 30 ppb over one hour and below other international standards (ATSDR, 2006; California Environmental Protection Agency, 2009). We thus identified no immediate risk to the sampled communities. Continued vigilance and reporting of potent rotten egg smells by residents, however, could assist LCPHD in identifying new geothermal vents.

We detected hydrogen sulfide in Clearlake, Clearlake Oaks, Cobb, Kelseyville, and Paradise Cove. Only one of eight clusters in Clearlake had detectable hydrogen sulfide levels, despite Clearlake geothermal venting experiences triggering this investigation. This finding suggests venting in Clearlake might be sporadic or highly localized. But detectable hydrogen sulfide levels were found in two-thirds of the clusters in Clearlake Oaks, suggesting more venting in Clearlake Oaks on the day of air sampling.

Given these findings, systematic tracking of reports of concerns and complaints from communities throughout Lake County could help LCPHD assess the need for further air monitoring and investigation in these areas. If warranted, long-term air monitoring in Clearlake and Clearlake Oaks could help LCPHD to characterize community exposure over time. One possible study design would be to use passive diffusers at multiple locations over an extended period, as done recently in Rotorua, New Zealand (Bates, Garrett, Crane, & Balmes, 2013; Horwell, Allen, Mather, & Patterson, 2004).

Experiences With Geothermal Venting

Risk perception is subjective. It can result from such factors as hazard characteristics, voluntary nature of exposure, and the level of trust in public officials to manage risk adequately. We did not find risk perceptions and experiences to differ significantly between households living in clusters with detectable and undetectable hydrogen sulfide levels. We used odor as an exposure marker and asked households whether they ever noticed a rotten egg smell in or around their homes. One in seven households reported having noticed a rotten egg smell. This might not be concerning, given the odor threshold is much lower than the irritant threshold and historically, unpleasant odor was only thought to serve as a warning signal for potential risk. Still, studies have shown health effects associated with hydrogen sulfide concentrations in the window between the odor and irritant thresholds (Jaakkola, et al., 1990; Kilburn & Warshaw, 1995; Schiffman & Williams, 2005). Therefore, improving risk communication, responding to community complaints, and continued monitoring of geothermal gas effects on the community could reduce the risk of health effects.

TABLE **4**

Perceptions, Experiences, and Evidence of Geothermal Venting for Surveyed Households Living in Area With Detectable and Undetectable Hydrogen Sulfide (H_2S) Levels for Survey Conducted in Lake County, California, on November 26–28, 2012

Survey Item	*n* (%) (*N* = 161)	Projected Number of Households (*N* = 26,730)	Weighted % (95% *CI*[a])	Detectable H_2S Levels* *n* (%) (*N* = 53)	Undetectable H_2S Levels* *n* (%) (*N* = 86)	Odds Ratio (95% *CI*)
Geothermal gases						
Aware of geothermal gases	109 (67.7)	18,106	67.7 (58.6–76.9)	40 (75.5)	58 (67.4)	0.62 (0.28–1.37)
Had at least one concern about potential effects¥	58 (36.0)	8,664	32.4 (23.7–41.1)	14 (26.4)	33 (38.4)	1.73 (0.82–3.67)
Concerned about effects on health of family	55 (34.2)	8,231	30.8 (22.1–39.5)	12 (22.6)	32 (37.2)	2.03 (0.93–4.41)
Concerned about effects on health of pets/livestock	38 (23.6)	5,995	22.4 (14.8–30.1)	10 (18.9)	22 (25.6)	1.48 (0.64–3.43)
Concerned about effects on property	33 (20.5)	5,287	19.8 (12.3–27.2)	9 (17.0)	20 (23.3)	1.48 (0.62–3.55)
Experiences in or around home						
Have had at least one experience with geothermal venting in or around home†	33 (20.5)	5,626	21.0 (12.3–29.8)	12 (22.6)	16 (18.6)	0.78 (0.34–1.81)
Noticed rotten egg smell	23 (14.3)	4,311	16.1 (7.5–24.8)	7 (13.2)	14 (16.3)	0.79 (0.30–2.10)
Seen unusual corrosion on metal surfaces	11 (6.8)	1,634	6.1 (1.7–10.5)	4 (7.5)	3 (3.5)	2.31 (0.37–16.46)ǂ
Seen bubbling in puddles	5 (3.1)	849	3.2 (0.3–6.1)	2 (3.8)	2 (2.3)	1.67 (0.12–23.75)ǂ
Encountered unexpected flames	1 (0.6)	127	0.5 (0–1.5)	1 (1.9)	0 (0)	–
Evidence of geothermal venting outside home						
Had evidence of geothermal venting outside home+	4 (2.5)	849	3.2 (0–7.9)	0 (0)	4 (4.7)	–

Note. Don't know: aware of geothermal gases (*n* = 1); noticed rotten egg smell (*n* = 2); seen unusual corrosion on metal surfaces (*n* = 3); seen bubbling in puddles (*n* = 1).

[a]*CI* = confidence interval.

*A cluster is defined as having detectable levels when ≥80 of the individual H_2S measurements in the cluster were ≥3 parts per billion (ppb) at the water meter box, 6", or 30" levels. Highest reading detected was 5 ppb; 22 household surveys were conducted in the four clusters where no measurements were taken.

¥Any household that reported concerns about effects on health of family, health of pets/livestock, or concern about effects on property.

†Any household that reported that they have noticed rotten egg smell, encountered unexpected flames, seen unusual corrosion on metal surfaces, or seen bubbling in puddles in or around their home.

+Any household where the interview teams noted unusual corrosion on metal surfaces, rotten egg smell, or bubbling in puddles outside home; unusual rusting on metal surfaces (*n* = 4); bubbling in puddles (*n* = 0); rotten egg odor (*n* = 0).

ǂFisher's exact test was used to estimate odds ratio when *n* ≤ 5.

Population Vulnerabilities

Vulnerability to a health hazard is determined by a set of characteristics that affect individual, household, or communal ability to cope with the hazard (Blaikie, 1994). We examined vulnerability to geothermal gas exposure, including age of household members and characteristics and age of housing structures. Greater susceptibility to air pollution–related health effects among children and the elderly is well documented and is attributed to the developing respiratory system in children and comorbidities in the elderly (Zummo & Karol, 1996). And as dense hydrogen sulfide settles near the ground it might result in higher exposure to children due to their smaller stature (ATSDR, 2006). Still, although nearly half of the interviewed households had a child or elderly person in the home, our air sampling findings showed that no immediate concerns arose, given that gases present were not above the California Environmental Protection Agency air quality standard of 30 ppb over one hour.

We limited our investigation to outdoor air sampling in residential areas. This limitation was intended to identify only those areas with geothermal venting where a risk of vapor intrusion into homes might occur. Vapor intrusion is the process whereby geothermal gases seep via micro cracks in the concrete foundation under homes either directly into the living space, or into basement and crawl space where gases can accumulate to dangerously high concentrations as seen, for example, in Rotorua, New Zealand (Durand & Scott, 2005; U.S. EPA, 2002, 2012). The potential risk of vapor intrusion can also increase in older homes and in less well-constructed mobile homes. Although many homes in this study had characteristics that might increase the risk of vapor intrusion, however, we concluded that the actual risk for vapor intrusion in the areas sampled was low because outdoor levels of hydrogen sulfide were not detected above the California Environmental Protection Agency air quality standard of 30 ppb over one hour and methane was not near levels of explosion risk.

Limitations

We caution against generalizing the air sampling findings to the entire county or cities where measurements were taken. Air sampling in our study provided only a snapshot of hydrogen sulfide levels. The sampling only indicated hydrogen sulfide levels in the immediate sampled areas and at the times when measurements were taken. Geothermal venting in a single location depends on underground geothermal activities; thus it can vary and be difficult to measure consistently (Chiodini, Brombach, Caliro, & Cardellini, 2002; Horwell et al., 2004). Furthermore, after gases are vented into the atmosphere, their dispersion is determined by meteorological factors such as wind speed, mixing depth of wind turbulence, and humidity, creating more variability that is difficult to capture using spot measurements (Horwell et al., 2004; Wright & Diab, 2011). Lack of detection of hydrogen sulfide in one area at one time does not mean venting does not occur on other days. Consequently, in our stratified analysis we might have misclassified some clusters as having "undetectable hydrogen sulfide levels." Experiences with geothermal venting by households were self-reported, therefore a degree of bias may be possible. Lastly, because the response was <80% of our target sample size of 210, our sample may not be large enough to reliably project population estimates.

Conclusion

This investigation identified many households with characteristics that could make them more vulnerable to both the exposure and the effects of geothermal venting. But we did not observe any outdoor measurements of hydrogen sulfide above the California Environmental Protection Agency air quality standard of 30 ppb over one hour or methane above the LEL. Households were aware of geothermal venting and some residents expressed concerns. To better inform concerned residents about the risks of geothermal venting, carefully tailored risk communication could be the next step.

Systematic tracking of reports of concerns and complaints from communities throughout Lake County could help LCPHD assess the need for further air monitoring and investigation in these areas. If reports of concerns and complaints about geothermal gases increase or new geothermal vents are identified, long-term air monitoring could help LCPHD to characterize community exposure over time.

Acknowledgements: We would like to thank the following people for their contribution to this work: Mr. Doug Gearhart from the Lake County Air Quality Management District for offering practical advice and support for the air sampling; Dr. Jason Wilken from CDPH/CDC for assisting with the survey implementation and reviewing the manuscript; and Dr. Brian Christensen from Air Pollution and Respiratory Health Branch, CDC, for assisting with the air sampling. We would also like to thank the many others who volunteered in the field from LCHSD and CDPH.

Corresponding Author: Cindy H. Chiu, Epidemic Intelligence Service Officer, National Center for Environmental Health, Centers for Disease Control and Prevention, 4770 Buford Highway, NE, Atlanta, GA 30341.
E-mail: drcindyhchiu@gmail.com.

References

Agency for Toxic Substances and Disease Registry. (2006). *Toxicological profile for hydrogen sulfide.* Retrieved from http://www.atsdr.cdc.gov/toxprofiles/tp114.pdf

Bates, M.N., Garrett, N., Crane, J., & Balmes, J.R. (2013). Associations of ambient hydrogen sulfide exposure with self-reported asthma and asthma symptoms. *Environmental Research, 122*, 81–87.

Bates, M.N., Garrett, N., Graham, B., & Read, D. (1997). Air pollution and mortality in the Rotorua geothermal area. *Australian and New Zealand Journal of Public Health, 21*(6), 581–586.

Bates, M.N., Garrett, N., Graham, B., & Read, D. (1998). Cancer incidence, morbidity, and geothermal air pollution in Rotorua, New Zealand. *International Journal of Epidemiology, 27*(1), 10–14.

Bates, M.N., Garrett, N., & Shoemack, P. (2002). Investigation of health effects of hydrogen sulfide from a geothermal source. *Archives of Environmental Health, 57*(5), 405–411.

Blaikie, P.M. (1994). *At risk: Natural hazards, people's vulnerability, and disasters* (1st ed.). London: Routledge.

California Environmental Protection Agency. (2009). *History of hydrogen sulfide ambient air quality standard.* Retrieved from http://www.arb.ca.gov/research/aaqs/caaqs/h2s/h2s/htm

Centers for Disease Control and Prevention. (2012). *Community assessment for public health emergency response (CASPER) toolkit* (2nd ed.). Retrieved from http://emergency.cdc.gov/disasters/surveillance/pdf/casper_toolkit_version_2_0_508_compliant.pdf

Chiodini, G., Brombach, T., Caliro, S., & Cardellini, C. (2002). Geochemical indicators of possible ongoing volcanic unrest at Nisyros Island (Greece). *Geophysical Research Letters, 29*(16), 6.1–6.4.

Durand, M., & Scott, B.J. (2005). Geothermal ground gas emissions and indoor air pollution in Rotorua, New Zealand. *The Science of the Total Environment, 345*(1–3), 69–80.

Durand, M., & Wilson, J.G. (2006). Spatial analysis of respiratory disease on an urbanized geothermal field. *Environmental Research, 101*(2), 238–245.

Ecology and Environment, Inc. (2011). *Clearlake hydrogen sulfide trip report to U.S. Environmental Protection Agency.* Unpublished manuscript.

References

Etiope, G., Papatheodorou, G., Christodoulou, D., Ferentinos, G., Sokos, E., & Favali, P. (2006). Methane and hydrogen sulfide seepage in the northwest Peloponnesus petroliferous basin (Greece): Origin and geohazard. *American Association of Petroleum Geologists Bulletin, 90*(5), 701–713.

Hansell, A., & Oppenheimer, C. (2004). Health hazards from volcanic gases: A systematic literature review. *Archives of Environmental Health, 59*(12), 628–639.

Horwell, C.J., Allen, A.G., Mather, T.A., & Patterson, J.E. (2004). Evaluation of a novel passive sampling technique for monitoring volcanogenic hydrogen sulfide. *Journal of Environmental Monitoring, 6*(7), 630–635.

Horwell, C.J., Patterson, J.E., Gamble, J.A., & Allen, A.G. (2005). Monitoring and mapping of hydrogen sulfide emissions across an active geothermal field: Rotorua, New Zealand. *Journal of Volcanology and Geothermal Research, 139*(3–4), 259–269.

International Programme on Chemical Safety. (2000a). *Hydrogen sulfide*. Retrieved from http://www.inchem.org/documents/icsc/icsc/eics0165.htm

International Programme on Chemical Safety. (2000b). *Methane*. Retrieved from http://www.inchem.org/documents/icsc/icsc/eics0291.htm

Jaakkola, J.J., Vilkka, V., Marttila, O., Jappinen, P., & Haahtela, T. (1990). The South Karelia air pollution study. The effects of malodorous sulfur compounds from pulp mills on respiratory and other symptoms. *The American Review of Respiratory Disease, 142*(6 Pt. 1), 1344–1350.

Kilburn, K.H., & Warshaw, R.H. (1995). Hydrogen sulfide and reduced-sulfur gases adversely affect neurophysiological functions. *Toxicology and Industrial Health, 11*(2), 185–197.

Legator, M.S., Singleton, C.R., Morris, D.L., & Philips, D.L. (2001). Health effects from chronic low-level exposure to hydrogen sulfide. *Archives of Environmental Health, 56*(2), 123–131.

McCabe, L.C., & Clayton, G.D. (1952). Air pollution by hydrogen sulfide in Poza Rica, Mexico: An evaluation of the incident of Nov. 24, 1950. *AMA Archives of Industrial Hygiene and Occupational Medicine, 6*(3), 199–213.

National Institute for Occupational Safety and Health. (1977). Biologic effects of exposure. In *Criteria for a recommended standard: Occupational exposure to hydrogen sulfide* (pp. 22–64). Atlanta, GA: Centers for Disease Control and Prevention.

Schiffman, S.S., & Williams, C.M. (2005). Science of odor as a potential health issue. *Journal of Environmental Quality, 34*(1), 129–138.

U.S. Census Bureau. (2012). *State and county quickfacts—Lake County, California*. Retrieved from http://quickfacts.census.gov/qfd/states/06/06033.html

U.S. Environmental Protection Agency. (2002). *OSWER draft guidance for evaluating the vapor intrusion to indoor air pathway from groundwater and soils (subsurface vapor intrusion guidance)*. Retrieved from http://www3.epa.gov/epawaste/hazard/correctiveaction/eis/vapor.htm

U.S. Environmental Protection Agency. (2012). *Vapor intrusion: Basic information*. Retrieved from http://www2.epa.gov/vaporintrusion

U.S. Geological Survey. (2004). *Clear Lake volcanic field, California*. Retrieved from http://vulcan.wr.usgs.gov/Volcanoes/California/ClearLake/description_clear_lake.html

U.S. Geological Survey. (2010). *Volcanic gases and their effects*. Retrieved from http://volcanoes.usgs.gov/hazards/gas/index.php

World Health Organization. (2000). Hydrogen sulfide. In *Air Quality Guidelines*. (2nd ed.). Copenhagen, Denmark: Author.

Wright, C.Y., & Diab, R. (2011). Air pollution and vulnerability: Solving the puzzle of prioritization. *Journal of Environmental Health, 73*(6), 56–64.

Zummo, S.M., & Karol, M.H. (1996). Indoor air pollution: Acute adverse health effects and host susceptibility. *Journal of Environmental Health, 58*(6), 25.