Gaia's Exhalation from the 2019 Searles Valley Earthquake

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November 25, 2022

Abstract

The earth's crust is a leaky geofluid system where surface trace gas emissions relate to open migration pathways and the presence of subsurface source(s). Seismic activity can open sealed migration pathways leading to trace gas emissions from the surface intersection of the active fault, which may not relate to observable surface fault rupture or offset. After the M7.1 Ridgecrest earthquake, we collected mobile surface trace gas and meteorology data with AMOG (AutoMObile trace Gas) Surveyor, a mobile atmospheric chemistry and meteorology lab, in the Death Valley Park and Searles Valley within 24 hours of the quake, the following week, and after several weeks with air samples also were collected for detailed later laboratory analysis. We found widespread highly elevated CO2 emissions along Panamint Valley including overall elevated SO2 and H2S with strong enhancements around Manly Pass, where aftershocks occurred at the northern edge of the Slate Range and along a trend parallel to Water Canyon. This is in contrast to AMOG data collected in Death and Panamint Valleys in 2014, where concentrations were typical of California desert levels–near ambient and uniform. Significant sulfur trace gas emissions were discovered escaping from the rim of Ubehebe Volcano, last active ~2500 B.P., 115-km north of the Slate Range. Faults appear to play an important role in these geogas emissions, activated by the major earthquake and aftershocks. Further investigations are planned to characterize the system's return towards quiescence.

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***now Ridgecrest**

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Setting

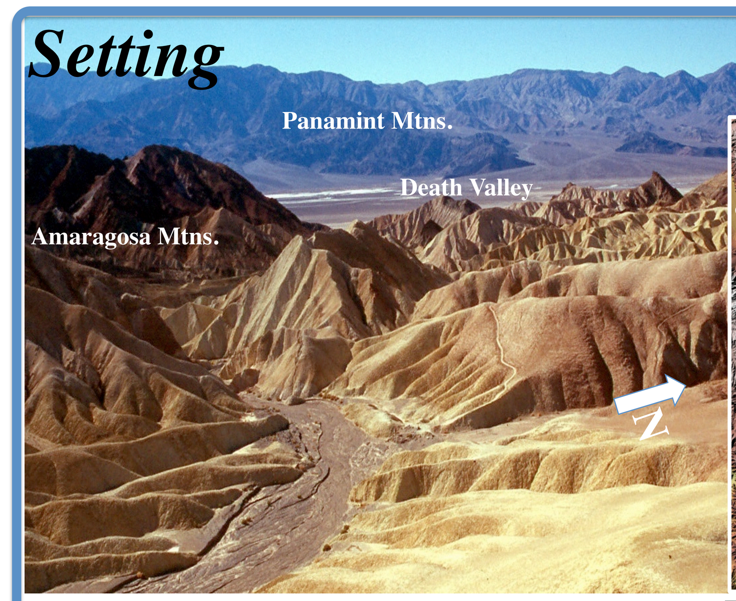

Fig. 1. Death Valley is the driest location on earth, a rift valley as deep as -86 m. Photo from Zabriske Point. (upload.wikimedia.org/wikipedia/commons/2/21/Death_Valley_Zabriskie_Point.jpg)

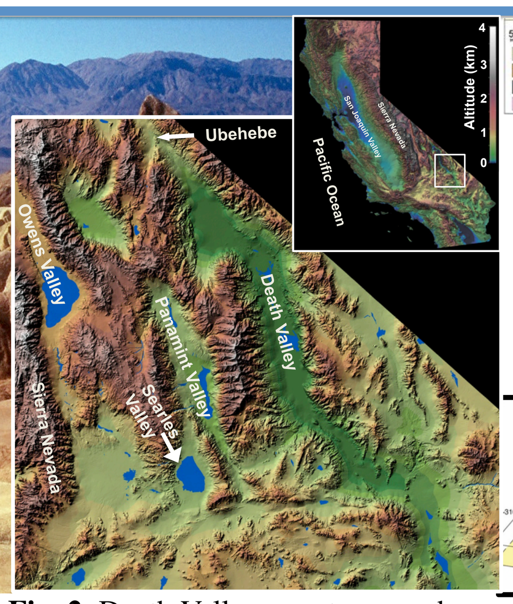

Fig. 2. Death Valley area topography. Inset shows California topography.

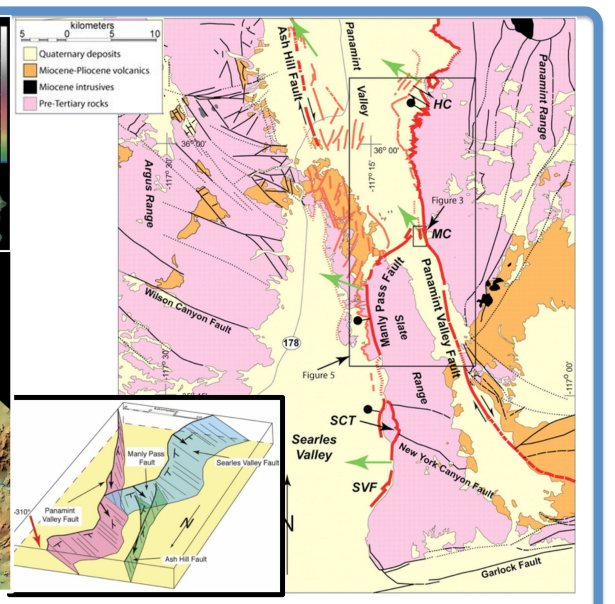

Fig. 3. Panamint/Searles Valley geology. From Walker et al., 2005

Death Valley is a rift valley bisected by a strike slip fault system / graben (dropped block edged by mountains – the Amaragosa and Grapevine Ranges to the east and Panamint and Last Chance ranges to the west). The Death Valley Fault follows the Valleys east edge in the north, west edge in the south. Panamint Valley (beyond the Panamint & Last Chance ranges), abuts the Saline Range and is connected to Searles Valley through Slate Crossing.

The Panamint Valley Fault Zone is in the Death Valley Extension region, ending at the Garlock Fault zone in the south. The North Death Valley Fault converges with the Tin Mountain Fault close to Ubehebe Crater in North Death Valley.

The Manly Fault and Searles Valley Fault are the main structures on the western side of the Slate Range. Slip on the Manly Fault is directed northwest towards the Ash Hill Fault and also the Panamint Fault after curving east.

Winds are heavily channeled by the mountain ranges along the Death and Panamint Valleys, and can be very strong (and hot) late in the day.

A survey conducted in 2014 with an early version of AMOG Surveyor found near ambient and highly uniform concentrations of CO_2 and CH_4 in Panamint Valley and south Death Valley (**Fig. 4**).

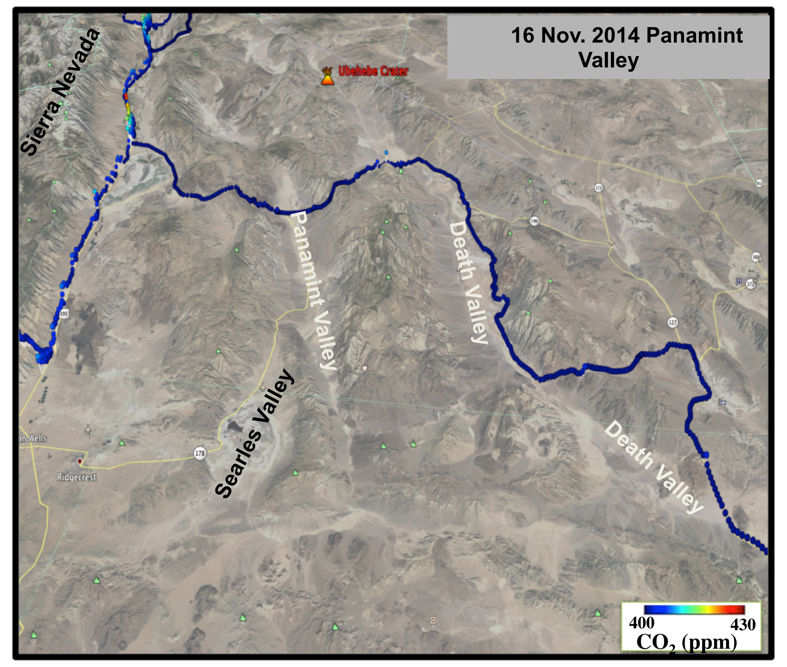

Fig. 4. AMOG Surveyor CO_2 data collected in Death Valley and Panamint Valley in Nov 2014. Data key on figure. Note CO_2 is close to ambient.

AutoMObile trace Gas (AMOG) Surveyor

Approach: Repeat in *situ* atmospheric trace gas composition surveys in Death Valley, Panamint Valley, Searles Valley, and Rose Valley where faults were activated by the earthquake (aftershocks are spreading into Rose Valley) from short term (several months) to quasi-baseline (half year). Analysis determines emission source locations and strengths and anomaly strengths

Fig. 5. A) AMOG Surveyor towed by TMOG. B) TMOG in north Death Valley.

While returning from a field campaign in Railroad Valley, NV (AMOG being towed behind TMOG – Truck MObile trace gas Surveyor), based on the Ridgecrest news reports, it was decided to survey Death Valley and Ridgecrest (July 5). Although capable, AMOG could not handle Death Valley temperatures (>120°F in shade). Thus, AMOG was idled on the trailer while being towed. The same approach was used July 13, when air sample canisters were collected for laboratory analysis in the Blake Lab. Typical Death Valley traffic was 2 cars per hour. When resurveyed on 4 Aug. several analyzers were installed in TMOG (back seat) and an anemometer projected off the roof rack. This allowed collection of data and air samples on a dirt road data downwind of the Ubehebe Volcano.

AMOG Surveyor (Fig. S2) is a mobile atmospheric chemistry, solar spectroscopy, and meteorology lab in a car that collects data at up to highway speed and uses real-time data integration and visualization to enable adaptive surveying (Thompson et al., 2015) slowing where gradients are strong and collecting targeted atmospheric samples (Leifer et al., 2016b).

AMOG Surveyor includes fast-response Cavity Enhanced Absorption Spectroscopy (CEAS) analyzers (CH_4, $\delta^{13}CH_4$, C_2H_6, CO_2, H_2O, NH_3, H_2S, N_2O, CO) and slower fluorescence analyzers (NO_X, NO, NO_2, H_2S, SO_2, O_3) all at sub-ppb accuracy (except CO_2, H_2O). AMOG also measures aerosol size (Grimm, 32 channels 0.1-32 µm, 0.16 Hz) and has a ceilometer (Vaisala 31L) to measure aerosol backscatter, allowing planetary boundary layer (PBL) derivation.

AMOG uses a high flow vacuum pump (850 L min^{-1}) to draw sample air down Teflon® lines from 5 and 3 m (NH_3). Meteorology includes 3D winds, humidity, fast temperature (1 Hz), and accurate pressure (0.03 mbar). A pyranometer and pyrgeometer measure downwelling radiation (Apogee Inst.), while four solar spectrometers (Ocean Optics) acquire solar spectra for a UV-O3, O2-B, and full spectrum (200-1100 nm) at 3152 bands, and NIR (900-1700 nm) channel in 256 bands.

Fig. 6. AMOG Surveyor. **Upper Right:** AMOG Cockpit. **Lower Right:** Real-time display and rear view camera for the Salton Sea. From *Leifer et al.* (2018a).

Ridgecrest Earthquake

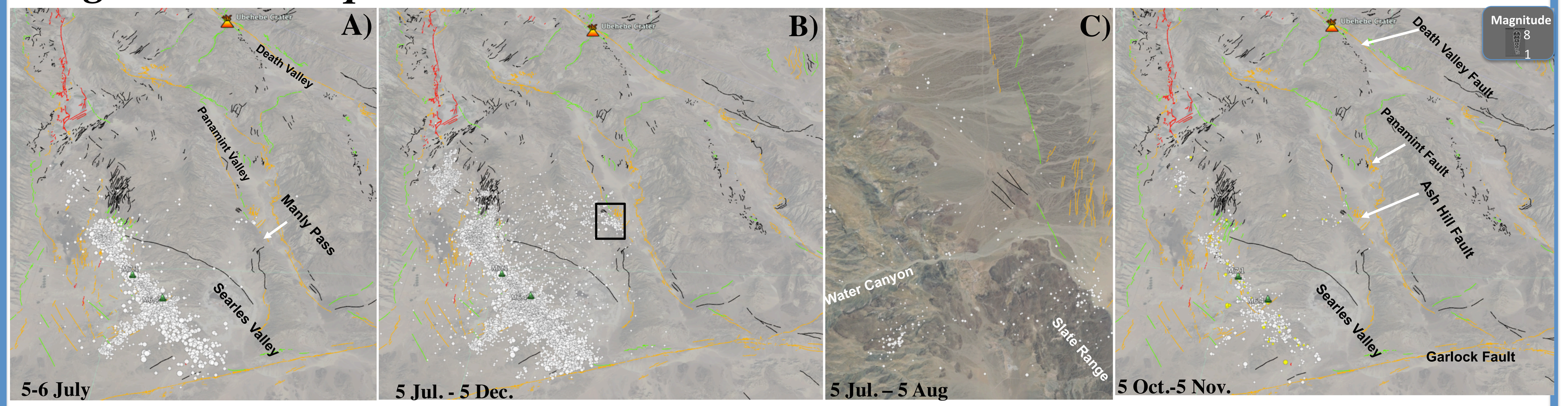

Fig. 7. Earthquake locations and magnitudes (M>1.3) and faults for **A)** 5-6 Jul., **B)** 5 Jul. – 5 Nov., inset shows location panel C. **C)** 5 Jul. - 5 Aug. for Slate Range Crossing /Water Canyon Area, **D)**5 Oct. – 5 Nov. From USGS.

The Ridgecrest earthquake struck on 5 July 2019 0408 PDT after several foreshocks on July 4 rupturing ~16 km of an unnamed fault, with 15-20 cm lateral shifts. Swarms of aftershocks occurred by the thousands in the first week, with aftershocks continuing to today (**Fig. 7B**). The south extent was well constrained by the Garlock Fault, and by the Sierra Nevada to the west. The number of aftershocks was well fit by two exponential functions with 6 and 60 day time scales (**Fig. 8**).

Although there were only a few aftershocks near the northern extent of the Pass in the immediate few days; aftershocks continued even as those along the main rupture fault decreased by orders of magnitude. and also along the Panamint Fault Zone on the Panamint Valley's western flank, mostly on the eastern flank of the Slate Range where it intersects the Ash Hill Fault system (**Fig. 7C**).

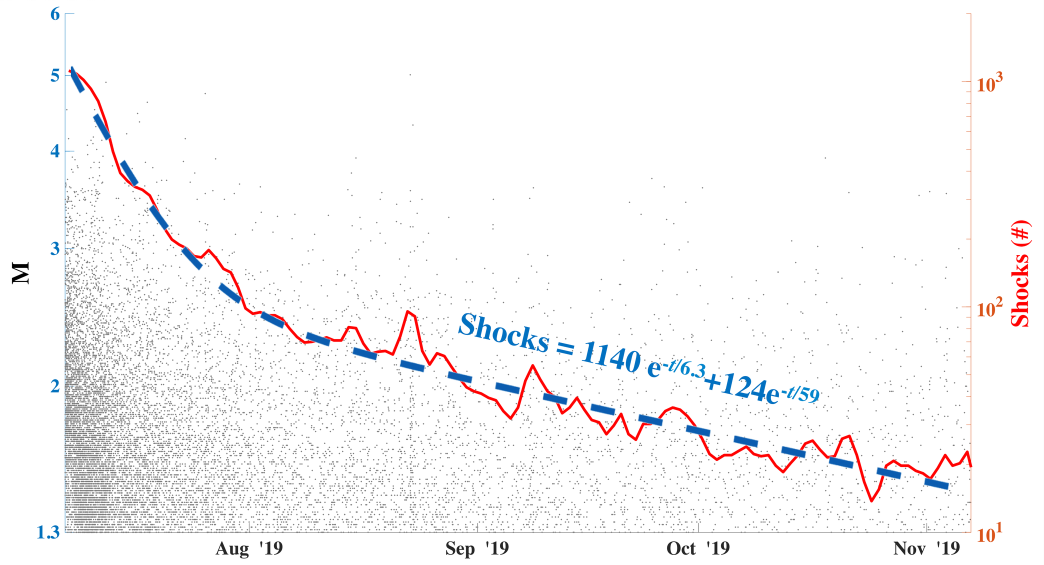

Fig. 8. Magnitude, *M*>1.3, and number of earthquakes (3-day rolling average) in the Death Valley area since the Ridgecrest earthquake, and fit to number of earthquakes, *t* in days. See **Fig 7B** for location of earthquakes used in fit.

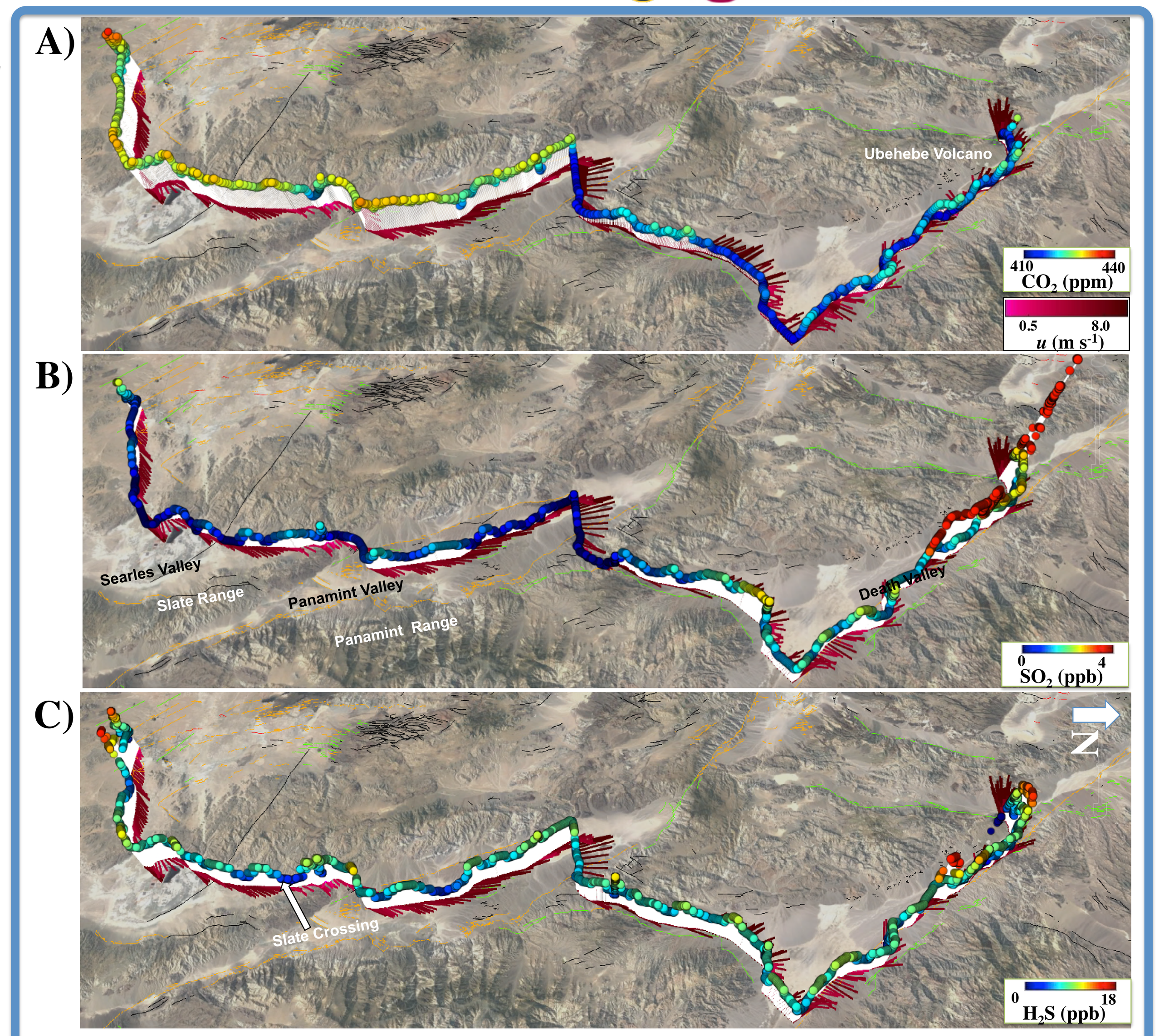

Fig. 9. Faults and AMOG winds, *u*, from Ridgecrest to Ubehebe **A)** CO_2 **B)** SO_2, **C)** H_2S.

On 13 July, winds generally were from the south to southwest, albeit clearly channelized by topography. Although winds were such that Searles Valley data likely are not anthropogenic, there are some mining and other human activities in Searles Valley. Panamint Valley CO_2 levels were significantly elevated compared to Death Valley levels with highest concentrations near the Slate crossing. SO_2 showed numerous anomalies corresponding in some cases to fault locations and elevated CO_2 with more sources in Death Valley. The same was true for H_2S. Ubehebe Crater is a strong emissions source.

Ubehebe Crater Field

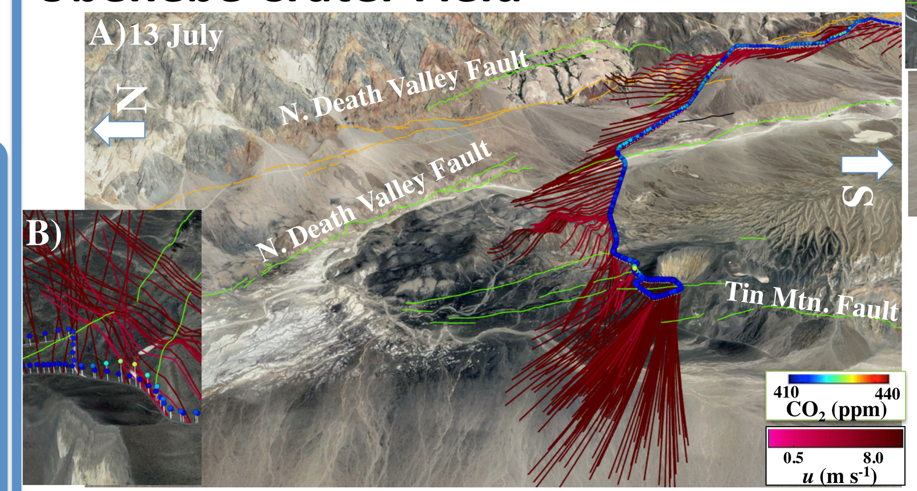

Fig. 10. AMOG A) CO_2 and winds from north Death Valley and Ubehebe crater field for 13 July and **B)** Crater rim CO_2 plume detail.

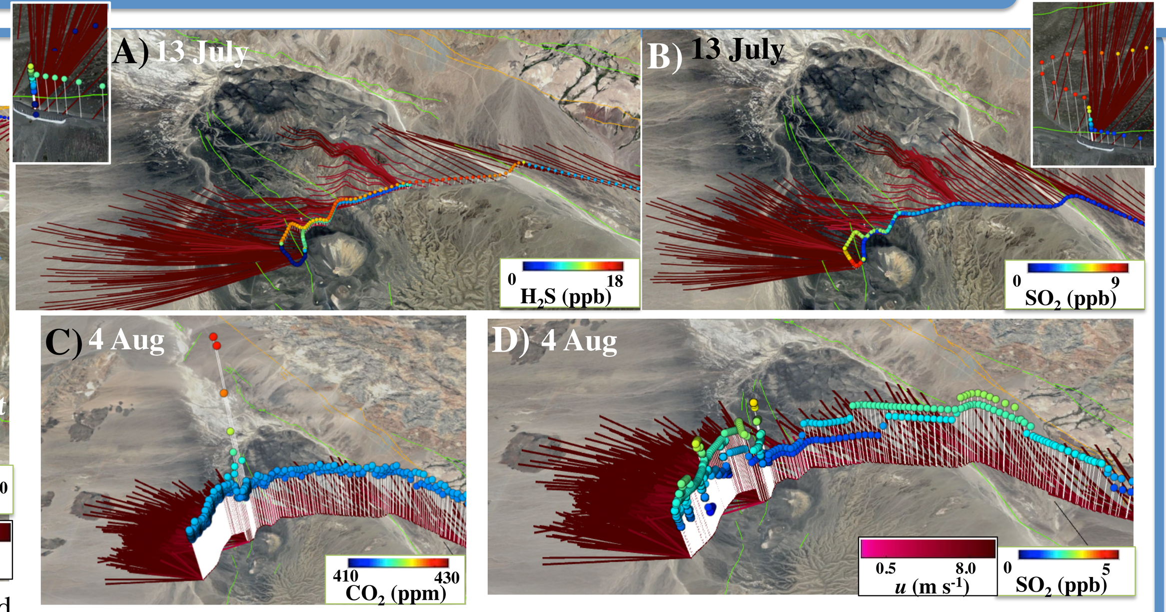

Fig. 11. Ubehebe AMOG winds, *u*, for 13 July and **A)** H_2S, and **B)** SO_2. **Insets:** Close ups of parking lot data on crater west rim. Analyzer time response is 1 minute. **C)** TMOG *u* and CO_2 and **D)** SO_2 for 4 Aug.

The Ubehebe Volcanic Crater field consists of 14-16 craters, which were formed by a phreatomagmatic (water and magma) eruption around 2500 B.P. It lies near the intersection of the Tin Mountain Fault and the North Death Valley Fault zone at the northern extent of the Panamint Range. The largest crater is 800-m across and surrounded by pyroclastic deposits. There are no reports of modern crater activity of volcanic gas emissions.

Unfortunately, AMOG did not survey north Death Valley on 5 July. Data were collected 13 July under extremely strong east winds (to 22 m s^{-1}) at the crater, strongly north (~ 10 m s^{-1}) to the east in Death Valley (**Fig. 10A**). CO_2 anomalies to 430 ppm (ambient 414 ppm) correlated well with the location of faults on the crater's north rim (**Fig. 10B**) and on death valley floor. The north rim CO_2 plume only was observed for one direction.

Very strong but unsteady H_2S hotspots (to 29 ppb) were observed along the northwest and west crater flanks (**Fig. 11A**). There also was a strong H_2S plume to the east on the crater's incline in Death Valley, which was not observed on the return. SO_2 showed a different pattern (**Fig. 11B**) with strong anomalies (to 9 ppb) more focused on the crater's west rim than the north east (for H_2S). During 14 minutes of stationary data in the parking lot (no cars), the SO_2 slowly decreased while H_2S increased (**Fig. 11 Insets**)– suggesting oxidation chemistry – although O_3 and NO_2 data were collected analysis is incomplete. Given the dilution inherent in 20^+ m s^{-1} winds, these represent very strong emissions.

TMOG 4 Aug. data showed the same narrow, NW rim CO_2 plume of similar strength (**Fig. 11C**). TMOG surveyed more slowly, including downwind of several craters (4WD road) and saw elevated SO_2 associated with several craters in the field. Anomalies were ~1/3 of July 15. The SO_2 plume on Death Valley floor clearly relates to the N. Death Valley Fault.

Searles-Manly-Ash Hill Fault System

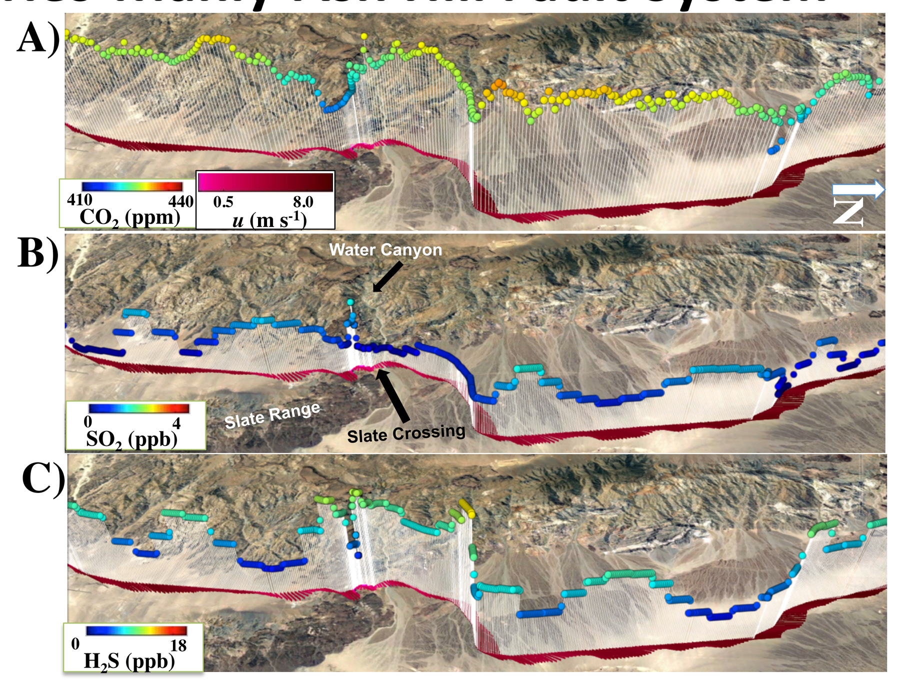

Fig. 12. AMOG winds, *u*, from Searles Valley through Slate Crossing into Panamint Valley for **A)** CO_2 **B)** SO_2, C) H_2S.

The Slate Crossing (Searles to Panamint Valleys) showed relatively clean air downwind of the air outflow from Water Canyon (**Fig. 12**). Elsewhere, elevated CO_2 was common in north Panamint Valley (unlike Death Valley), particularly for the strain transfer zone from the Manly Fault to the Ash Hill Fault zone and north in Panamint Valley along the Ash Hill Fault Zone. H_2S is significantly elevated here, too, roughly mirroring the CO_2 enhancement and depression - note, away from pollution sources, typical California H_2S is <1 ppb. Interestingly, SO_2 shows a small enhancement where H_2S is depressed, suggesting chemical conversion.

Aftershocks and Emissions

Between Ridgecrest and Searles Valley, under south-southwest winds (clean Mojave air) strong enhancement of both H_2S and CO_2 were observed immediately downwind of the major zone of aftershocks (**Fig. 13**). In addition, a strong H_2S plume was observed closer to Ridgecrest near a second aftershock zone. This suggests fault connectivity between the surface and extensive subterranean geothermal sources also exist close to Ridgecrest.

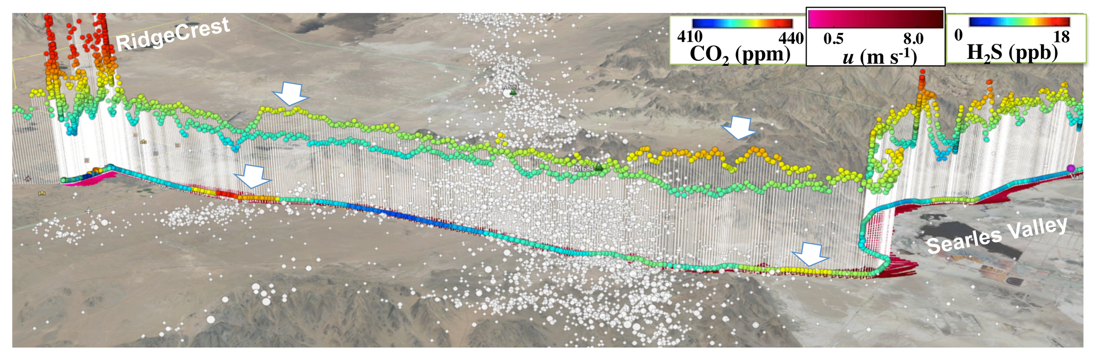

Fig. 13. Earthquakes and AMOG winds, *u*, from Ridgecrest to Searles Valley and **A)** CO_2 (plotted above ground) and H_2S (plotted on ground).