6-23-2017

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Accepted Manuscript

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PII: S0009-2541(17)30386-8
DOI: doi: [10.1016/j.chemgeo.2017.06.028](https://doi.org/10.1016/j.chemgeo.2017.06.028)
Reference: CHEMGE 18385
To appear in: *Chemical Geology*
Received date: 26 July 2016
Revised date: 19 June 2017
Accepted date: 21 June 2017

Please cite this article as: Y. Cui, D. Ouzounov, N. Hatzopoulos, K. Sun, Z. Zou, J. Du, Satellite observation of CH₄ and CO anomalies associated with the Wenchuan MS 8.0 and Lushan MS 7.0 earthquakes in China, *Chemical Geology* (2017), doi: [10.1016/j.chemgeo.2017.06.028](https://doi.org/10.1016/j.chemgeo.2017.06.028)

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Satellite observation of CH₄ and CO anomalies associated with the Wenchuan M_s 8.0 and Lushan M_s 7.0 earthquakes in China

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Abstract.

Spatial and temporal variations of total column of CH₄ and CO (TotCH₄ and TotCO) associated with the 12 May 2008 Wenchuan and 20 April 2013 Lushan earthquakes in western Sichuan, China were investigated using satellite data from AQUA AIRS in order to understand the lithospheric and atmospheric interactions during the seismic activity. The Wenchuan M_s 8.0 and Lushan M_s 7.0 earthquakes occurred in the Longmenshan fault zone. It was observed that large amounts of gases emitted from the earth's crust into the atmosphere before, during and after the earthquakes. The anomalies of TotCH₄ and TotCO occurred along the fault zone, and the peak values were found at the intersection areas where the crust stress approached the maximum. Furthermore, temporal anomalies of TotCH₄ and TotCO occurred during and after the Wenchuan earthquake, but 3 months before the Lushan earthquake. The anomalies related to the Lushan earthquake could be partially attributed to the Wenchuan earthquake because of the seismotectonic changes and fractures in the crust produced by the Wenchuan earthquake.

Keywords: methane, carbon monoxide, earthquake, hyper-spectrum, anomaly

1. Introduction

Large amounts of gases emitted from the active fault zones before, during and after great earthquakes were found by geochemical survey on the ground (Irwin & Barnes, 1980; King, 1986; Toutain & Baubron, 1999; Khilyuk et al., 2000; Famin et al., 2008). Identified emissions of carbon-bearing gases are generally originated from the crust and mantle in different geochemical processes. The variations of gas emission were caused by the action of local crust stress and seismic wave. Release mechanism of CO₂ and CH₄ was investigated experimentally, indicating the strong CO₂ and CH₄ emissions when friction was applied to marly-type rock (Martinelli & Plescia, 2005; Italiano et al., 2008). With the development of remote sensing technology, a relationship between the gas appearance and earthquake processes has been investigated using the hyper spectral sensors (Tronin, 2006; Ganguly, 2009; Singh et al., 2010; Cui et al., 2013). Meanwhile, the surface deformation and crustal

stress were studied using the GPS and seismic data (Wang et al., 2011; Wu et al., 2015).

The 12 May 2008 Wenchuan M_s 8.0 earthquake (epicenter at 31.0°N, 103.4°E) (Fig.1) occurred in the Longmenshan fault zone in western Sichuan Province, China, which produced about 300 km ruptures (Zhang et al., 2008; Fu et al., 2011). The main shock was followed by a sequence of powerful aftershocks (Table 1). Large amounts of CO₂, Rn, Hg (Zhou et al., 2015), CH₄ (Yue, 2013; Zheng et al., 2013) emitted from the Longmenshan fault zone due to the Wenchuan earthquake. The 20 April 2013 Lushan M_s 7.0 earthquake (30.3°N, 103.0°E) occurred in the southern part of Longmenshan fault zone. It was reported that two great earthquakes were located on the same high angle thrust fault, and distance between the epicenters of two main shocks was just 85 km (Liu et al., 2013). Therefore, these two events are good cases for us to investigate the relationship between geochemical anomalies of gases and the earthquakes. This paper aimed at investigating the variations of CH₄ and CO concentrations in the region around the epicenter before and after the Wenchuan M_s 8.0 and Lushan M_s 7.0 earthquakes.

Figure 1. Map of active faults and the locations of Wenchuan and Lushan earthquakes
Table 1. The parameters of Wenchuan earthquake and aftershocks of $M \geq 6.0$ and the Lushan earthquake and aftershocks of $M \geq 5.0$

Date (yyyy/mm/dd)	Lat (°N)	Lon (°E)	Depth (km)	Magnitude (M)	Date (yyyy/mm/dd)	Lat (°N)	Lon (°E)	Depth (km)	Magnitude (M)
2008/05/12	31.0	103.4	10	8.0	2013/04/20	30.3	103.0	17	7.0
2008/05/12	31.0	103.5	10	6.0	2013/04/20	30.3	102.9	10	5.4
2008/05/12	31.4	103.6	10	6.0	2013/04/20	30.2	102.9	15	5.4
2008/05/13	30.9	103.4	10	6.1	2013/04/21	30.4	103.1	27	5.4
2008/05/18	32.1	105.0	12.1	6.0	2013/04/21	30.3	103.0	17	5.4
2008/05/25	32.6	105.4	18	6.4					
2008/07/24	32.8	105.5	15	6.0					

2008/08/01	32.1	104.7	12.7	6.1
2008/08/05	32.8	105.5	10	6.1

Note: the depth of the main shock and aftershocks of Wenchuan earthquake are from the International Seismological Centre and others are from the China Seismic Information.

2. Data and Method

2.1. Data

The total column CH_4 (Tot CH_4) and total column CO (TotCO) data were obtained from the Atmospheric Infrared Sounder (AIRS) that was equipped on NASA's spacecraft Aqua and the products were derived with the Singular Value Decomposition (SVD) method using the 7.66 μm and 4.58–4.50 μm spectrum, respectively (Barnet et al., 2003; Susskind et al., 2003; McMillan et al., 2005; Xiong et al., 2008). AIRS dataset comes with a spatial resolution of roughly 45×45 km at nadir, and with a near global coverage twice for every day (Aumann et al., 2003; Hearty et al., 2015). The remote sensed product is mapped with a 1.0×1.0° resolution and it is time-averaged into an 8-day and monthly product. In this study, the Version 6 and level 3 standard gridded product of Tot CH_4 and TotCO in descending model (local night-time) were used, which are freely available from NASA's Goddard Earth Sciences Data and Information Services Center (<http://disc.sci.gsfc.nasa.gov/>).

2.2. Method

The anomalies were derived by the approach that was described as equation (1) and reported for defining the anomalies of thermal field (Tramutoli et al., 2001; Ouzounov et al., 2007). The anomaly represents the anomalous amplitude in a given region and within a predefined duration:

$$\text{Anomaly}(x, y, t) = [G(x, y, t) - G_{bac}(x, y, t)] / \sigma(x, y, t) \quad (1)$$

$$G_{bac}(x, y, t) = \sum_{i=1}^N G_i(x, y, t) / N \quad (2)$$

$$\sigma(x, y, t) = \text{sqrt} \left\{ \sum_{i=1}^N [G(x, y, t) - G_{bac}(x, y, t)]^2 / (N - 1) \right\} \quad (3)$$

Where $G(x, y, t)$ stands for the current gas value, $G_{bac}(x, y, t)$ for the computed mean from the background field, defined as a monthly mean value of gas $G(x, y, t)$ over an area with x, y coordinates for the t^{th} month of the N years. For this study N was defined as 10 for the years from 2003 to 2015 except for the years of 2008, 2009 and 2013 in order to eliminate the effect of the great earthquakes. $\sigma(x, y, t)$ is the standard deviation over the same region (x, y) and time (t) for a given gaseous component.

3. Results

The Eqs. 1 to 3 were applied to identify the spatial and temporal variations of atmospheric TotCH₄ and TotCO anomalies associated with the Wenchuan M_S 8.0 and Lushan M_S 7.0 earthquakes using AIRS data.

3.1. Characteristics of the spatial anomalous patterns

It was found that the anomalies of TotCH₄ (Fig.2, 4) and TotCO (Fig.3, 5) associated with the Wenchuan (Fig.2, 3) and Lushan (Fig.4, 5) earthquakes appeared along the NE trending Longmenshan fault and NW trending Xingjing-Mabian fault zones. The peak values were found at the intersection of the faults where the action of crustal stress was intense (Wu et al., 2015). The TotCH₄ and TotCO anomalies appeared from May 12 to 28 of 2008 during and after the occurrence of Wenchuan earthquake, but 3 months prior to the Lushan earthquake.

Figure 2. Spatial distributions of 8-day nighttime TotCH₄ anomaly from Feb. 14 to Jun. 05, 2008 related to the Wenchuan Earthquake. The TotCH₄ anomalies appeared along the fault zones, and the peak values appeared at the intersection of faults in May 12 - 20. (Black star stands for the epicenter, red '*' for the control site, red line for active fault, black line for province boundary, the same in the following diagrams)

Figure 3. Spatial distributions of 8-day nighttime TotCO anomalies from Feb. 14 to Jun. 05, 2008 related to the Wenchuan Earthquake. The TotCO anomalies appeared along the fault zones, and the peak values appeared at the intersection of faults in May 12 - 20.

Figure 4. Spatial distributions of 8-day nighttime TotCH₄ anomalies from Jan. 02 to Apr. 24, 2013 related to the Lushan Earthquake. The TotCH₄ anomalies appeared obviously along the fault zones near the epicenter from Jan. 02 to Feb. 03, and the maximum appeared at the intersection of faults in Feb. 27.

Figure 5. Spatial distributions of 8-day nighttime TotCO anomalies from Jan. 02 to Apr. 24, 2013 related to the Lushan Earthquake. The TotCO anomalies appeared obviously along the fault zones near the epicenter in Jan. 18 - 26, Feb. 19 and Apr. 16, and the peak values appeared at the intersection of faults in Jan. 02 and Apr. 16.

3.2. Characteristics of the temporal anomalous patterns

The temporal variations in the selected areas were analyzed in order to validate the relationship among the anomalies and the time of the major earthquakes. The anomalous site in the areas was account for the anomaly pixel with the maximum of anomalous values. A control site (Fig. 2) was a selected pixel without anomalous values far from the epicenter and the fault zones. The gaseous concentrations at those sites in 2008 and 2013 were compared for the Wenchuan earthquake (Fig.6) and for the Lushan earthquake (Fig.7), respectively. The values of TotCH₄ and TotCO over the control pixel were significantly lower than those over the selected location account for the maximum of anomaly in the same duration with exception of 23rd July to 1st August, 2008 when 3 earthquakes of magnitudes ≥ 6.0 occurred. The anomalies related to the Wenchuan earthquake appeared about one week before the main shock, but those related to the Lushan one appeared 3 months before the main shock (Fig.6 and 7).

The variations of gas concentrations could be driven by the processes of earthquake preparation. (1) In case of Wenchuan earthquake, pre-seismic TotCO anomaly of May 04 and co-seismic anomalies of TotCO and TotCH₄ on May 12 occurred over the anomaly pixel (Fig.6). The maximum of TotCH₄ and TotCO anomalies occurred on May 20, 2008, which resulted in the anomaly levels of 2.5 and 3.76 respectively, indicating a direct association with the Wenchuan earthquake (Fig.6, Table 2). Post-seismic anomalies of TotCH₄ and TotCO occurred over the control

pixel around on 1st Aug. (Fig.6) were probably caused by the big aftershocks. (2) For the Lushan earthquake, the anomalies of TotCH₄ and TotCO over the anomaly pixel appeared before and after the main shock, and the maximum of TotCH₄ and TotCO anomalies appeared on February 27 (53 days before the earthquake) and March 23, 2013 (28 days before the earthquake), of which the anomaly levels were 3.8 and 2.85, respectively (Fig.7, Table 2).

Figure 6. Temporal variations of 8-day TotCH₄ (top), TotCO (middle) associated with the Wenchuan earthquake over the anomaly pixel (near to the epicentral area, red vertical bars) and control pixel (far from the seismic activities, violet vertical bars). The time series of earthquakes of $M \geq 4.0$ in the study area in 2008 is shown at the bottom. Pre-seismic TotCO anomaly of May 04 and co-seismic TotCO and TotCH₄ anomalies of May 12 appeared over the anomaly pixel. Post-seismic type of TotCH₄ and TotCO anomalies appeared over the control pixel around 1st Aug. were likely related to the big aftershocks. Black vertical line stands for the time of the main shock.

Figure 7. Temporal variations of 8-day TotCH₄ (top) and TotCO (middle) associated with the Lushan earthquake over the anomaly pixel (red vertical bars, the same meaning in Fig. 6) and control site (violet vertical bars, the same meaning in Fig. 6). The time series of $M \geq 4.0$ earthquakes in the studying area in 2013 is shown at the bottom. The TotCH₄ and TotCO anomalies over the anomaly pixel appeared before and after the main shock.

Table 2. The parameters of TotCH₄ and TotCO anomalies associated with the Wenchuan and Lushan earthquakes

Earthquake	M_S	Pixel	Location		TotCH ₄			TotCO		
			Lon(°E)	Lat(°N)	Date (mm/dd/2008)	$G(10^{19})$	Max. anomaly	Date (mm/dd/2013)	$G(10^{18})$	Max. anomaly
Wenchuan	8.0	anomaly	102.5	30.5	05/20	2.71	2.50	05/20	1.54	3.76
		control	104.5	30.5	06/13	3.58	1.95	04/10	2.59	2.71
Lushan	7.0	anomaly	103.5	31.5	02/27	2.79	3.80	03/23	1.64	2.85
		control	104.5	30.5	02/19	3.70	1.57	03/31	2.43	0.99

Note: G unit is molecules/cm²

4. Discussion

The spatial (Fig.2 to 5) and temporal (Fig.6 to 7) variations of the TotCH₄ and TotCO anomalies were most likely caused by the geological processes and/or action of crustal stress in the lithosphere which resulted in the Wenchuan and Lushan earthquakes as well as the aftershocks. Large amounts of gases, such as CO₂, CO,

CH_4 , H_2 , N_2 , H_2O , H_2S , etc., remained within the deeper layers of the Earth. Since all these gases contained in geological formations at pressures higher than the atmospheric one, they tend to migrate upwards and pervade into the porosity of the fractured rock and sediments in shallower ground (Gold, 1979). A large amount of fractures were formed by enhancing action of the ground stress during pregnancy and occurrence of the earthquake. Additionally, the increase of ground stress favored gas emission (Martinelli & Plescia, 2005). Therefore, such processes resulted in more gaseous emissions from the fractures, which resulted in the anomalies of TotCH_4 and TotCO distributed along the seismic fault zones and the peak values appeared in the intersection area (Italiano et al., 2008). The anomalies of gases were intrinsically connected with the earthquakes and triggered by the seismic activities. However, gaseous anomaly can be affected by climate change and weather patterns, human activities, vegetation coverage and many other factors beyond seismic activities. The effects of background factors can be eliminated by calculation with Eqs. (1 to 3). Therefore, the identified anomalies of TotCH_4 and TotCO can be considered as an earthquake-related anomaly.

The variations of TotCH_4 and TotCO anomalies related to the Lushan earthquake were affected by the Wenchuan earthquake. The Longmenshan faults appeared to be in a locking status during an earthquake development. A deadlock segment could not bring deformation due to the elastic deformation limit before the occurrence of Wenchuan earthquake (Jiang et al., 2009; Wang et al., 2011; Wu et al., 2015). In this case, it was difficult to increase gas emission from underground because there were not too many paths available. As a result, the TotCH_4 and TotCO anomalies appeared shortly before the Wenchuan earthquake (Fig.2, 3). However, large amounts of fractures were caused by the Wenchuan earthquake and a sequence of aftershocks in the Longmenshan region, which eventually provided the paths for the gas emission. The gases escaped from the fractured rocks in the fault zones under the increased pressure so that the anomalies of TotCH_4 and TotCO were observed before the Lushan earthquake (Fig.4, 5). These anomalies occurred to be noticeable 3 months before the Lushan earthquake (Fig.4, 5) and with duration of a longer period comparing to the anomalies caused by the Wenchuan earthquake.

It is well known that CH_4 can be oxidized into CO or CO_2 under condition of higher oxygen fugacity (Thompson & Cicerone, 1986), as a result of this phenomenon CH_4 could be the main driver of CO . In case of the Wenchuan earthquake, the temporal variations of TotCH_4 and TotCO showed that higher value of CH_4 was followed by the higher value of CO in two stages: (1) before and during the main shock (Fig 6, May 4th and 12th, red vertical bars), and (2) During the aftershocks sequence in an area near the control pixel (Fig.6, violet vertical bars). In case of the Lushan earthquake, the trends of TotCO anomalies were smaller than those of the TotCH_4 anomalies, which might be controlled by the change of oxygen fugacity that was affected by the quantity of fractures (Fig.2-5).

5. Conclusions

In both cases of the Wenchuan and Lushan earthquakes, satellite data showed that the anomalies of TotCH₄ and TotCO appeared around the time of the main shocks. Due to the earth's geodynamic processes, large amounts of gases emitted from the earth's crust. This was probably connected with enhances of the degassing rate of the lithosphere, which could provide additional source for flux of gas emission near the major faults. The large change of gas flux created variety of gas anomalies in the atmosphere. A multi-year analysis of satellite observations indicated that the anomalies most likely to be related to the geodynamic processes of large earthquake pregnancy. This case study demonstrated that the anomalies of TotCH₄ and TotCO before, during and after the Wenchuan and Lushan earthquakes distributed along the fault zones, and the peak values appeared within the intersection area of faults. The variations of TotCH₄ and TotCO anomalies related to the 2013 Lushan earthquake were affected by the occurrence of the 2008 Wenchuan earthquake too. In both cases, anomaly level of CH₄ could lead to the CO anomalies. Our results suggest that continuous study of TotCH₄ and TotCO from satellite observations can be employed to investigate the lithosphere-atmosphere processes associated with the great earthquakes. Further, the relationship among TotCH₄ and TotCO and the great earthquakes should be statistically studied over China territory during the entire time period of AIRS satellite observations.

Acknowledgements. This work was supported by the National Natural Science Foundation of China (Rank No. 41403099, 41373059, 41573121 and 41303076) and Key Laboratory of Earthquake Prediction, CEA(Project No.2016IES010103). The authors would like to thank NASA for making available the AIRS dataset.

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