Nat. Hazards Earth Syst. Sci. Discuss., 1, 2439–2454, 2013
www.nat-hazards-earth-syst-sci-discuss.net/1/2439/2013/
doi:10.5194/nhessd-1-2439-2013

Natural Hazards and Earth System Sciences
Open Access
Discussions

Quasi-synchronous ionospheric and surface latent heat flux anomalies before the 2007 Pu'er earthquake in China

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Received: 12 April 2013 – Accepted: 15 May 2013 – Published: 29 May 2013

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Pre-earthquake ionospheric and thermal anomalies are two widely-reported short-term earthquake precursors. This paper attempts to examine the possible relationship between the ionospheric anomaly and the thermal anomaly related to the 2007 $M_s = 6.4$ Pu'er earthquake. The spatio-temporal statistical analyses of multi-years SLHF data from USA NCEP/NCAR Reanalysis Project reveal that local SLHF enhancements appeared 11, 10 and 7 days before the Pu'er earthquake, respectively. As contrasted to the formerly reported local ionospheric Ne enhancement 9 days before the shocking observed by DEMETER satellite, it is discovered that the SLHF and Ne anomalies are quasi-synchronous and have nice spatial correspondence with the epicentre and the local active faults. Based on current physical models presented, we suggest that the air ionization in Pu'er seismogenic process, possible resulted from radon leaking out and subsequent alpha particles emitting, and/or positive holes activating and recombining, is the common cause of the observed ionospheric and SLHF anomalies before the Pu'er earthquake. This is valuable for understanding the seismogenic coupling processes and for recognizing earthquake anomaly with multiple parameters from integrated Earth observation system.

1 Introduction

Over the past two decades, many researchers have carried out investigations on ionospheric and thermal anomalies in relation to seismic activity by using Earth observation system (EOS). On one hand, ionospheric disturbances caused by seismic activities have been observed by the Global Positioning System (GPS) and the DEMETER (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions) satellite (Liu et al., 2001; Parrot, 2012; He et al., 2012); On the other hand, abnormal variations of multiple thermal parameters provided by the developing Global Earth Observation System of System (GEOSS) have been reported frequently including thermal infrared radiation (TIR) (Qianget al., 1991; Tronin, 1996; Saraf and Choudhury, 2004; Tramutoli etal., 2005; Blackett et al., 2011), surface temperature (Qinet al., 2012a), outgoing long-wave radiation (Ouzounov et al., 2007) and surface latent heat flux (SLHF) (Dey and Singh, 2003; Cervone et al., 2006; Qin et al., 2009, 2011, 2012b). Those anomalies appeared several days to a few hours before the impending large earthquakes, and their spatial patterns have usually nice correspondence with the local active faults. Recently, Cervone et al. (2006) presented the first attempt to compare the abnormal variations of sub-ionospheric low frequency (LF) radio and SLHF before the $M_w = 8.3$ Tokachi-Oki earthquake, Japan, which showed a complementary behavior both in terms of temporal and spatial distribution. Meantime, Pulinets et al. (2006a) found synchronous ionospheric total electron content (TEC) and SLHF anomalies before the 2003 $M_w = 7.8$ Colima earthquake, Mexico.

According to the China Earthquake Network Centre (CENC, http://www.ceic.ac.cn/), a destructive shock of $M_s = 6.4$ occurred at 21:35 UTC on 2 June 2007 (Beijing Time: 2 June 2007, 05:35 LT) in Pu'er region, Yunnan Province, southwest China. The epicentre located at 23.1° N, 101.1° E, and the focal depth was 10 km about. The causative fault was the Wuliangshan Fault (F1 in Fig. 4) which strike in NNW–SSE direction and was featured by right-lateral movement. A large number of houses and buildings got collapsed, with 3 people killed, more than 300 people injured, and 536 000 people affected (Zhang et al., 2009). Abnormal variations of ionospheric electromagnetic parameters possibly related to this earthquake were reported (Zhu et al., 2008; Ouyang, 2008a; Ouyang et al., 2008b). In this paper, multi-years SLHF data from USA NCEP/NCAR Reanalysis Project are employed to detect possible thermal anomaly before the earthquake. Then, the relationships between the ionospheric anomaly and the SLHF anomaly are examined, and the possible mechanisms are also discussed.

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2 Ionospheric electron density anomaly

Soon after the 2007 Pu'er earthquake, the team led by X. H. Shen in the Institute of Earthquake Science of China Earthquake Administration (CEA), had investigated the electromagnetic parameters including electron density (Ne), electron temperature (Te), ion density (Ni), spectrogram of electric field and spectrogram of magnetic field measured by DEMETER, which is a low-altitude satellite launched in June 2004 by France Centre National d'Etudes Spatiales (CNES) for seismo-ionospheric studies. They analysed the quicklook frames of the orbits passed through the region within 1888 km from the epicentre (referring to the distance between the satellite and the epicentre) before the earthquake (Zhu et al., 2008; Ouyang, 2008a; Ouyang et al., 2008b). First, the orbits when solar and geomagnetic activities were relatively strong were discarded. Secondly, the orbits recorded synchronous perturbations in more than three electromagnetic parameters were identified as candidate anomalies. The results showed that two candidate anomalies with synchronous perturbations of Ne, Te and spectrogram of electric field, were recorded by the orbit 15440-1 on 24 May 2007 and the orbit 15572-1 on 2 June 2007 (Ouyang, 2008a), and the abnormal variations of Ne were more obvious compared with the other parameters (Ouyang et al., 2008b). The orbit of DEMETER satellite is a nearly Sun-synchronous circular orbit (10:30–22:30 LT), with a revisited period of about 16 days. The revisited orbits record the data over the same place almost at the same local time. Hence, the Ne data on the orbits 15440-1 and 15572-1 with their revisited orbits were compared (Ouyang, 2008a; Ouyang et al., 2008b). The results showed that the general variation curves of zonal Ne in contiguous orbits during the period from April to June 2007 were similar, having several peaks near the equator, 20° N, 40° N and 30° S, respectively, and several jumps in circumpolar latitudes, especially for the orbit 15440-1 on 24 May 2007 (Fig. 1). It is interesting to note that the data of orbit 15440-1 is obviously greater than the other revisited orbits in the range of 18° N–38° N (dotted box in Fig. 1), which falls within the scope of possible ionospheric disturbance area related to the Pu'er earthquake. Here, we further focus on the analysis of the revisited orbits of 15440-1 in a small area with 3° to the epicentre at north and south (20° N–26° N, red box in Fig. 2a), supported with more extended data, from 21 May 2006 to 27 July 2007. The three-dimensional surface (Fig. 2b) plotted using the Matlab software, shows that the Ne data on 24 May 2007 is the the maximum of the whole period. Combining the reports by Zhu et al. (2008), Ouyang (2008a) and Ouyang et al. (2008b) with our analysis, we suggest that the local ionospheric Ne enhancement on 24 May 2007 might have been related to the Pu'er earthquake.

3 Surface latent heat flux anomaly

The SLHF is used to describe the flux of heat discharge from the Earth's surface to the atmosphere that is associated with the evaporation and/or transpiration of water at the surface and the subsequent condensation of water vapor in the troposphere. Traditionally, SLHF has been calculated from bulk formulas which employ ship or ground measurements. The availability and accuracy of station-derived fluxes, however, is relatively limited, because of the low spatio-temporal resolution of point observations. By assimilating multi-source observations from land surface, ship, rawinsonde, pibal, aircraft, satellite, and other sensors, USA NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) Reanalysis Project successively provides various fluxes and other atmospheric parameters, at a T62 Gaussian grid with 192 × 94 pixels (94 lines of latitude from 88.542° N to 88.542° S, with a regular 1.875° longitudinal spacing from 0° E to 358.125° E). The evolution of the global observing system in NCEP/NCAR Reanalysis Project is officially divided into three major phases: the "early" period from the 1940s to the International Geophysical Year (IGY) in 1957; the "modern rawinsonde network" from 1958 to 1978; and the "modern satellite era" from 1979 to the present. The accuracy of SLHF is 10–30 $\mathrm{W\,m^{-2}}$ after 1979 (Dey and Singh, 2003).

The occurrence of abnormal SLHF peaks several days to several weeks before some coastal earthquakes was first reported by Dey and Singh (2003). Then, SLHF anomalies occurred before inland earthquakes were also revealed (Qin et al., 2009). Referring to the time of the appearance of SLHF anomalies in previous studies (Dey and Singh, 2003; Cervone et al., 2006; Qin et al., 2009, 2011, 2012b) and the time of the Pu'er earthquake, we investigated the daily SLHF data from NCEP/NCAR Reanalysis Project in May and June of 1979–2012. First, we analysed the long time series of SLHF data on the epicenter pixel (23.8092° N, 101.15° E, white rectangular in Fig. 4). For the comparison of the data for 2007 with historical data, the mean (μ), standard deviation (σ), maximum and minimum were calculated using the multi-years (1979–2012) data on the same day. Secondly, we analysed the spatial distributions of the changed SLHF (ΔSLHF). The spatial distribution of daily SLHF is affected by many factors such as geography latitude, regional terrain, climate seasons, and weather conditions. We subtracted the daily SLHF from the multi-years means, representing a normal background, to get ΔSLHF:

$$\Delta\mathrm{SLHF} = \mathrm{SLHF}_{\mathrm{EQ}} - \frac{1}{n}\sum_{i=1}^{n} \mathrm{SLHF}_i \tag{1}$$

where $\mathrm{SLHF}_{\mathrm{EQ}}$ is the daily SLHF of 2007; SLHF_i is the corresponding daily SLHF for 1979–2012.

Although SLHF is affected by many factors, statistically, it will be limited to the fluctuations within a certain range. However, there is an obvious peak beyond $\mu + 2\sigma$ on 23 May 2007, which shows statistical significance in the time series of SLHF (Fig. 3). Also, it is the maximum of 23 May 1979–2012. After the statistical processing, we plotted using the Generic Mapping Tools software the spatio-temporal evolution images of ΔSLHF (Fig. 4), with the epicenters of the $M \geq 4$ earthquakes occurred in the study area from 1 May to 30 June 2007. A local anomaly with high amplitude of around 80 W m^{-2} is revealed northeast to the epicenter on 22 May (Fig. 4a). On 23 May, another local anomaly appears at the middle of the Wuliangshan fault (F1), north to the epicenter (Fig. 4b). After two days of quiet, a thrid one appears again on 26 May, covering a larger area around the epicenter, which is confined by the Wuliangshan Fault

(F1) and the Honghe Fault (F2). The amplitudes of all the three ones are much larger than the specified accuracy ($30\,\mathrm{W\,m^{-2}}$) of the SLHF data from NCEP/NCAR Reanalysis. After the Pu'er earthquake on 2 June, a smaller earthquake ($M_S = 4.3$) occurs at 24° N, 103.4° E near the anomaly in Fig. 4a at 12:16 UTC on 9 June. The spatial patterns of the SLHF anomalies and the epicenter location would had shown us a possible geo-association with the seismogenic process.

4 Discussion and conclusion

Currently, the mechanisms of pre-earthquake ionospheric and thermal anomalies are not yet well understood. Some ones suggested interpreting these different short-term earthquake precursors observed in atmosphere and in ionosphere using a unified Lithosphere-Atmosphere-Ionosphere (LAI) coupling mode (Pulinets et al., 2011). To emphasize the great influence of Earth coversphere (including surface sand, soil, water body, and vegetation, which is quite different from the crustal rock in lithosphere), Wu et al. (2012) further proposed the Lithosphere-Coversphere-Atmosphere-Ionosphere (LCAI) coupling mode. The key idea in LAI/LCAI coupling mode is the air ionization in the seismogenic process whose role lies in two-folds. In one hand, it produces an additional electric field, penetrating into the ionosphere and causing the large scale electron density perturbation; in the other hand, it releases simultaneously latent heat due to water condensation on the new formed ions.

Air ionization refers to the process whereby air molecules turn into electrically charged ions by gaining or losing electrons. This can take place as a result of natural processes such as thunderstorms and sunlight, also severalpossible physical processes linked to seismic activity. Pulinets et al. (2006b) considered that enhanced radon emission from the active tectonic faults is the primary source of air ionization in the case of earthquakes. As local radon-rich crustal rocks are stressed and get fractured, the embodied radon will leak out through rock cracks and emit alpha particles during radon decay process. Using the radon data from 23 observation stations in Yunnan, some researchers (He et al., 1999) found a better agreement between the abnormal variations of radon concentration in ground water and the local seismicity. This proves indirectly that radon is rich in the crustal rocks of the study area of the Pu'er earthquake. In addition, the charge generation and propagation with positive holes (P-holes), proposed by Freund and his colleagues (Freund, 2009; Freund et al., 2011), is also one of the possible processes leading to air ionization in the seismogenic process. P-holes are electronic charge carriers, pre-exist in essentially all igneous and high-grade metamorphic minerals (which make up a major portion of the Earth's crust), and albeit in a dormant state as peroxy links. P-holes are highly mobile, and can be activated by tectonic stresses and move to rocksurface (Freund, 2009; Freund et al., 2011). The activation and movement of P-holes under seismogenious stress will build up very high electric fields on the Earth's surface, which will lead to local air ionization at the ground-air interface.

In this paper, we attempt to examine the possible spatio-temporal relationships between the ionospheric anomaly and the thermal anomaly related to the Pu'er earthquake, rather than to reveal exactly the mechanism of the anomalies. We found, from the analysis of the DEMETER satellite data and the NCEP/NCAR Reanalysis Project data, not only that local ionospheric Ne enhancement occured on 24 May 2007, i.e., 9 day before the main shocking, but also that local SLHF enhancements occured on 22, 23 and 26 May 2007, i.e., 11, 10 and 7 days before the main shocking, respectively. The anomalies are not only quasi-synchronous but also in nice spatial relations, i.e., geo-adjacency, with the epicenter and the local active faults. In particular, the abnormal SLHF on 26 May 2007, 7 days before the main shocking, covered the epicenters of coming shocks of $M \geq 4$ perfectly (Fig. 4e). This could be of precautionary significance. Their temporal quasi-synchronism and spatial adjacency obey well with the data mining rules or diagnosis criterions, for earthquake anomaly recognition (EAR) with multiple parameters defined by Wu et al. (2012), and can be explained by the air ionization theory (Fig. 5). Although it is impossible to expect this phenomenon in all other seismogenic processes, we suggest that the investigation to the spatio-temporal features of and the relations between the ionospheric Ne and thermal SLHF anomalies is of great importance for understanding better the complex LAI/LCAI coupling processes associated with the preparation of medium-to-large earthquakes, and for providing an gradually improved scheme of seismic forecasting in the future.

Acknowledgements. This work was jointly supported by the National Basic Research Program (973 Program, Grant No. 2011CB707102), and the Project Funded by the Priority Academic Program Development (PAPD) of Jiangsu Higher Education Institutions. We acknowledge the France CNES and USA NCEP/NCAR Reanalysis Project for providing data used in this study.

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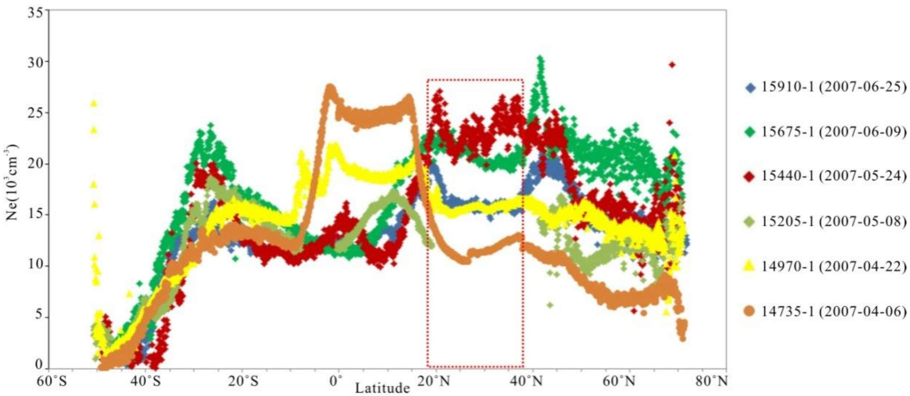

Fig. 1. Variation curves of zonal Ne in contiguous orbits during the period from April to June 2007.

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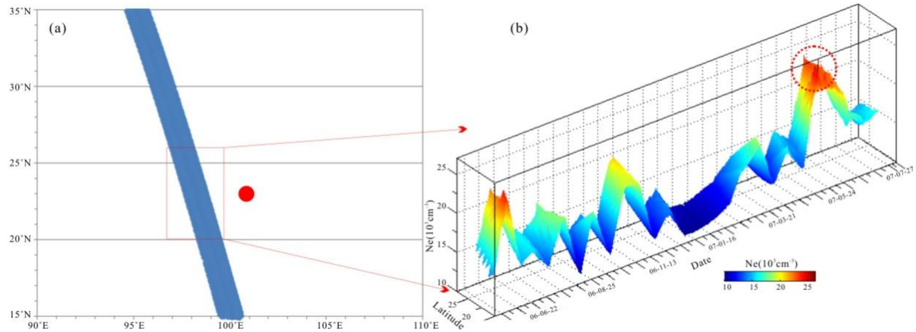

Fig. 2. (a) Trace of the revisited orbits of the orbit 15440-1 from 21 May 2006 to 27 July 2007, the red dot indicates the epicenter of the Pu'er earthquake; **(b)** Surface plot of the Ne data in the range of 20° N–26° N from 21 May 2006 to 27 July 2007, The dashed circle indicates a possible anomaly, which is the the maximum of the whole period.

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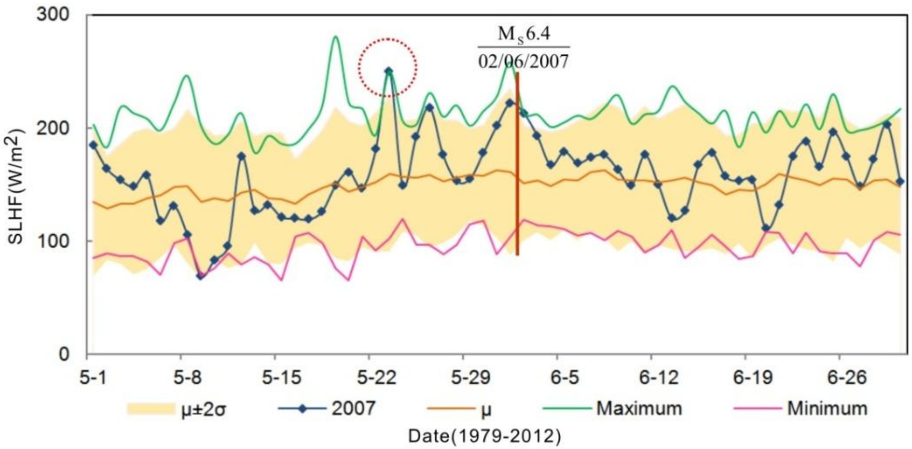

Fig. 3. Time series of SLHF on the epicenter pixel (23.8092° N, 101.15° E), the dashed circle indicates a possible anomaly beyond $\mu + 2\sigma$ on 23 May 2007, which is also the maximum of 23 May 1979–2012.

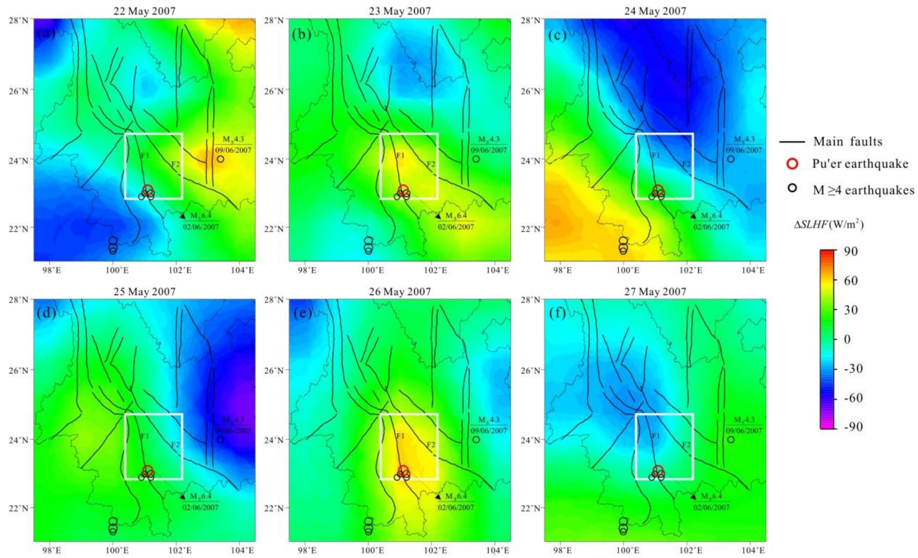

Fig. 4. Spatio-temporal evolution of the changed SLHF (ΔSLHF); the red circle indicates the epicenter of the Pu'er Ms 6.4 earthquake, the black circles indicate the epicenters of the other $M \geq 4$ earthquakes occurred in the study area from 1 May to 30 June 2007; F1 and F2 indicate Wuliangshan Fault and Honghe Fault, respectively; the white rectangles indicate the epicenter pixel (23.8092° N, 101.15° E) for the time series analysis.

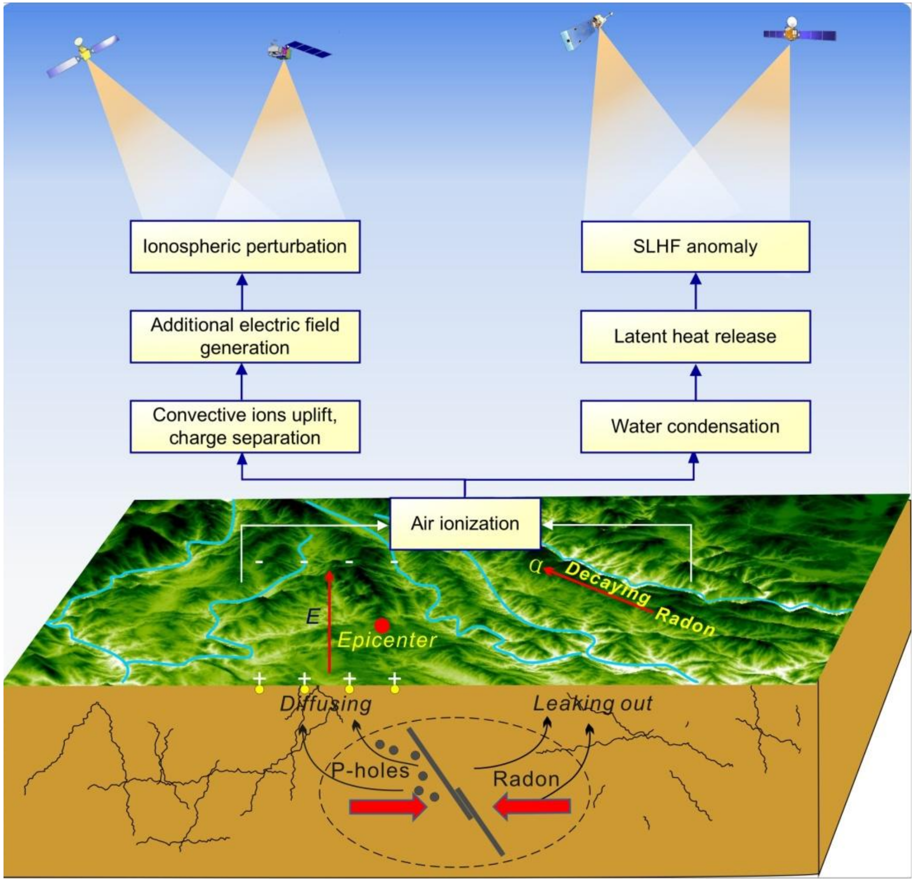

Fig. 5. Possible mechanisms, might had functioned bothly, gave rise to the quasi-synchronous ionospheric and SLHF anomalies before the Pu'er earthquake, based on current physical models suggested by Pulinets et al. (2006), Pulinets and Ozounov (2011), Freund et al. (2009), and Freund (2011).

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