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On the reported ionospheric precursor of the 1999 Hector Mine, California earthquake

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[1] Using Global Positioning System (GPS) data from sites near the 16 Oct. 1999 Hector Mine, California earthquake, Pulinets et al. (2007) identified anomalous changes in the ionospheric total electron content (TEC) starting one week prior to the earthquake. Pulinets (2007) suggested that precursory phenomena of this type could be useful for predicting earthquakes. On the other hand, and in a separate analysis, Afraimovich et al. (2004) concluded that TEC variations near the epicenter were controlled by solar and geomagnetic activity that were unrelated to the earthquake. In an investigation of these very different results, we examine TEC time series of long duration from GPS stations near and far from the epicenter of the Hector Mine earthquake, and long before and long after the earthquake. While we can reproduce the essential time series results of Pulinets et al., we find that the signal they identified as being anomalous is not actually anomalous. Instead, it is just part of normal global-scale TEC variation. We conclude that the TEC anomaly reported by Pulinets et al. is unrelated to the Hector Mine earthquake. **Citation:** Thomas, J. N., J. J. Love, A. Komjathy, O. P. Verkhoglyadova, M. Butala, and N. Rivera (2012), On the reported ionospheric precursor of the 1999 Hector Mine, California earthquake, *Geophys. Res. Lett.*, *39*, L06302, doi:10.1029/2012GL051022.

1. Introduction

[2] The moment magnitude (M_w) 7.1 Hector Mine, California earthquake of 16 Oct. 1999, 09:46 UTC occurred approximately 55 km northwest of Twentynine Palms and 190 km northeast from Los Angeles in a remote region of the Mojave Desert (34.6°N, 116.3°W) at a depth of 5 ± 4 km. Fault rupture of about 3.8 m occurred for 45 km along the Lavic Lake fault [*Rymer et al.*, 2002; *Hauksson et al.*, 2002]. Shaking was reported in southern California, western Arizona, southern Nevada, and northern Baja California. There were no fatalities and only minimal damage. Similar to the M_w 7.3 Landers earthquake of 1992, the Hector Mine earthquake was associated with fault rupture within an 80-km wide deformation region known as the eastern California shear zone.

[3] In a report that was prominently featured on the cover of the *EOS* newsletter of the American Geophysical Union, *Pulinets* [2007] claimed that the Hector Mine earthquake might have been predicted by monitoring changes in the ionosphere in a broad geographic area above the fault zone. Using Global Positioning System (GPS) data, *Pulinets et al.* [2007] and *Pulinets* [2007] reported anomalous changes in ionospheric total electron content (TEC) starting about one week prior to the earthquake. They reported that the identified anomaly is distinct from normal TEC variation driven by solar-terrestrial interaction and TEC signals that are known to follow after an earthquake [e.g., *Calais and Minster*, 1995; *Otsuka et al.*, 2006]. In contrast to *Pulinets et al.* [2007], other investigations of the Hector Mine earthquake have not found anomalous precursory signals. Using different analysis techniques, *Afraimovich et al.* [2004] concluded that the TEC increase identified before the earthquake occurrence was normal variation that was unrelated to the earthquake. More generally, and concerning other data types, *Mellors et al.* [2002] observed no aseismic fault slip on the Lavic Lake fault or on adjacent faults. *Karakelian et al.* [2002] found no association between ultra low-frequency (ULF, 0.01 – 10 Hz) electromagnetic fields and aftershock activity. *Dautermann et al.* [2007] found no statistically significant correlation, temporally or spatially, between TEC perturbations and 79 earthquakes in Southern California during 2004–2005.

[4] Despite these contradictory results, the work of *Pulinets et al.* [2007] remains influential in the subject of earthquake prediction. It and other similar reports have, for example, motivated (1) the development of physical theories to explain precursory processes [*Freund et al.*, 2009; *Pulinets*, 2009], (2) the study of other earthquakes for similar precursory signals [*Liu et al.*, 2009; *Pulinets and Tsybulya*, 2010; *Pulinets et al.*, 2011; *Heki*, 2011], and (3) coordinated ground and space-based measurements for possible earthquake precursors [*Bhattacharya et al.*, 2009; *Pulinets*, 2009]. In recognition of the importance of earthquake prediction, we choose to examine the results of *Pulinets et al.* [2007]. Our approach is similar to that used by *Thomas et al.* [2009a, 2009b] and *Masci* [2010, 2011a, 2011b] in their examinations of reported electromagnetic earthquake precursors.

2. TEC Time Series

[5] The phases of GPS satellite signals (1575.42 and 1227.60 MHz carrier frequencies), transmitted to ground stations through the ionosphere, are affected by the path-integrated electron density known as slant TEC (measured in TEC units, where 1 TECU = 10^{16} electrons/m²). We

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Table 1. The 15 GPS Stations Used to Calculate TEC Sorted by Distance From Hector Mine Earthquake Epicenter

Station Number	Station Name	Geodetic Longitude (deg)	Geodetic Latitude (deg)	Magnetic Latitude (deg)	Distance From Earthquake (km)
1	gol2	−116.88	35.42	41.91	107
2	sio3	−117.25	32.86	39.20	214
3	cat1	−118.48	33.44	39.55	241
4	scip	−118.48	32.91	39.00	278
5	fern	−112.45	35.34	42.74	357
6	harv	−120.68	34.46	40.14	405
7	echo	−114.26	37.91	45.01	410
8	casa	−118.89	37.64	43.77	412
9	cosa	−111.88	33.56	41.02	420
10	fred	−112.49	36.98	44.42	431
11	farb	−123.00	37.69	42.95	695
12	pie1	−118.11	34.30	42.53	748
13	azcn	−107.91	36.83	45.17	794
14	flin	−101.97	54.72	64.18	2496
15	sch2	−66.83	54.83	63.92	4383

examine the vertical TEC (hereafter TEC), which is the integrated electron density in a vertical column of the ionosphere above each station. This is derived from slant TEC with the JPL Global Ionosphere Map (GIM) software [*Mannucci et al.*, 1998, 2004; *Komjathy et al.*, 2005]. We use TEC time series derived from 30-sec GPS data recorded at the same 13 stations that were used by *Pulinets et al.* [2007, Figure 5] and which they assert provide coverage of the Hector Mine earthquake "preparation zone" within 1200 km of the earthquake epicenter. For controlled comparison, we also use data from two stations (flin and sch2) that are located in Canada very far from the earthquake region (2496 km and 4383 km, respectively). The 15 stations used are listed in Table 1. The duration of each TEC time series used here is approximately 3 months (26 Aug. – 6 Dec. 1999), considerably longer than the 1-month period of time considered by *Pulinets et al.* [2007, Figure 6].

[6] We follow the data processing procedures of *Pulinets et al.* [2007]. Redundant TEC values from multiple and simultaneous GPS satellite transmissions are removed by choosing the TEC values with the lowest measurement uncertainty for a given epoch. The median measurement uncertainty of these non-redundant time series is about 0.12 TECU and has a small standard deviation (±0.015 TECU) from station to station. We calculate the 10-min minimum-to-maximum range for each TEC time series, and then calculate what Pulinets et al. called the variability index ΔTEC, defined as the 10-min minimum-to-maximum range for TEC time series among a set

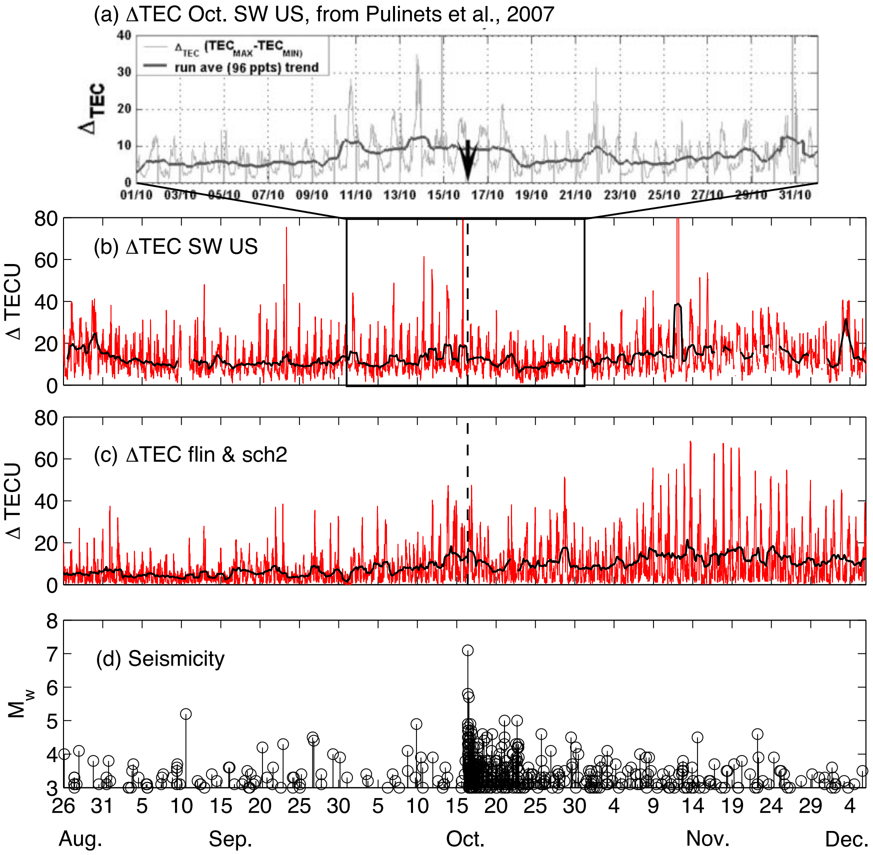

Figure 1. (a) Ionospheric vertical total electron content (TEC) for Oct., 1999 reproduced from *Pulinets et al.* [2007, Figure 6, Courtesy of Advances in Space Research]: 10-min ΔTEC and 1-day running average for the set of GPS stations 1–13 in Table 1. (b, c, d) TEC and earthquake activity for 26 Aug. – 6 Dec. 1999: (b) 10-min ΔTEC (red) and 1-day running average (black) for the set of GPS stations 1–13 in Table 1. Oct. ΔTEC are within the rectangle. (c) shows 10-min ΔTEC (red) and 1-day running average (black) for the set of two stations flin and sch2. (d) magnitude (M_w) of earthquakes that occurred within 1200 km of the Hector Mine earthquake epicenter (black circles). Only $M_w > 3$ are included. The Hector Mine earthquake and subsequent aftershocks are seen starting on 16 Oct. The units for the TEC are known as TEC units (TECU), where 1 TECU = 10^{16} electrons/m².

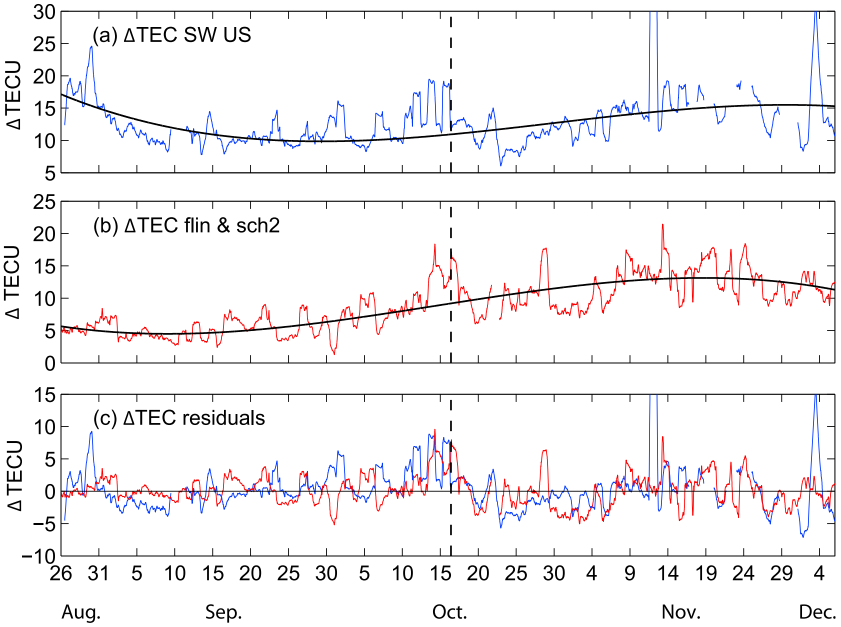

Figure 2. TEC for 26 Aug. – 6 Dec. 1999: (a) 1-day running average ΔTEC (blue, same as in Figure 1b) and cubic least-squares fit curve (black) for the set of GPS stations 1–13 in Table 1. (b) 1-day running average ΔTEC (red, same as in Figure 1c) and cubic least-squares fit curve (black) for the set of two stations flin and sch2. (c) Residuals of cubic least-squares fit curves for GPS stations 1–13 (blue) and stations flin and sch2 (red).

of GPS stations. We calculated ΔTEC for the 13 stations in the earthquake "preparation zone". We also calculate ΔTEC for the two stations (flin and sch2) that are far from the epicenter.

[7] To examine the ΔTEC time series in the broad context of seismicity in Southern California and Western North America, where earthquakes of small magnitude occur very frequently, we acquired a listing from the USGS National Earthquake Information Center of earthquakes having moment magnitude (M_w) greater than 3 that occurred within the Hector Mine earthquake "preparation zone" during 26 Aug. – 6 Dec. 1999.

3. Results

[8] It is important to recognize that we are able to reproduce the main TEC time series results of *Pulinets et al.* [2007] over the limited duration of time that they considered (the month of October). Figure 1b shows the 10-min ΔTEC time series (red curve) for stations in the southwest US, along with the 1-day running average ΔTEC (black curve), centered on the time of the Hector Mine earthquake. Compare our Figure 1b with *Pulinets et al.* [2007, Figure 6], reproduced here in our Figure 1a, where they also use a 1-day running average. In our analysis, ΔTEC increased on about 10 Oct. until just prior to the earthquake on 16 Oct. As shown in our Figure 1a, Pulinets et al. reported a similar increase that started on about 10 Oct., but ended on 18 Oct., a few days later than our processed observations. The magnitudes of the ΔTEC values (baseline near 12 TECU) in our analysis are slightly greater than those reported by Pulinets et al. (baseline near 8 TECU), which is not of consequence for our discussion here.

[9] Where we differ from *Pulinets et al.* [2007] is in the interpretation of the TEC time series. In contrast to their presentation, ours gives a broader panoramic view of the ΔTEC time series. From this, we can see ΔTEC variation long before and long after the Hector Mine earthquake that is greater than or equal to the anomaly identified by Pulinets et al. For instance, during 26–31 Aug. and 12–16 Nov. we see ΔTEC (Figure 1b) increases similar in magnitude and duration to the increase that occurred prior to the earthquake. Other signals having amplitudes similar to the seemingly anomalous signal identified by Pulinets et al. are apparently part of normal TEC variation. That these are independent of seismicity can be seen from Figure 1d where we show the moment magnitude (M_w) of earthquakes that occurred within the vicinity of the Hector Mine earthquake epicenter (black circles). The main Hector Mine earthquake shock and subsequent aftershocks can be seen starting on 16 Oct. In examining Figures 1b and 1d, there appears to be no clear relationship between ΔTEC and the earthquake activity in the region.

[10] To investigate whether the increase in ΔTEC on 10–16 Oct. was local to the earthquake, we next examine ΔTEC calculated from a set of two stations: flin and sch2 (2496 km and 4383 km from the earthquake, respectively). In Figure 1c we present the 10-min ΔTEC (red) and 1-day running average (black) for these two stations. Although Figure 1c includes only stations flin and sch2 that are far from the earthquake, Figures 1b and 1c do show some agreement, especially for about 4 days prior to the earthquake where both show enhanced ΔTEC.

[11] To better compare ΔTEC from stations near the earthquake with ΔTEC from distant stations, we need to remove longer-term ΔTEC trends from the time series. In Figures 2a and 2b, we find the cubic least-squares fit (black curve) to the 1-day running average ΔTEC for (a) the 13 southwest US stations and (b) stations flin and sch2. These cubic fit curves characterize the longer-term (3-month) trend of the ΔTEC time series. In Figure 2c we show the residuals

of these cubic fit curves, which are the ΔTEC time series with the longer-term trends removed. Both residual ΔTEC time series show enhancement prior to the earthquake and at other times within the 3-month period – evidence for a global mechanism likely related to solar-terrestrial interaction. We should point out that some variations are not well-correlated between the two residual time series, but might still be related to solar-terrestrial interaction. We do not, in general, expect a good correlation between these ΔTEC time series [see, e.g., *Tsurutani et al.*, 2008]. Moreover, the ΔTEC index of *Pulinets et al.* [2007] was not designed to measure solar-terrestrial interaction. But the lack of a tidy correlation does not, therefore, mean that it is related to earthquakes. In summary, the observations presented in Figures 1 and 2 show that global TEC variations occurred prior to the earthquake and at other times during the 3-month period.

[12] *Afraimovich et al.* [2004] analyzed TEC time series derived from 125 GPS stations in the southwest US (including stations 1–13 in Table 1 examined here) for a few days prior to and after the Hector Mine earthquake. Their processing techniques were different from those used here and by *Pulinets et al.* [2007], namely, they band-pass filtered the TEC time series derived from individual stations for periods of 32–129 min, 10–25 min, and 2–10 min, and then averaged these variations over all stations. Much like the increase in ΔTEC found in our analysis, *Afraimovich et al.* [2004, Figures 3 and 4] observed an increase in 32–129 min TEC variations during 13–16 Oct. Suggesting solar-terrestrial drivers, they found that these TEC variations agree well with the horizontal geomagnetic field measured at the USGS Geomagnetic Observatory in Fresno, CA (394 km from the earthquake epicenter) and the K_p index, a global index of geomagnetic activity [see *Afraimovich et al.*, 2004, Figures 4 and 7]. While we do note that ΔTEC has a tight correlation with other solar terrestrial activity indices, we also point out that ΔTEC is not related to localized seismic activity.

4. Conclusions

[13] We find that the signal identified by *Pulinets et al.* [2007] as being anomalous and possibly related to the Hector Mine earthquake was not actually particularly anomalous. Similar signals occurred long before and long after the earthquake, and the specific signal of *Pulinets et al.* [2007] as precursory to the Hector Mine earthquake was actually global. Our results can be viewed in the wider context of earthquake prediction, a subject that remains enormously controversial [*Jordan*, 2006]. Moreover, some well-cited reports of magnetic precursory changes prior to large earthquakes have been shown to be due to instrument failure or global, solar-driven variability [*Thomas et al.*, 2009a, 2009b; *Masci*, 2010, 2011a, 2011b]. Those works, and the results presented here for the ionospheric precursor result of *Pulinets et al.* [2007], demonstrate the need for controversial scientific claims to be scrutinized through independent hypothesis testing and the communication of results between scientific peers.

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References

Afraimovich, E. L., E. I. Astafieva, M. B. Gokhberg, V. M. Lapshin, V. E. Permyakova, G. M. Steblov, and S. L. Shalimov (2004), Variations of the total electron content in the ionosphere from GPS data recorded during the Hector Mine earthquake of October 16, 1999, California, *Russ. J. Earth Sci.*, *6*, 339–354, doi:10.2205/2004ES000155.

Bhattacharya, S., S. Sarkar, A. K. Gwal, and M. Parrot (2009), Electric and magnetic field perturbations recorded by DEMETER satellite before events of the 17th July 2006 *M* 7.7 earthquake in Indonesia, *J. Asian Earth Sci.*, *34*, 634–644, doi:10.1016/j.jseaes.2008.08.010.

Calais, E., and J. B. Minster (1995), GPS detection of ionospheric perturbations following the January 17, 1994, Northridge earthquake, *Geophys. Res. Lett.*, *22*, 1045–1048, doi:10.1029/95GL00168.

Dautermann, T., E. Calais, J. Haase, and J. Garrison (2007), Investigation of ionospheric electron content variations before earthquakes in southern California, 2003–2004, *J. Geophys. Res.*, *112*, B02106, doi:10.1029/2006JB004447.

Freund, F. T., I. G. Kulahci, G. Cyr, J. Ling, M. Winnick, J. Tregloan-Reed, and M. M. Freund (2009), Air ionization at rock surfaces and pre-earthquake signals, *J. Atmos. Sol. Terr. Phys.*, *71*, 1824–1834, doi:10.1016/j.jastp.2009.07.013.

Hauksson, E., L. M. Jones, and K. Hutton (2002), The 1999 M_w 7.1 Hector Mine, California, earthquake sequence: Complex conjugate strike-slip faulting, *Bull. Seismol. Soc. Am.*, *92*, 1154–1170, doi:10.1785/0120000920.

Heki, K. (2011), Ionospheric electron enhancement preceding the 2011 Tohoku-Oki earthquake, *Geophys. Res. Lett.*, *38*, L17312, doi:10.1029/2011GL047908.

Jordan, T. H. (2006), Earthquake predictability, brick by brick, *Seismol. Res. Lett.*, *77*, 3–6, doi:10.1785/gssrl.77.1.3.

Karakelian, D., G. C. Beroza, S. L. Klemperer, and A. C. Fraser-Smith (2002), Analysis of ultralow-frequency electromagnetic field measurements associated with the 1999 *M* 7.1 Hector Mine, California, earthquake sequence, *Bull. Seismol. Soc. Am.*, *92*, 1513–1524, doi:10.1785/0120000919.

Komjathy, A., L. Sparks, B. Wilson, and A. J. Mannucci (2005), Automated daily processing of more than 1000 ground-based GPS receivers to study intense ionospheric storms, *Radio Sci.*, *40*, RS6006, doi:10.1029/2005RS003279.

Liu, J. Y., et al. (2009), Seismoionospheric GPS total electron content anomalies observed before the 12 May 2008 M_w7.9 Wenchuan earthquake, *J. Geophys. Res.*, *114*, A04320, doi:10.1029/2008JA013698.

Mannucci, A., B. Wilson, D. Yuan, C. Ho, U. Lindqwister, and T. Runge (1998), A global mapping technique for GPS-derived ionospheric total electron content measurements, *Radio Sci.*, *33*(3), 565–582, doi:10.1029/97RS02707.

Mannucci, A. J., et al. (2004), GPS-based remote sensing of the geospace environment: horizontal and vertical structure of the ionosphere and plasmasphere, *Proc. SPIE*, *5660*, 1, doi:10.1117/12.580048.

Masci, F. (2010), On claimed ULF seismogenic fractal signatures in the geomagnetic field, *J. Geophys. Res.*, *115*, A10236, doi:10.1029/2010JA015311.

Masci, F. (2011a), On the seismogenic increase of the ratio of the ULF geomagnetic field components, *Phys. Earth Planet. Inter.*, *187*, 19–32.

Masci, F. (2011b), On the recent reaffirmation of ULF magnetic earthquakes precursors, *Nat. Hazards Earth Syst. Sci.*, *11*, 2193–2198, doi:10.5194/nhess-11-2193-2011.

Mellors, R. J., L. Sichoix, and D. T. Sandwell (2002), Lack of precursory slip to the 1999 Hector Mine, California, earthquake as constrained by InSAR, *Bull. Seismol. Soc. Am.*, *92*, 1443–1449, doi:10.1785/0120010244.

Otsuka, Y., et al. (2006), GPS detection of total electron content variations over Indonesia and Thailand following the 26 December 2004 earthquake, *Earth Planets Space*, *58*(2), 159–165.

Pulinets, S. A. (2007), Natural radioactivity, earthquakes, and the ionosphere, *Eos Trans. AGU*, *88*(20), 217, doi:10.1029/2007EO200001.

Pulinets, S. A. (2009), Physical mechanism of the vertical electric field generation over active tectonic faults, *Adv. Space Res.*, *44*, 767–773, doi:10.1016/j.asr.2009.04.038.

Pulinets, S. A., and K. G. Tsybulya (2010), Unique variations of the total electron content in the preparation period of Haitian earthquake (*M*7.9) on January 12, 2010, *Geomagn. Aeron.*, *50*, 686–689, doi:10.1134/S0016793210050166.

Pulinets, S. A., N. Kotsarenko, L. Ciraolo, and I. A. Pulinets (2007), Special case of ionospheric day-to-day variability associated with earthquake preparation, *Adv. Space Res.*, *39*, 970–977, doi:10.1016/j.asr.2006.04.032.

Pulinets, S. A., A. A. Rozhnoi, M. S. Solovieva, and L. Ciraolo (2011), Radiophysical techniques of short-term earthquake precursors and their congruence. The case of L'Aquila earthquake of 06 April 2009, paper presented at General Assembly and Scientific Symposium, Union Radio Sci. Int., Istanbul.

Rymer, M. J., V. E. Langenheim, and E. Hauksson (2002), The Hector Mine, California, earthquake of 16 October 1999: Introduction to the special issue, *Bull. Seismol. Soc. Am.*, *92*, 1147–1153, doi:10.1785/0120000900.

Thomas, J. N., J. J. Love, and M. J. S. Johnston (2009a), On the reported magnetic precursor of the 1989 Loma Prieta earthquake, *Phys. Earth Planet. Inter.*, *173*, 207–215, doi:10.1016/j.pepi.2008.11.014.

Thomas, J. N., J. J. Love, M. J. S. Johnston, and K. Yumoto (2009b), On the reported magnetic precursor of the 1993 Guam earthquake, *Geophys. Res. Lett.*, *36*, L16301, doi:10.1029/2009GL039020.

Tsurutani, B. T., et al. (2008), Prompt penetration electric fields (PPEFs) and their ionospheric effects during the great magnetic storm of 30–31 October 2003, *J. Geophys. Res.*, *113*, A05311, doi:10.1029/2007JA012879.

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