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**Reply to**

**Comment on "On the reported magnetic precursor of the 1989 Loma Prieta earthquake" by J.N. Thomas, J.J. Love, and M.J.S. Johnston**

A.C. Fraser-Smith, P.R. McGill, and A. Bernardi

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**Comment on "On the reported magnetic precursor of the 1989 Loma Prieta Earthquake" by J. N. Thomas, J. J. Love, and M. J. S. Johnston**

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Following the 18 Oct 1989 Ms 7.1 Loma Prieta earthquake, Fraser-Smith et al. (1990) and Bernardi et al. (1991) inspected Ultra Low Frequency (ULF, < 10 Hz) magnetic field data collected by a single sensor that they had been operating at Corralitos, about 7 km from the earthquake epicenter. They noted an anomalous increase in magnetic noise 13 days prior to the earthquake, seemingly unusual changes in the character of the noise up until the earthquake, and a continuation of anomalous noise levels after the earthquake. Fraser-Smith et al. (1990) and Bernardi et al. (1991) suggested that these anomalous signals might reflect a precursor that was causally related to the subsequent earthquake. And, indeed, in the two decades of time since the Corralitos results were published, Fraser-Smith et al. (1990) has been among the most frequently cited papers in the literature of earthquake prediction. Still, it is important to recognize that Fraser-Smith et al. (1990) and Bernardi et al. (1991) only reported on the examination of two months of data from the single Corralitos sensor and they did not make any direct comparisons with any other magnetometer data collected simultaneously at other locations. Nineteen years later, Thomas et al. (2009) obtained a much longer (21-month) data section from the same Corralitos sensor, a duration of time that included the period used in the original reports by Fraser-Smith et al. (1990) and Bernardi et al. (1991). From comparison of these data with others collected simultaneously in California and in Japan, Thomas et al. (2009) concluded that the anomalous signals were most likely some sort of artifact of instrument malfunction that was not related to the earthquake. And now, three years after the publication of Thomas et al. (2009), both Fraser-Smith et al. (2012) and Glen et al. (2012) argue that instrument malfunction cannot explain the COR data. Here, we respond to their comments.

The data speak for themselves. The focus of Fraser-Smith et al. (1990, their Figure 3) was on one of several 30-min-average band-pass-limited "indices" (MA3; 0.0110–0.0183 Hz) from the Corralitos (COR) sensor. Therefore, as a brief summary of the more detailed analysis given in Thomas et al. (2009), we focus our attention on the same MA3 index. As described in our original study, we also obtained data collected simultaneously at Fresno, California (FRN, 201 km from the epicenter) and Kakioka, Japan (KAK, 8284 km from the epicenter). We prepared indices similar to MA3 from COR for both the FRN and KAK data. Ratios of the indices from the three locations show relative differences in noise level. These ratios are shown in Figure 1 for the extended 21-month period of time from 1 Jan 1989 – 2 Oct 1990 considered by Thomas et al. (2009). In Figure 1 we also show the calibration (CAL) signal that was supposed to measure changes in instrument gain (Fraser-Smith et al., 1990). The occurrence time of the Loma Prieta earthquake is shown as a grey vertical line on 18 October 1989. To emphasize the importance, in this case, of examining long durations of data, we highlight in green the short duration of time considered in the reports of Fraser-Smith et al. (1990) and Bernardi et al. (1991). To emphasize the presence of instability in baseline noise levels, we show as horizontal blue lines the time-series mean baseline calculated for times before the anomalous period identified by Fraser-Smith et al. (1990) for 5 October 1989 and after the time when the Corralitos logbook (Thomas et al., 2009, their Table 1) reports maintenance on the Corralitos sensor on 11 July 1990.

At least four step-like changes or multi-day periods of ramping are seen in the COR/FRN and COR/KAK ratios. These anomalous changes are seen both during the 2-month duration of time considered by Fraser-Smith et al. (1990) and Bernardi et al. (1991) in the context of the October 1989 Loma Prieta earthquake, and they are seen long after the 2-month duration that they suggest is related to the earthquake. It is important to recognize that the COR/FRN and COR/KAK ratios do not return to their "pre-precursory" levels until immediately after the Corralitos sensor maintenance in July 1990. In contrast, the FRN/KAK ratio time series is, over long periods of time, extremely stable. Since we have three independently acquired data sets, these ratios and their offsets indicate that the Corralitos sensor was, specifically, delivering data having different "anomalous" levels of noise. This simple and straightforward observation has three mutually exclusive interpretations of relevance. (1) All COR anomalies are due to sensor-system malfunction of some type; they are all unrelated to the Loma Prieta earthquake. This is the interpretation favored by Thomas et al. (2009), and they suggested that a malfunction might have been related to the amplifier that was replaced in July 1990. (2) All COR anomalies are natural and at least some of them might possibly be related to the October 1989 Loma Prieta earthquake. We know of nobody who advocates this interpretation. (3) The COR anomalies at about the time of the Loma Prieta earthquake are natural, but subsequent anomalies are not. This is apparently the interpretation favored by both Fraser-Smith et al. (2012) and Glen et al. (2012). The first two interpretations are, at least, internally consistent. The third interpretation is, we assert, difficult to objectively justify.

In their comments, Fraser-Smith et al. (2012) acknowledge that the Corralitos sensor had operational problems after the Loma Prieta earthquake. But their dismissal of the conclusion of Thomas et al. (2009) that the same sensor also had problems at the time of the Loma Prieta earthquake is not actually supported by any convincing evidence. We explain. Fraser-Smith et al. (2012) assert that the calibration (CAL) signal did not show signs of system problems during the 13-d period of anomalous magnetic noise prior to the Loma Prieta earthquake. We do not dispute this. We do assert, however, that this does not, therefore, mean that the Corralitos sensor was working properly. Putting aside, for the moment, the fact that the CAL signal shows numerous glitches and numerous data drop outs (Figure 1a), the behavior of the CAL signal is perhaps most obviously inconsistent with the magnetic data immediately before and after sensor-system maintenance on 11 July 1990. Following a data gap on 6 June 1990, the COR data record a rapid multi-day ramp increase in noise. But during this time there was no corresponding change in CAL -- none -- until 17 June 1990 when the baseline noise level in the magnetic data nearly stabilized at about seven times (COR/FRN in Figure 1b) and two times (COR/KAK in Figure 1c) background. This anomalous rise in noise was sufficient to motivate maintenance of the sensor system. Afterwards, magnetic noise finally returned to apparently normal levels, those that had not been seen for 9 months since before the anomalous period that Fraser-Smith et al. (1990) suggest was related to the Loma Prieta earthquake. We learn, now, from Fraser-Smith et al. (2012) that the most important issue in this maintenance was "magnetic noise being produced within the magnetometer circuitry"; that the amplifier that was replaced was apparently of less importance. We accept this. However, it does not give us confidence in the overall quality of the COR data. After maintenance, the CAL signal increased in amplitude (Figure 1); it did not decrease, as one might expect for a corresponding decrease in magnetic noise. In other words, the CAL index was simply not diagnostic of the corresponding seven-fold noise increase in COR/FRN from 6 June 1990 to 11 July 1990. Why, then, do Fraser-Smith et al. (2012) express so much confidence in the CAL index at the time of the Loma Prieta earthquake?

Fraser-Smith et al. (2012) make several more comments. We respond. (1) Fraser-Smith et al. (2012) strenuously emphasize their expertise in designing magnetic-field sensor systems. We do not question their expertise. Our interest is in their data and the interpretations that can reasonably be drawn from their data. (2) Fraser-Smith et al. (2012) describe it as "most unfortunate" that in part of our analysis we applied a running average to remove diurnal variation. Removing natural ionospheric diurnal variations from the data is important for identification of mean behavior but we emphasize that we also show 30-min data that are identical to the 30-min values shown in Fraser-Smith et al. (1990). These are shown in both Thomas et al. (2009, Figures 1-4, and Figure 6) and in Figure 1 here. Therefore, their "most unfortunate" concern is simply without substance. (3) Fraser-Smith et al. (2012) express concern about our comparison of the COR data with those from far away Japan (KAK) and those with slightly different frequency content from Fresno (FRN). Their concern, here, is meaningless. What Figure 1 shows is that the KAK and FRN data are remarkably consistent and periods of disturbance recorded in the COR data track those at KAK and FRN. Figure 1 also shows that the COR data are anomalous. That these anomalies do not appear to be natural and, indeed, that they continued until maintenance was performed on the sensor, is what we find so worrisome.

We turn, now, to the comments of Glen et al. (2012). They also acknowledge that the Corralitos sensor had operational problems after the Loma Prieta earthquake, but Glen et al. (2012) argue that a certain subset of the COR data, those that happened to be collected just before and after the Loma Prieta earthquake, record the "hallmarks" of a "true precursor". While we might quibble as to whether or not a true precursor has ever been identified, we respond to the main points of Glen et al. (2012). In the first of their enumerated comments, they assert that the magnetic-noise spectrum, with greater (lesser) noise amplitude at low (higher) frequency, is "exactly" as would be expected for an attenuated internal source at depths of earthquake nucleation. While we agree with the concept being pronounced by Glen et al. (2012), the "exact" answer depends on the electrical conductivity of the crust in the vicinity of the earthquake nucleation point and assumptions about the source noise spectrum. We elaborate. If we accept published observations of those conductivities in this region (Bedrosian et al. 2002; Unsworth and Bedrosian 2004), then a simple skin-depth estimate of the attenuation of a white noise source at the depth of the Loma Prieta earthquake hypocenter leads to very substantial frequency-dependent attenuation – far more than is actually observed in the COR data. Of course, alternative evaluations are possible, and each will depend on both an assumed conductivity structure in the lithosphere and assumptions about the source spectrum. This means that, contrary to the assertion of Glen et al (2012), it is not possible to draw definitive conclusions from the COR spectrum.

In their second enumerated comment, Glen et al. (2012) call attention to the fact that, prior to the Loma Prieta earthquake, the COR data show an increasing multi-day trend in wideband enhancement, but with higher-frequency rapid geomagnetic pulsations becoming proportionally smaller, as if this were a local earthquake-precursor source being "drowned out" by global ionospheric signals. We agree with Glen et al. (2012) that the enhancement in COR data prior the earthquake shows an increasing multi-day trend. However, we point out that the enhancement in June/July 1990 attributed to a faulty operational amplifier or connector problems also shows an increasing multi-day trend. Indeed, when examining the entire 21-month COR/FRN and COR/KAK time series, the enhancement prior the earthquake looks very similar to the enhancement due to acknowledged sensor problems in June/July 1990. Both enhancements show a seven-fold increase in COR/FRN data (Figure 1b) and a two-fold increase in COR/KAK data (Figure 1c) over 2.5-day periods (5-7 October 1989 and 14-17 June 1990). The part of this comment regarding "rapid geomagnetic pulsations becoming proportionally smaller" during the wideband enhancement is somewhat unclear. We find that perhaps there is slightly less rapidly varying noise in COR data prior to the earthquake. However, this is something also seen in the FRN and KAK data (Thomas et al. (2009), Figures 4 and 6), which shows that the change in noise character is global rather than local to the earthquake region. We also note that there are numerous other changes in noise character within the 21-month time series, not just prior to the earthquake. Therefore, contrary to the assertion of Glen et al (2012), wideband enhancement is not a unique occurrence in the COR time series.

In their third enumerated comment, Glen et al. (2012) call attention to “dramatic increase” in noise in the COR data just three hours prior to the Loma Prieta earthquake, something they assert is seen “nowhere else” in the multi-year COR records. We too see an increase in noise just before the earthquake, but we also find similar rates of change at other times in the COR data. In the COR/FRN and COR/KAK time series (Figure 1b,c) we find an increase of about a factor of two on 17 October 1989 for this three-to-four hour period, something that can be seen as upward spike in the time series prior to the data gap starting at about the earthquake time. This type of increase is not unique in the COR data and is seen at multiple other times during the 21-month time series. For example, during a three-to-four hour period on 7 June 1990, COR/FRN data show a five-fold increase and COR/KAK data show a two-fold increase. Therefore, contrary to the assertion by Glen et al. (2012), the “dramatic increase” in magnetic noise is not a unique or “singular” occurrence in the COR time series.

Finally, we differ with the opinion expressed by Glen et al. (2012) that a negative assessment of the reported Loma Prieta magnetic precursor requires “proof” that the anomalous signal is an artifact. This opinion is a contradiction of conventional scientific methods, where a candidate hypothesis of interest, call it H1, is compared with an uninteresting null hypothesis, H0. If there is any reasonable possibility that H0 might be true, then no conclusion is obtained for H1. Unfortunately, the COR data set came from only one sensor, so it is impossible to conclude that any particular subset of the COR data is reliable. Retrospectively, we consider it significant that other sensor systems have not found precursory signals similar to those reported by Fraser-Smith et al. (1990) associated with other large earthquakes both within the San Andreas fault system and in other parts of the world (Mueller and Johnston, 1990; Karakelian et al., 2002; Johnston et al., 2006; Masci, 2010). Indeed, other data collected in studies of the Loma Prieta earthquake do not support the interpretation of the COR data anomalies as being related to the earthquake (Johnston et al., 1990; Mueller and Johnston, 1990).

We again conclude that the magnetic noise that is observed in the COR data prior to the Loma Prieta earthquake can be best explained by sensor-system problems, and not as a precursor that was physically related to the earthquake.

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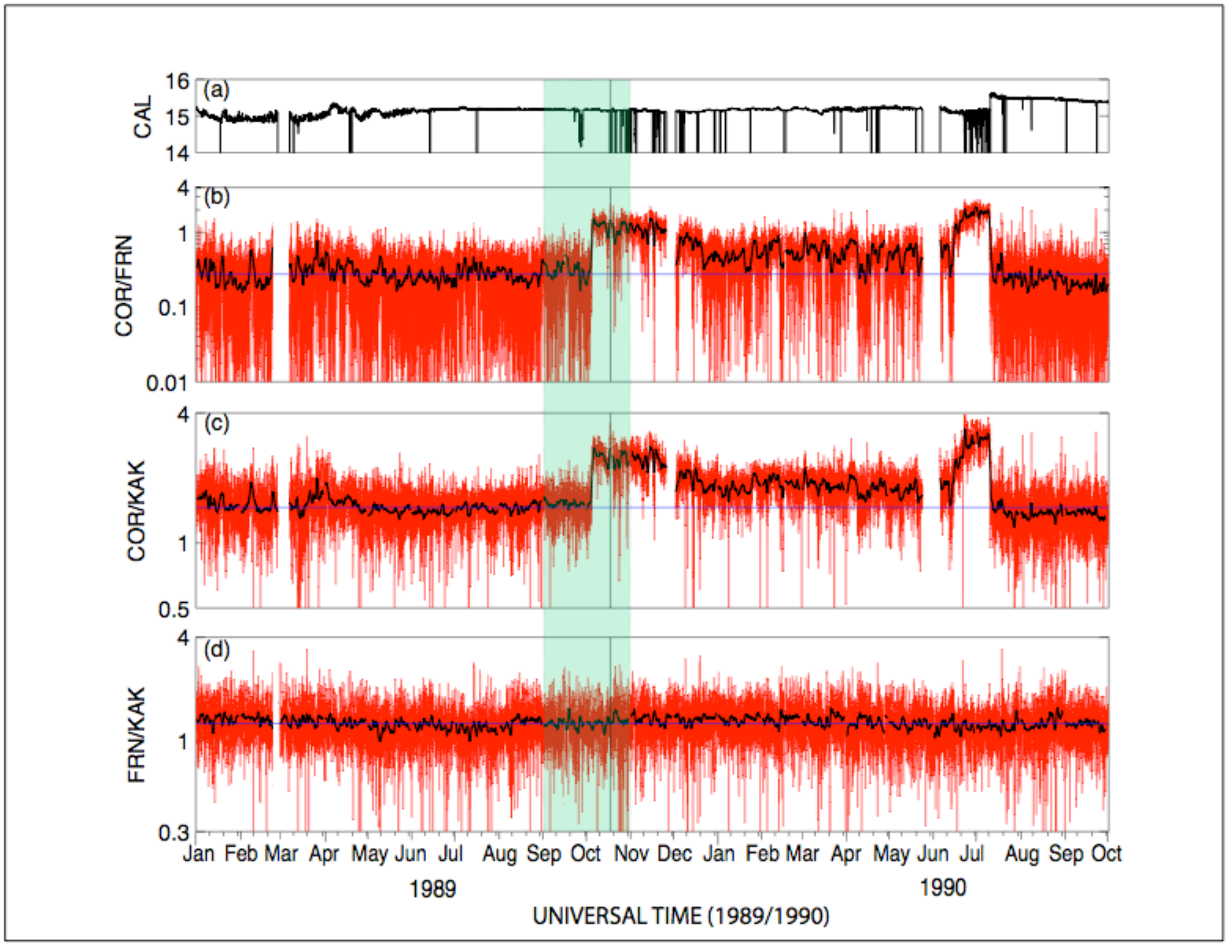


**Figure 1:** Corralitos (a) calibration CAL index, (b, c) COR magnetic index MA3 (0.0110–0.0183 Hz) divided by Fresno (FRN) and Kakioka, Japan, and (d) FRN divided by KAK for the 21-month period of time (1 January 1989 – 2 October 1990); red are 30-min average values, black show smoothed time series obtained with a 2-d triangle function. The earthquake time is shown as grey vertical lines on 18 October 1989 and the blue horizontal lines are the means of the times series for times before the precursor (January 1 – October 4, 1989) and after the op-amp replacement (July 11 – October 2, 1990). The green shaded region, September - October, 1989, indicates the time period that was the focus of the original report by Fraser-Smith et al. (1990).