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Reply to "Comment on 'Seismomagnetic Effects from the Long-Awaited 28 September 2004 M 6.0 Parkfield Earthquake' by M. J. S. Johnston, Y. Sasai, G. D. Egbert, and R. J. Mueller" by P. Varotsos and S. Uyeda

by M. J. S. Johnston, Y. Sasai, G. D. Egbert, and S. K. Park

Introduction

The comment by Varotsos and Uyeda (2008) (VU hereafter) does not have much to do with our article, which reports electromagnetic data and their implications prior to, during, and following the 2004 **M** 6 Parkfield earthquake (EQ). In fact, our article did not include any extensive discussion of the possible flaws in the seismic electric signal (SES) approach to EQ prediction. The four main points VU discuss in their comment are from a summary sentence in the introduction that is preceded by the phrase "controversy about these (SES) results exists because (1), ... (2) ... (4)," where (1)–(4) are the specific points that VU list. We respond to each of these points in the following discussion. A final comment made by VU concerns our observation that SES-type signals are not seen in the data that we have. We could have provided more detailed evidence about the lack of SES in the months preceding the earthquake but see little point in including long data plots that show nothing. Note that all of these data are freely available from the Northern California Earthquake Data Center (NCEDC, www.ncedc.org, last accessed October 2007). In our article, we presented null results from sites above the Parkfield EQ rupture without extrapolating to the conclusion that SESs do not exist anywhere. In fact, Park *et al.* (2007) report additional data from 10–20 km lines over the entire region that also show no evidence for SES-type signals preceding the Parkfield EQ. Such signals were also not seen in 16 yr of previous monitoring with these lines (Park, 1991, 1997). Furthermore, no signals were seen in 2 yr of data on 10 km lines both along and within the fault and orthogonal to the fault a little farther to the north (Johnston, 1989). To suggest that all of these observations resulted from an inadvertent choice of insensitive sites effectively admits that the SES hypothesis is inherently untestable. We would disagree that it would be more scientifically sound of us to assume the validity of this hypothesis and then try to find physical reasons why SESs are not observed. The SES concept thus appears to fail for the central San Andreas fault, and this draws into question previous suggestions that these signals should be expected to precede local and distant earthquakes.

Detailed Response to the VU Comment

We stand by all four summary points in the sentence from our introduction (Johnston, Sasai, *et al.*, 2006) that states "controversy about these (SES) results exists because (1) there are no similar coseismic signals observed when the primary energy is released that can be causally related to the earthquake source, (2) no clear physical explanation exists describing how SES signals can relate to earthquakes occurring sometimes hundreds of kilometers away (Bernard, 1992), (3) no independent data (strain, seismic, pore pressure, conductivity, etc.) exist that support the proposed earthquake/SES relationship, and (4) the SES signals have the form expected from the rectification/saturation effects of local radio transmissions from high power transmitters on nearby military bases (Pham *et al.*, 1998)." Here, we were attempting to objectively and concisely summarize the primary reasons for the controversial status of this hypothesis, not take a negative stance as VU suggest. We will go through each of these points in order to elaborate the background reasoning.

(1) "There are no similar coseismic signals observed when the primary energy is released that can be causally related to the earthquake source." In their comment, VU discuss the electromagnetic (EM) seismogram effects, not similar SESs occurring during rupture nucleation and propagation at the EQ source. These SESs are most likely to occur near the EQ origin time, not during EM seismogram arrivals. EM seismograms do, of course, occur as a result of the radiated seismic stress wave propagation (Johnston and Kappler, 2007), sensor movement in the geomagnetic field as a result of ground displacement and movement of the conducting crust through the geomagnetic field (Ujihara *et al.*, 2004), but this is not what we are discussing. If SESs are phenomena related to stress state then, because stress accumulation continues to within seconds or less of the time of an earthquake, one would expect the SES production would occur continuously after initiation up to peak stress right before failure. Furthermore, SES should occur during and after failure in initiated regions where the stress has been increased by the EQ above the previous accumulated stress level (Johnston, Borcherdt, *et al.*, 2006). Figure 1 shows stress/strain observed on either side of the San Andreas fault for years prior to and following the **M** 6 Parkfield earthquake on 28 September 2004. These sites are about 1 km from the San Andreas fault and 4 km directly above the Parkfield EQ rupture (see Johnston, Borcherdt, *et al.*, 2006, for details of

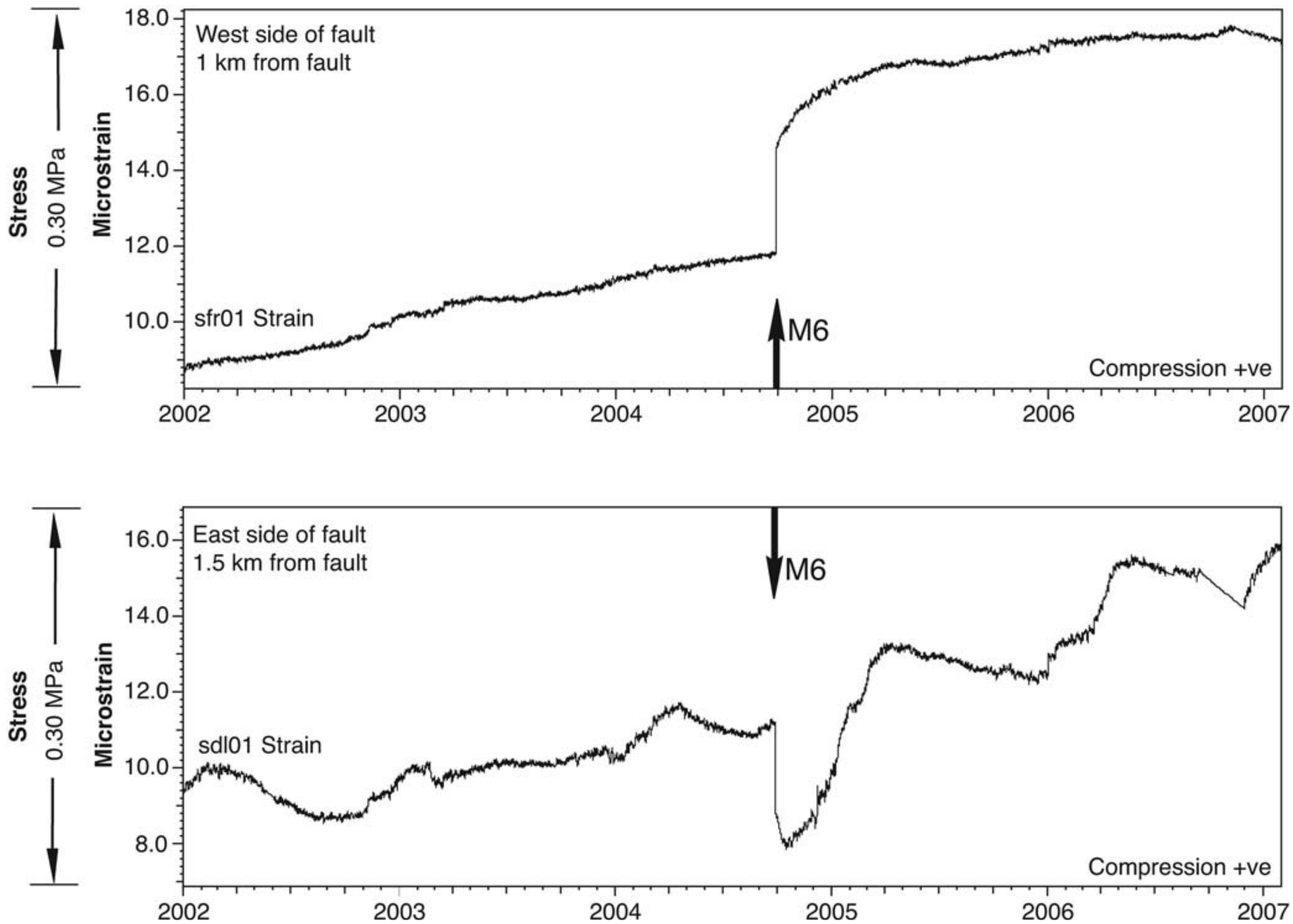

Figure 1. Strain at sites FR and DL on either side of the San Andreas fault for the years before and after the 28 September 2004 **M** 6 Parkfield earthquake. The rupture passed beneath these sites and stopped at the electromagnetic monitoring site PK just to the northwest. Details of site location can be found in Johnston, Sasai, *et al.* (2006) and Johnston, Borcherdt, *et al.* (2006). Crustal strain is converted to crustal stress using a modulus of 30 GPa. The apparent annual term in the DL data is due to meterological loading response.

the instrument locations). Shorter-term strain records, easily converted to stress, can be found in this reference. Furthermore, the dynamic radiating stress pulse during rupture far exceeds the static stress drop during earthquakes by one to many orders of magnitude and would also be expected to play a role in stress-triggered phenomena. We are certainly aware of the response of electrodes to seismic shaking and of the drift response, such as reported by Nagao *et al.* (2000), to this shaking in fluid-filled crustal materials, but these responses are not SES as described by Varotsos and Alexopoulos (1984a). And clearly, none of this response can be causally related to the seismic source.

If we accept the results from 50 yr of rock mechanics, it is unreasonable to assume that the physics of crustal failure is different weeks before rupture compared to seconds before rupture when fracture and crack coalescence is increasing exponentially. Actual observations of local and regional crustal stress/strain in the seconds to months to years before EQs in the San Andreas fault system, Japan, and other places, similar to Figure 1, are also inconsistent with this assumption. Thus, there is no physical reason to assume SESs should occur only weeks to months before EQs and not before, during, and after rupture. The SES hypothesis might be more believable if SES did occur at these times. Occam's razor tells us that, until more simple hypotheses are have been conclusively ruled out, more complex hypotheses should not be proposed.

(2) "No clear physical explanation exists describing how SES signals can relate to earthquakes hundreds of kilometers away (Bernard, 1992)." No realistic physical explanation that includes known crustal structure and material properties in Greece has ever been proposed. In particular, Bernard (1992) pointed this out in his article. Varotsos *et al.* (1993) and VU have tried to avoid this criticism by appealing to an exotic conductivity distribution that distributes electrical signals to different special places. Such speculative appeals to exotic conductivity distribution should not be taken seriously unless supported by direct measurement of this heterogeneous conductivity distribution. Even if it were true, dependence on heterogeneous conductivity distribution precludes general

use of this technique because observations would be a function of very special and variable local conductivity. Furthermore, the argument that SES can be seen only at very rare sensitive sites makes the existence of SES an untestable hypothesis and their occurrence, if real, to be inherently inhomogeneous. This is inconsistent with other VU arguments that the signals can be separated from noise because they are homogeneous.

The conductivity structure at Parkfield (and along the fault to the north and south) is relatively simple and can be generally described as a high-conductivity region of 1–3 S/m located around the vertical fault zone region with conductivities of 0.001 and 0.01 S/m, respectively, on the west and east side of the fault Unsworth *et al.* (2000). The fault has a similar conductivity structure further to the north near the San Andreas Geophysical Observatory (SAGO) site. In fact, the article by Bedrosian *et al.* (2004) referred to by VU as indicating complex conductivity near fault zones actually describes this same conductivity structure close to the SAGO site. At Parkfield, inspection shows that the PK site is within this higher conductivity region near and including the fault zone as reported by Unsworth *et al.* (2000). However, sites used by Park *et al.* (2007) cover a larger area with some in the fault zone, some to the west in a more resistive area (according to VU, this is ideal for observation of SES), and some to the east on intermediate resistive material. Thus, if VU are correct, we should be well positioned to see SES events. We see no evidence for SES-type events using data with a resolution far below that of the Greece data (Varotsos *et al.*, 1984a,b; Sarlis *et al.*, 1999). Note that our higher resolution at PK allows detection of weaker SESs even if we were not as optimally located as we appear to be.

(3) "No independent data (strain, seismic, pore pressure, conductivity, etc.) exist that support the Earthquake/SES relationship." Appeals to some critical state in the earth that exists weeks to months before earthquakes but does not exist in the hours to seconds before these events are not supported by any independent geophysical data. Observed strain/stress data such as shown in Figure 1 show no indications of changes in the hypothetical critical stress that VU are appealing to. (See Johnston, Borcherdt, *et al.* [2006] for records of other stress related parameters). During the past 20 yr, we have obtained similar near-field strain records for some 50 other earthquakes with M 5–7.4 on the San Andreas fault (Johnston and Linde, 2002) and many more have been obtained in Japan and other seismically active places in the world. This concept of a hypothetical critical state on a scale of hundreds of kilometers is not expected theoretically nor is it observed in reality.

(4) "The SES signals have the form expected from the rectification/saturation effects of local radio transmissions from high power transmitters on nearby military bases (Pham *et al.*, 1998)." Saturation signals from radios, phones, electric motors, vehicles, etc., are common problems in electric field measurements. Here, we are summarizing the conclusions of Pham *et al.* (1998) based on their study of electric field measurements in Greece. Proponents of SESs need to show that this is not a problem particularly because many of the sites are on Greek military bases, where unmonitored electromagnetic transmissions and noise should be expected to occur often. Appeals to signal homogeneity by showing that electric fields are dipole length independent are not guarantees of local noise identification and are inconsistent with other appeals that SESs are from heterogeneous sources.

Final VU Point

VU chide us for not doing extensive experimentation to find sensitive sites before concluding that SESs are not observable in Parkfield. There were in fact eight electric field observation lines at Parkfield—six large scale dipoles described in Park *et al.* (2007), plus two shorter 100 m and two 200 m orthogonal measurement systems at PK. This becomes 10 if we include another pair of orthogonal measurement systems at SAGO some 115 km to the northwest. Three of the lines monitored at Parkfield are within the conducting fault zone region, and the rest are off the fault in more resistive material. None of these 10 electric field observations recorded SES in the form described by Varotsos *et al.* (1984a) either in the near-field of the fault zone, the intermediate field 5–10 km distant, or at 115 km but also in the conducting fault zone that seems to be preferred by VU. While it was not the primary purpose of our article to try to prove or disprove the existence of SES, it is clear that, if SESs do exist, they would be so unique to be of little general use in EQ prediction. We would strongly disagree with VU's suggestion that SESs are "well observed in other parts of the world."

Conclusions

We see no reason to change or modify any of our four summary points. SESs are not observed on the San Andreas fault on monitoring systems that scale from hundreds of meters (Johnston, Sasai, *et al.*, 2006) to tens of kilometers (Johnston, 1989; Johnston, Sasai, *et al.* 2006; Park *et al.* 2007). Furthermore, convincing observations of precursory SESs have also not been obtained in Japan, or in other parts of the world, during the past decades despite considerable efforts by many research groups. The Parkfield experiment was designed specifically to test many such hypotheses of EQ physics with multiple colocated, high-precision measurements of different geophysical parameters. For the SES hypothesis, in particular, these data indicate no evidence for its existence at Parkfield or elsewhere near large EQs along the San Andreas fault. This draws into question suggestions by VU that these signals should be expected to precede local and distant earthquakes. We see no obligation to try to find physical reasons for the failure of the SES hypothesis. That obligation falls to VU.

With all this being said, it is important to remember that electric and magnetic changes do occur with earthquakes and do provide independent information on physical processes at the EQ source and during the faulting process. It is extremely important that we remain focused on extracting the physics of these processes by careful observations corrected for external noise and implications and interrelations with other geophysical parameters.

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