Dear Del, Bob D., Jim, Ed, Bob E., Bill, John, and other interested readers,

Having read your reports, it is clear to me that your reasoning for a magmatic event was more substantial than what I gleaned from the original Time Critical Studies website release, which did not include a time versus magnitude plot for the swarm. Clearly the pattern for this plot is different from one for a typical fault slip, main-shock after-shock sequence. I appreciate this very thorough and interesting presentation of the justification for going to sea. For future event responses of this type, I think it would make sense to look at two other types of precursory data to improve the chances of observing hydrothermal plumes, new lava flows, etc. I could not tell from the discussions so far if these data had been considered.

The first is harmonic tremor. For those of you reading this who are not seismologists, harmonic tremor is often observed on seismograms during volcanic earthquake swarms and subsequent eruptions (see the work of Bernard Chouet and colleagues at USGS). When observed, this provides fairly unambiguous seismic confirmation of a volcanic/magmatic event, and has been used successfully to evacuate cities in danger of a volcanic eruption. Since none of the seismologists involved have mentioned harmonic tremor so far, I assume it was not observed. The equivalent magnitude of such tremors can be in the M>2 range, so they should be detectable even if they are not easy to locate (very emergent arrivals). When I talked with Bernard recently, he told me that a hydrophone array capable of locating M=2.5 events should be sensitive enough to detect volcanic tremor. In addition, the array of OBS's still deployed on the Endeavor segment may be useful once they are recovered. For future events, a cabled Neptune array will really solve the problem.

The second is evidence for a crustal or uppermost mantle magma chamber in the swarm area from existing refraction or multi-channel seismic surveys. Based on the AGU presentations of Carbotte et al and Detrick et al in 2003 and 2004, I recall that a magma chamber reflector was not observed in the overlap region between the Endeavor and Middle Valley segments where most of the swarm occurred, only along the shallow portions of the Endeavor segment away from the segment ends.

I think if all three data sets confirm each other; time-magnitude anomalies (as Del documented), harmonic tremor and presence of a magma chamber, then the chances of success in rapid response measurements of a magmatic event are vastly improved. I suggest that at least two out of the three criteria be satisfied. This is especially true when responding to swarms near ridge axis discontinuities where hydrothermal activity is generally sparse and well-sedimented lavas suggest infrequent occurrence of volcanic-hydrothermal events.

Some other details: Time-magnitude plots, taken alone, can be misleading. Little is known about the time-magnitude patterns for an array of interacting, closely spaced bookshelf faults such as those in the 2005 swarm area. They are likely to be atypical too, with multiple events of similar magnitude, and could mimic a magmatic event, we just don't know.

The time-distance plot posted on the pmel blog supporting north-south migration of epicenters is not that clear to me. Would the north-south migration be more obvious if the southern Middle Valley part of the swarm were treated separately? There is also a curious gap in activity just after the swarm started.

It might be useful to calculate b-values for the swarm (for non-seismologists, a b-value of 1 means there are 10 times as many M=4 events as M=5 events; b=2 means 100 times as many M=4 events as M=5, etc.; i.e., high b-value means a preponderance of small quakes). Although the physical significance of b-values is not well understood in detail, they can be a useful indicator. Values of 1 are typical for fault slip events, and b greater than about 1.5 is typical for volcanic events. I calculated an unusually high b value of 3 for a swarm of events (dead benthic fish on the surface too) on the Galapagos Spreading Center (Macdonald and Mudie, 1974) which turned out to be at the same location as the Rose Garden, the first deep mid-ocean ridge hydrothermal vent field explored by Corliss et al. (1979) several years later. So volcanic and, especially, hydrothermal events might have very distinctive b-values, i.e., a significant preponderance of smaller earthquakes. This can be determined from the SOSUS sonograms.

Lastly, I want to thank all of you for working so hard on a difficult and daring winter season mission to capture a mid-ocean ridge event in action. My initial cursory comments and these additional comments are meant to be helpful in planning future event responses, and in understanding the results of the most recent response cruise. Ever since John Lupton and I chaired the first RIDGE Event Response Workshop in Santa Barbara over a decade ago, I have had an intense interest in this subject, and I (hopefully others too) are learning from these discussions.

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Refs.

Macdonald, K. C. and J. D. Mudie (1974). "Microearthquakes on the Galapagos spreading center and the seismicity of fast-spreading ridges." Geophys. J. Roy. Astr. Soc. **36**: 245-257. (Available, but only on parchment.)

Corliss, J. and others (1979). "Submarine thermal springs on the Galapagos rift." Science **203**: 1073-1082.