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Reply to "Comment on 'Minimum Magnitude of Completeness in Earthquake Catalogs: Examples from Alaska, the Western United States, and Japan,' by Stefan Wiemer and Max Wyss," by Paul A. Rydelek and I. S. Sacks

by Stefan Wiemer and Max Wyss

Rydelek and Sacks (2003) (R&S) have criticized our mapping of the minimum magnitude of completeness, M_c, in earthquake catalogs (Wiemer and Wyss, 2000). They suggest that their own approach, based on Schuster's (1897) method, is superior. Clearly, tracking down variations in M_c as a function of three-dimensional space and time is a complex task, and every method of attempting to do this has advantages, paid for by shortcomings. We maintain our position that, in the balance of advantages and shortcomings, our method is preferable.

While we agree with the concluding statement of R&S that temporal variations can introduce problems, we feel that this criticism does not limit the applicability of our approach based on measuring the deviation from the frequency-magnitude distribution (FMD). Additionally, evidence presented by R&S in their comment supports our criticism of their earlier work (Rydelek and Sacks, 1989; Taylor *et al.*, 1990): consequently, our interpretation remains that the breakdown in earthquake scaling that R&S claimed to see a decade ago is an artifact, and one should not draw conclusions about earthquake physics from it.

R&S's first objection is that, in some cases, the assumption of a linear FMD is not valid. While this is true under unusual conditions, we disagree with R&S's conclusion that our method is incapable of finding evidence for such deviations. In fact, in our article we devoted an entire section to this topic and identified several regions where such a breakdown occurs (figures 4b, d, and f of Wiemer and Wyss, 2000). These regions are generally identified as regions with a poor goodness of fit or a sudden jump in completeness. Once identified, these regions can be specifically investigated to find the reason for the deviation (e.g., quarry blasts, temporal variations in M_c, volcanic swarms) and the problem can be solved by excluding them from the M_c mapping.

The second objection of R&S is that our approach of using constant sample size volumes, rather than constant radii, makes the resulting maps of completeness difficult to understand. Because there are advantages and disadvantages in both approaches, we conduct most of our analyses using both methods, requiring that the results are not significantly affected by this choice. In our articles, we publish only the results of the approach for which the balance of advantages and disadvantages is more favorable, in our opinion. R&S constructed a scenario where results based on constant sample size may be misleading. While this is a possibility, we have pointed out in several publications (e.g., Wiemer and Wyss, 1994; Wiemer and Katsumata, 1999; Wiemer, 2000; Wyss *et al.*, 2000) that the alternative approach, constant volume gridding, can be misleading as well. The uncertainty in estimating seismicity parameters such as M_c, *b*-values, and rate changes is strongly dependent on the sample size. In a constant sample volume approach, sample size can vary dramatically across a map; hence the parameter uncertainty varies strongly. In a constant sample size approach, on the other hand, spatial resolution varies. In either approach one should eliminate poorly resolved regions, as we routinely do, either by limiting the minimal sample size or the maximum allowed sample radius. Either approach seems valid to us. We recommend comparing results form either method, because significant differences need to be evaluated carefully, if they exist (Wiemer and Wyss, 2002).

For mapping M_c in the context of our article, it seemed more sensible to us to use a constant number approach. One of the reasons is that we do not know how to get a good estimate of the uncertainty of M_c; hence we cannot show uncertainty maps. This is only a minor problem in the constant sample case, because the uncertainties in all volumes are similar, whereas in the constant volume approach they would be vastly different. Secondly, variable-sampling radii optimize spatial resolution, much like variable grid spacing does, which is commonly applied in numerical modeling to resolve critical areas. R&S suggested that variable sample radii result in variable sample times. While this is true, we fail to see how this is different in a fixed radius approach or any other approach we could think of.

R&S's main criticism seems to be that temporal variations in completeness can go undetected using the FMD approach. While this can happen, it is not a limitation of the method itself. In most of our work, we have studied M_c as a function of time, using the FMD-based approach. Given space limi-

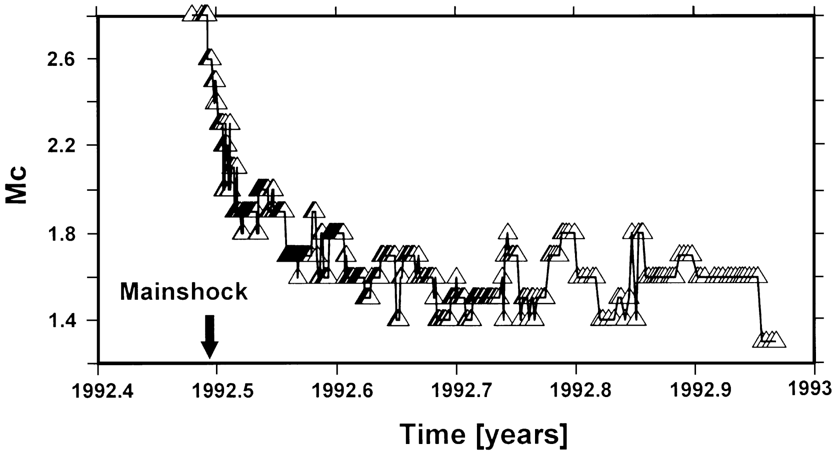

Figure 1. Magnitude of completeness (M_c) as a function of time in the source volume of the 1992 M 7.2 Landers earthquake. M_c is computed using the frequency-magnitude distribution in overlapping windows, each containing 250 events. M_c is abnormally high in the first hours to days, because small events hide in the coda of larger ones, because network operators are overwhelmed, and because additional stations were installed only after the mainshock. This change cannot be detected using the method advocated by R&S.

tations, our article focused on spatial variations over extended regions, and in many instances, spatial variations are dominating. We have published numerous articles on catalog quality and temporal variations and state specifically in our Method section that we assume that we correctly determined the starting time of the high-quality catalog, after which no further significant reporting changes occur.

The FMD method is fully capable of resolving temporal changes in M_c, as we demonstrate here for the case of an aftershock sequence (Fig. 1). Completeness right after the mainshock increases over that during background time by up to 2 magnitude units, because small events are hidden in the coda of larger ones and because analysts are often overwhelmed by the shear number of events. This well-known behavior was documented, for example, in Wiemer *et al.* (2002) and Wiemer and Katsumata (1999). Detailed knowledge of M_c is necessary to correctly assess aftershock hazard (Reasenberg and Jones, 1989; Wiemer *et al.*, 2002). Using the FMD as a guideline, we can derive with some confidence the spatial and temporal behavior of completeness (Fig. 1). In this situation, we believe that Schuster's method is not helpful, simply because completeness changes occur on a timescale of hours; the FMD may be the best, if not only, realistic method for assessing completeness.

R&S claim that Schuster's test identified an earthquake swarm on 25 January 1989, between 5 and 7 a.m. in their article on seismicity in Hokkaido. We disagree with this interpretation. A magnitude 5.2 mainshock at 5:03 a.m. occurred in this location, followed by a typical aftershock sequence that lasted several months (Fig. 2). In the first hours of the sequence, the network was unable to detect all small earthquakes, hence M_c increased temporarily, just as it did for the Landers sequences shown in Figure 1. This temporal change in M_c, and the spatial changes in completeness, have not been identified in R&S's original papers (Rydelek and Sacks, 1989; Taylor *et al.*, 1990), where they claim a breakdown of power law scaling for natural reasons and subsequently draw conclusions about scaling and self-organized critically. Negating the (in our opinion) strong evidence for spatial and temporal variability of M_c, R&S reiterated in their comment that they believe a breakdown in scaling exists. It is surprising that R&S criticize our article in what we consider a minor detail, while not admitting that their own analysis and conclusions drawn from it are likely fundamentally flawed.

The curvature in the FMD for the Parkfield region, indicating lack of complete reporting, seen in figure 3 of R&S, is again an expression of the same problem we criticized in their analysis of the Hokkaido data set. In the bulk-data

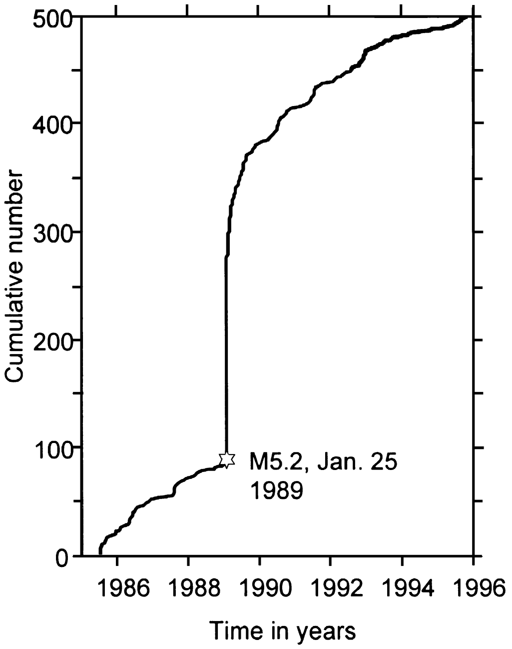

Figure 2. Cumulative number of earthquakes as a function of time in the source volume that fails the Schuster test with a high probability in Hokkaido, Japan. The catalog used is the JUNEC data set with $M \geq 2.0$. A mainshock of magnitude M 5.2 occurs on 25 January 1989, 5:03 a.m., and is followed by a decaying aftershock sequence.

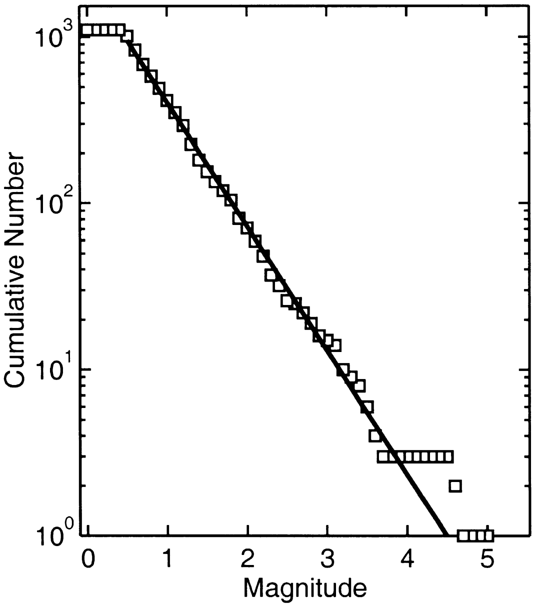

Figure 3. Frequency-magnitude distribution for the earthquakes contained in the catalog derived from the downhole seismograph network at Parkfield and located between latitudes 35.92° and 35.98°.

FMD, shown in figure 3 of R&S, one gets the impression that the entire data set is incomplete up to relatively large magnitudes. However, we have mapped the M_c in that data set, as we advocate one needs to do in all earthquake catalogs. We find that at the center of the area covered by the downhole seismograph network the M_c is 0.4 (near latitude 35.92°). In the fault segment between 35.92° and 35.98° the completeness level is M_c 0.5 (Fig. 3). Further from the center of coverage, for example at latitudes 35.88° and 36°, we map M_c as exceeding 1. Therefore, the apparent contradiction claimed by R&S with respect to their figure 3 does not exist. The FMD approach also estimates M_c as about 0.4–0.5 in the area well covered by the network. It is surprising to us that R&S insist on their interpretation, although we demonstrate (Fig. 3) that the estimate of M_c by Heimpel and Malin (1998; figure 3 of R&S) is incorrect by a large margin, and although an ellipse appears in figure 3 of R&S that was not present in the original by Heimpel and Malin, and that these authors are unable to define quantitatively.

It is a fact that completeness varies in four dimensions (three spatial and time). Unraveling this complex space-time pattern is challenging and often possible only to a first-order approximation, as we point out in our articles. R&S's comments highlight this complexity, and we are the first to admit that our method is not the ultimate answer to the problem. R&S's approach using Schuster's method, or simply mapping out spatially the hourly distribution of earthquakes, as we have done in past studies (Wiemer and Baer, 2000), can, and should, be used additionally to evaluate the reliability of the results.

Further stability of the M_c maps can be achieved in some cases in two ways: (1) Declustering of the earthquake catalog, using programs such as that by Reasenberg (1985). This will minimize the effect of clustered seismicity, such as aftershocks and swarms, which might have different completeness properties. (2) Mapping quarry blast contamination and eliminating them, using Schuster's method or daytime-to-nighttime ratio (Wiemer and Baer, 2000).

In conclusion, we see advantages and shortcomings in both methods, ours and that of R&S. For the reasons stated, we prefer our method for most applications. We note that R&S in their comment have not supplied any evidence that would support their earlier claim that the FMS power law breaks down at small magnitudes due to natural causes. In fact, their findings support our criticism, that there is no evidence for a violation of the power law FMD along the coast of Hokkaido.

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