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The Evaluation of VLF Guided Waves as Possible Earthquake Precursors

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Abstract

A group of Russian scientists have observed unexplained phase anomalies in signals broadcast by the Omega radio-navigation system. They proposed that these signals are earthquake precursors and have published a statistical analysis of the relationship between these signals and earthquakes within 1000 km of the path between the broadcast station and the receiver. Further work on this topic has been proposed as a joint Russia-US project under the auspices of the Gore-Chernomyrdian Commission. In order to help formulate a response to this proposal, we have undertaken an independent statistical analysis of the original record of Omega phase anomalies and earthquakes in order to determine if the phase anomalies preferentially precede the earthquakes. It turns out that a key element in this analysis is the choice of statistical distributions used to model the earthquakes. A Poisson model, which was used by the Russian researchers, does not include the clustering observed in the earthquake catalog and leads to underestimating the odds that the results are due to random chance. Using the empirical distribution of inter-earthquake times and a first-order autoregression allow us to model elements of the clustering process. Using these models increases the odds that the results are due to random chance to over 0.1 and suggest that the observed precursory relationship is not statistically significant. Further, varying the free parameters that define the data sets shows that this process is not stable and further erodes our belief that these phase anomalies are earthquake precursors.

Introduction

It has been proposed that phase anomalies in the propagation of VLF radio signals broadcast by the U.S. Omega system can be used to predict earthquakes. This idea is currently being championed by A.P. Reutov, a member of the Russian Academy of Sciences, and further work on this topic has been proposed as a joint U.S.-Russian project under the auspices of the Gore-Chernomyrdian Commission's Environmental Working Group. In order to respond to this proposal the U.S. side of the Environmental Working Group has initiated an examination of this idea and this paper is one part of that examination.

The literature in support of this idea comes from several papers in Russian (Gufeld, Marenko, and Yampolsky, 1989; Marenko, 1989a; Marenko, 1989b; Gufeld and Marenko, 1992; and Voinov et al., 1992), one paper in English and published in Russia (Gufeld et al., 1991), and one paper published in a western journal (Gokhberg et al, 1989). Most of these papers concentrate largely on the phenomenology of the radio signals and observations preceding a few seismic events. This does not provide adequate statistical support for this method.

The best statistical analysis comes from Marenko (1989b), where he performed a statistical analysis of the relationship between the phase anomalies and earthquakes observed along two paths: from the Liberia Omega station to a receiver in Omsk and from the Reunion Island Omega station to the same receiver. The data set was collected from September, 1983 through February, 1986. He found that the anomalies were precursors to the earthquakes and the probability that this relationship was due to random chance was under 0.01.

This study re-examines these data in order to make an independent assessment of the relationship between these anomalies and earthquakes. The issues we will address are how to parameterize the relationship, how to make a statistical model of the relationship, and how robust the results are to individual parameters used to define the relationship.

VLF Data

The U.S. operated Omega radio-navigation system consists of a set of VLF radio transmitters that are distributed around the world. Each transmitter emits a known signal that is tied to an accurate timebase. By receiving, and comparing, several of these signals a receiver can determine both the time and its location. Alternatively, if the position of the receiver is kept fixed, and is attached to an accurate timebase, then a system can determine if there are temporal changes in the radio wave propagation between the transmitter and receiver. This was done by Marenko (1989b) with a receiver at Omsk, Russia (73.35° E, 54.983° N). The VLF radio signals used in the earthquake prediction experiment were broadcast by two Omega transmitters: Liberia (10.6667° W, 6.3000° N) and Reunion Island (55.2833° E 20.9667° S) (Figure 1). For each transmitter the phase of the arriving signal was stored as a time series. One problem with the data set is that from September, 1983 through February, 1986, the recording is not continuous. Instead, due to equipment and other problems, there are gaps, or dropouts, in the data that vary in length from 30 minutes to 92 days and have a total duration of about a third of the time period. Some of the data gaps are clearly due to failure of the receiver and are simultaneous on both paths, but others occur on only one path and are of unknown origin, although we assume that they have no relationship to the earthquake record.

The VLF signals travel as guided waves trapped between the ionosphere and the earth's surface. The height of the ionosphere has a known diurnal variation due to daily changes in solar heating and irradiation and so the propagation of these waves, which is dependent on ionospheric thickness, also has a diurnal variation. Other variations are known to occur due to solar phenomena. Marenko (1989b) defined anomalies in the VLF signals as follows. The time series recorded are the phase of the arriving signal. Anomalies were declared when the current data was greater than two standard deviations from a monthly mean. If the deviation occurred on multiple paths or could be attributed to a known solar phenomena no anomaly was declared. Obviously these means must be determined for a specific time of day, but the details (including how to factor in data dropouts) are not clear.

For the data set from 1983 through 1986 used here we do not have access to the original time series, but instead rely on summary tables of the anomaly and dropout start and end times (Marenko, 1989b). Most anomalies occur at night, but some occur throughout the day (Figure 2). The average length of the anomalies is about 3 hours on the Liberia-Omsk path and 4 hours on the Reunion-Omsk path.

The mean time between anomalies is 124 hours for the Liberia-Omsk path and 53 hours for the Reunion-Omsk path. The distribution of inter-anomaly times is difficult to determine because the large number of dropouts may hide some anomalies. On the Liberia-Omsk path 112 anomalies were observed, so there are 111 possible inter-anomaly times that could be measured. However, due to the data dropouts only 42 inter-anomaly times could actually be measured. For the Reunion-Omsk path there were 270 anomalies but only 140 inter-anomaly times could be determined. The data dropouts make it particularly hard to observe long inter-anomaly times. The means given above were determined by taking the entire time of observation, subtracting the time covered by data dropouts, and dividing by the number of anomalies. Due to the difficulty of observing the inter-anomaly times, we can not develop a meaningful statistical model of the anomalies. Thus, when making the statistical models of the anomaly-earthquake system we will hold the anomalies and drop outs fixed and randomize the earthquakes.

Earthquake Data

In Marenko (1989b) the earthquakes used along each path were those that had magnitudes (M) ≥ 4 and were ≤ 1000 km from the great circle segment connecting the transmitter and receiver (Figure 1). The distance was chosen because the radio waves have a fresnel zone of about 300 km and effects within a few fresnel zones of the path could create an anomaly in the radio data.

The actual earthquake data used by Marenko have been lost and so we selected the data using these parameters from U.S.G.S. Preliminary Determination of Epicenters catalog (USGS/NEIC, 1992). Along the Liberia-Omsk path 785 events fit the parameters and along the Reunion-Omsk path there were 862 events. There are probably more events that actually fit these criteria, because the global earthquake catalogs are not complete at the $M \geq 4$ level.

The earthquake catalog depends on a large number of independently operated stations; this gives it a high level of redundancy and so there are no actual data dropouts, however for small earthquakes our ability to detect and locate them decreases and below a given "completeness threshold" the odds that a given earthquake will make it into the catalog decreases. These odds may vary with time due to inconsistent reporting by some local seismographic networks that contribute to the catalog. The completeness threshold varies with position due to uneven coverage of seismic stations over the globe, this is especially true because the stations are all on land.

The completeness threshold is usually determined by fitting the observed magnitudes to the Gutenberg-Richter relationship (Richter, 1958):

$$log(N(M \geq m)) = a - bm$$

Where N is the number of earthquakes with magnitudes (M) greater than or equal to m and a and b are constants determined for a particular data set. The value of b is usually close to 1. Determining a and b in this case is difficult because b varies with different seismotectonic regimes that are merged together over these long, wide, paths. This problem is compounded because a variety of magnitude scales have been used in compiling this catalog.

Least squares fits of the data to the Gutenberg-Richter relationship are shown in Figure 3. These fits suggest that the Liberia-Omsk catalog is complete to about $M \geq 4.3$ and the Reunion-Omsk catalog is complete to about $M \geq 4.5$. Based on experience compiling this catalog, Stuart Koyanagi (pers. comm., 1996) advises that $M \geq 4.3$ for the Liberia-Omsk path is reasonable, but that $M \geq 4.5$ for the Reunion-Omsk path may be low by as much as 0.5 units. Given these fits about 950 events are missing from the Liberia-Omsk catalog and almost 1400 are missing from the Reunion-Omsk catalog at the $M \geq 4$ level. In both cases this means that there may be more events missing from the catalog than were observed, but given the large regions and varied magnitude scales involved one must use these values with great caution.

Despite this problem we will proceed to do the analysis with the $M \geq 4$ cutoff in order to best duplicate the previous results. The missing earthquakes should only be a problem if there is a relationship between when the radio phase anomalies occur and when the earthquakes are missed. Fortunately, this seems like a remote possibility. We will also test different magnitude thresholds to see how this parameter affects the results.

Statistical Models of Earthquakes

Analyzing the relationship between the radio phase anomalies and the earthquakes is a two step process. First, we will make some measure of whether or not the anomalies preferentially precede the earthquakes. This measure will be discussed in the next section. Second, if the anomalies appear to preferentially precede the earthquakes we need to determine the probability that this apparent success is due to random chance. To determine this probability we will produce a large suite of simulated earthquake catalogs. Accurately determining this probability requires that these simulated earthquake catalogs are realistic. To do this we need to understand the statistical behavior of the time between successive earthquakes.

The simplest way to simulate the inter-earthquake times is to use a Poisson model which depends only on the mean of the observed inter-earthquake times. In a Poisson model each earthquake occurs independently and the odds of an earthquake occurring at any time are equal to the odds at any other time. Earthquake sequences can then be simulated by computing the mean inter-earthquake time and using a Poisson distributed random number generator. However, this process may not accurately simulate the actual earthquake process.

Figure 4 shows the distribution of inter-earthquake times for each path. Also shown are the predicted distributions if the earthquakes were distributed as a Poisson process. One can see that the observed distribution is above the predicted one for the smallest inter-event times and below for larger inter-event times. A Kolmogorov-Smirnoff two sample test between these observed and predicted distributions shows that the probability that the observed data are drawn from a Poisson process is below 0.005. Thus, we can reject the possibility that the earthquake process is well described by a Poisson model. This is characteristic of a clustered process and shows that the earthquakes do not occur independently of each other.

An improvement over the Poisson model would be to exactly reproduce the observed distribution of inter-earthquake times. This can be done by randomly selecting (with replacement) inter-earthquake times from the actual observations. We will refer to this method as the empirical model. While the empirical model will replicate the observed distributions shown in Figure 4, there are other parts of the earthquake process that it fails to reproduce.

The most obvious example of clustering is the aftershock process and an aftershock sequence generally includes multiple events. So not only are there an excess number of short inter-earthquake times, but once one short inter-earthquake time is observed it becomes more likely that the next inter-earthquake time will also be short. While the empirical model will reproduce the observed distribution of inter-earthquake times, it does not include any linkage between successive inter-earthquake times. This linkage can be partially modeled by using a first-order autoregression. In a first-order autoregression the next inter-earthquake time is generated by adding noise to the last inter-earthquake time. Thus, successive inter-earthquake times are partially linked. The amount of noise added depends on how strongly the successive inter-earthquake times are linked and the strength of this link is determined by the first lag of auto-correlation function of the inter-earthquake times (Figure 5).

Simulations of autoregressive sequences are best done with Gaussian distributed data, hence to simulate the auto-correlated earthquake sequences we will first transform the inter-earthquake times to a Gaussian distributed space, do the simulation in that space with a Gaussian distribution random number generator, and then transform the inter-event times back to the original space in hours. This transformation will be done using the observed distribution of inter-earthquake times in order to preserve these distributions in the simulations. In later sections we will refer to these simulations as the FOA model, after the initials of first-order autoregression.

In reality, this first-order autoregression process underestimates the amount of clustering. This is especially true for the data on the Reunion-Omsk path where the first 21 values of the auto-correlation function exceed the 95% confidence level. However, to make a more complete model of the clustering requires adding a much greater level of complexity to the modeling process. The Poisson, empirical, and FOA models each use a single statistical process to model the time history of earthquakes. A more complete model would be to superimpose a physical model of earthquake clustering (such as a modified Omori law for aftershocks) on a Poisson distribution of mainshocks. This level of complexity does not seem warranted for this paper, but it is important to note that even the FOA model underestimates the amount of clustering actually present in the data.

Method

Figure 6 shows a time line of the anomaly, dropout, and earthquake data for the Liberia-Omsk and Reunion-Omsk paths. This is the essential data that we will use to determine if the anomalies are precursors to the earthquakes. The question is do the anomalies preferentially precede the earthquakes. The answer to this question is not apparent, partially because there are many earthquakes and many anomalies.

Marenko (1989b) approached this problem by converting the data shown in Figure 6 into two binary time series with a sampling rate of one day. For each day the anomaly time series was either 0 if there was no anomaly and 1 if there was an anomaly. Similarly, the earthquake time series was 0 if there was no earthquake that day and 1 if there was one or more earthquakes that day. It is not clear how data dropouts were included in these time series. Then Marenko (1989b) took these two time series and computed a cross-correlation with shifts from -15 to 15 days, such that positive correlations at positive shifts would imply that the earthquakes preferentially follow the anomalies. This was done for both the Liberia-Omsk path and the Reunion-Omsk path. For the latter path he also looked at $M \geq 5$ earthquakes and subsets based on the depth of the earthquake. His results show the highest cross-correlations at shifts of 0 to 2 days depending on the data set analyzed. In order to determine if these results could have been caused by random chance he used a Poisson model to produce analytic results and found probabilities of less than 0.01 for all the data sets. This suggests that there is a real relationship between the anomalies and earthquakes, but is based on a Poisson model that we have shown does not adequately describe the earthquake data.

We have chosen not to replicate Marenko's method for several reasons. First, it is hard to interpret what the cross-correlation values mean; while positive cross-correlation values suggest a relationship it is hard to know how useful that relationship is. Second, the sampling of the data into daily samples is very arbitrary and the samples are large with respect to the average inter-anomaly and inter-earthquake times. Thus, it is likely that many days will have both anomalies and earthquakes and by using daily windows we loose the information about which happened first on a given day. Third, because the earthquake data he used have been lost it would not be possible to completely replicate his results. Fourth, even if we used this method we would have to redo the statistics because we do not believe the Poisson model is adequate.

The formulation used in this paper is based on declaring prediction windows after the radio phase anomalies. This formulation is summarized in Figure 7. We start with the radio observations which consist of anomalies and dropouts. A prediction window begins *shift* hours after the beginning of each anomaly and lasts until *shift* + *duration* hours after the end of the anomaly. Thus the window lasts for *duration* hours plus the length of the anomaly. The values of *shift* and *duration* are the free parameters that define the prediction windows. Due to the data dropouts there are also times when we don't know whether or not there is a prediction window, these are referred to as the unknown windows, and like the prediction windows they also vary as different values for *shift* and *duration* are chosen. The time not contained in either prediction or unknown windows will be referred to as other time. We have no theoretical reason to prefer any particular value of *shift* and *duration*, so we will search over a range of values to determine the optimal fit between the anomalies and earthquakes. To determine this optimal fit we need a measure of how well the earthquakes fall into the prediction windows.

Once the prediction and unknown windows are determined we can count the number of earthquakes that occur during the prediction (N_p), unknown (N_u), and other (N_o) time periods and compute the total duration of the prediction (T_p), unknown (T_u), and other (T_o) windows. The rate of earthquakes during prediction windows is $R_p = N_p / T_p$ and the rate of earthquakes during the other windows is $R_o = N_o / T_o$. The rate during the unknown windows can also be determined but is not useful. If the anomalies preferentially precede earthquakes by *shift* to *shift* + *duration* hours then the rate of earthquakes during the prediction windows (R_p) should be greater than the rate of earthquakes during the other windows (R_o). Thus, our overall prediction success measure is the rate difference: $R_d = R_p - R_o$. The larger the rate difference, R_d, the more successful the radio anomalies are at predicting the earthquakes. An alternative measure would be to use the ratio R_p / R_o; however for large values of *duration* T_o is very small and this ratio becomes unstable.

The next step is selecting values for *shift* and *duration*. In Marenko (1989b) *duration* was essentially held fixed to 24 hours while *shift* was varied over ±15 days. Thus, they only tested the hypothesis that there is a fixed offset (within a precision of 24 hours) between the time of an anomaly and the time of an earthquake. This is an unusual hypothesis in earthquake prediction, instead it is more common to test if an earthquake will come during a time period that starts right after the anomaly being tested. This would be the same as holding *shift* at 0 and varying *duration*. Using negative values for *shift*, as done in the previous study, tests if the earthquakes precede the anomalies. While this broader search is interesting we did not do this because our goal is only to see if the anomalies precede the earthquakes and not to make a full search for any relationship between the two. Also, if there is a precursory relationship, searching for the opposite relationship too could decrease the computed statistical significance of the result and cause us to miss the successful result.

To make a complete test we combined the previous study where only *shift* was varied and the more common seismological approach of varying *duration* by varying both of them. The *duration* was allowed to vary from 4 hours to 120 hours, in steps of 4 hours. The value of 120 was chosen as a stopping point because this is much greater than the average time between anomalies and beyond that value there is little change in the combined length of the prediction windows. The *shift* was varied from 0 to 240 hours, slightly less than used in the previous study. This was done because their best correlations occurred at 0 to 100 hours. Like *duration*, *shift* was changed in steps of 4 hours. The actual results do not strongly depend on the choice of either the step size or the search ranges.

For each pair of values for *shift* and *duration*, the rate difference (R_d) was computed. These values can be displayed as varying colors on a grid with *shift* and *duration* on the axes. The best result is the highest value of R_d, called R_d^{max}. The next question is how large does R_d^{max} need to be before the prediction method with that value of *shift* and *duration* is considered a success. We answer that question by comparing the observed results to a null hypothesis that assumes no relationship between the anomalies and earthquakes. Instead the null hypothesis assumes that the earthquakes are randomly distributed with respect to the anomalies. We then compute the probability of getting the observed value, or higher, of R_d^{max} by random chance.

To compute this probability we produce a random simulation of the earthquake series. This is done with either Poisson, empirical, or FOA models. Then, we again search over the values of *shift* and *duration* to determine R_d^{max} for the simulated data. This process is repeated many times for different simulations of the earthquake series, yielding a distribution of R_d^{max} values if the earthquakes are randomly distributed with respect to the anomalies. By comparing R_d^{max} for the real earthquake data to the distribution of values for the simulations we can determine the statistical significance of the real result.

The fraction of simulated $R_{d_{max}}$ values that are greater than or equal to the R_d^{max} value for the real earthquake data is the probability that the observed result, or a better result, could be obtained by random chance. This probability, known as the *p−value*, is our primary measure of success and is the probability that we will be incorrect if we reject the null hypothesis and instead believe that there is a real relationship between the anomalies and earthquakes. A standard test is to reject the null hypothesis and accept that there is a real, statistically significant, relationship if the *p−value* is less than or equal to 0.05. In the results shown below, 1000 simulated runs are used to determine each *p−value*, experiments with repeated sets of 1000 runs suggest that the p-values are accurate to approximately ±0.005.

Note, that when doing the simulations it is critical that we vary *shift* and *duration* in the same manner as when analyzing the actual data. The hypothesis being tested is if there is a higher rate of earthquakes in the windows defined by the anomalies and all tested values of *shift* and *duration*. If we limit the simulations to the values of *shift* and *duration* that produced the observed R_d^{max} value then we are testing a much more limited hypothesis which was determined from the data being analyzed. This is a process known as data fitting that should be avoided.

Results

The results of searching over *shift* from 0 to 240 hours and *duration* from 0 to 120 hours for the Liberia-Omsk and Reunion-Omsk data sets are shown in Figure 8. For these tests the earthquake data are selected as in Marenko (1989b): those with $M \geq 4$ that are within 1000 km of the great circle path connecting the transmitter and receiver.

For the Liberia-Omsk data set R_d^{max} occurs for *shift* = 42 and *duration* = 4. For these values the rate of earthquakes during prediction windows (R_p = 0.058 events/hour) is 70% higher than the rate during other times (R_o = 0.034 events/hour) for a difference of $R_d = 0.024$. When the Poisson model, which has no clustering in it, is used to simulate the earthquakes 6% of the simulated values of R_d^{max} are greater than or equal to this real value of R_d^{max} (Figure 8). This is a *p–value*=0.06 which is almost low enough to be considered a success. However, if the empirical model is used to simulate the earthquake sequences then the *p–value* increases to 0.13 and if the FOA model is used the *p–value* increases to 0.18. Neither of these values would be considered a success.

For the Reunion-Omsk data set the highest real value of R_d occurs for *shift* = 216 and *duration* = 116. For these values the rate of earthquakes during prediction windows (R_p = 0.043 events/hour) is 616% higher than the rate during other times (R_o = 0.006) events/hour for a difference of $R_d = 0.037$. When the Poisson model is used to simulate the earthquakes, 4% of the simulated values of R_d^{max} are greater than or equal to this real value of R_d^{max} (Figure 8). This is a *p–value*=0.04 which is low enough to be considered a success. However, if the empirical model is used to simulate the earthquake sequences then the *p–value* increases 0.11 and if the FOA model is used the *p–value* increases to 0.14. Neither of these values would be considered a success.

The Poisson, empirical, and FOA models each simulate aspects of the earthquake data and do a successively better job of simulating the observed earthquake data. The best measure of the *p–value* will come from the best simulation of the earthquake data. All three models have been used to illustrate how the choice of model affects the estimated *p–value* and because Marenko (1989b) used the Poisson model which is the weakest of the three. There is a simple reason why the *p–value* increases as the amount of the clustering in the simulations increases. For each simulated earthquake data set we determine R_d^{max} as *shift* and *duration* are varied. Thus, we are searching for the optimal relationship. When the earthquakes are independent and randomly spread out in time, as in the Poisson model, extreme behavior is unlikely to occur and the R_d^{max} values found in the simulations are relatively low. When the simulated R_d^{max} values are low, the real R_d^{max} value will be high with respect to the simulated values and the *p–value* will be low. As more clustering is included in the simulations more extreme behavior will occur and we observe higher R_d^{max} values in the random simulations. This, in turn, makes the R_d^{max} for the actual data value less significant. The empirical model has more clustering than the Poisson model and the FOA model has more clustering than the empirical model. Thus, it makes sense that using the FOA model yields the highest *p–values*. The actual earthquake data has even more clustering than the FOA model and so even the results from the FOA model probably underestimate the *p–values*.

In these results we have varied the parameters *shift* and *duration*, but in reality there are a variety of other parameters used to define each of the data sets. For instance, a radio anomaly was declared if the data at the given time was over two standard deviations from the monthly mean. There are two arbitrary parameters involved: the choice of monthly for the averaging interval and the two standard deviation criteria. However, because we don't have access to the original radio data we can not analyze the effect of these choices.

The earthquake data are selected by using two parameters: a minimum magnitude and a maximum distance from the great circle path connecting the transmitter and receiver. Marenko (1989b) also looked at data sets for earthquakes with different depths. Another set of arbitrary parameters is the start and end times of the experiment. Below we will vary each of these parameters and see how much it effects the results.

Given that the FOA model is the best of the three ways to estimate the amount of clustering in the earthquake data, these experiments will be done only with the FOA model.

In Figure 9 the results for the full time period are compared to results for the first and second halves of the time period. For the Liberia-Omsk data set the first half results are similar to the full time period results, although the *p−value* level is much higher at 0.32. However, for the second half of the time period the location of the R_d^{max} value moves from a short duration to a very long duration and the *p−value* increases to 0.65. Similar results are seen for the Reunion-Omsk data set, except that now the R_d^{max} value moves from being located at large to small *shift* values, from the first to second half of the time period. These results show that the relationship between the anomalies and earthquakes is not stable with respect to time and suggests that the relationship is not real.

In Marenko (1989b) they looked at earthquakes that occurred at all depths, above 40km, and below 40 km from sea level. Figure 10 shows the effect of these choices on the two data sets. Most of the earthquakes in these areas are shallower than 40 km, so it is not surprising that these results closely resemble the original results. However, the deep earthquakes also show similar results.

Figure 11 shows the effect of 50% changes in the maximum distance earthquakes can be from the great circle path. For Liberia-Omsk the maximum distance makes a small difference in the location of R_d^{max} and as less data is include the *p−value* increases. The same is true for the Reunion-Omsk data set, except here we note that for a maximum width of 1500 km the p-value is 0.05 and suggests a successful result.

Figure 12 shows the effect of increasing the minimum earthquake magnitude used from 4.0 to 4.5 and 5.0. For the Liberia-Omsk case increasing the minimum magnitude does not change the location of R_d^{max} but has a strong effect on the *p−values*. At $M \geq 4.5$ the p-value has fallen to 0.02 but at $M \geq 5$ it has risen again to 0.14. So, although we do have a result that is significant at below the 0.05 level there is not a simple relationship that the larger earthquakes tend to be predicted more than the smaller ones. For the Reunion-Omsk case there are some changes in the R_d values as a function of *shift* and *duration* but the results all have high *p−values*.

The final investigation was to look at the effect of varying both *shift* and *duration*. As discussed earlier, Marenko (1989b) varied only *shift* while some other prediction studies hold *shift* to zero and vary only *duration* (e.g. Keilis-Borok and Kossobokov, 1990). We tried setting *duration* to 24 hours and varying *shift* up to 240 hours and received a result with a *p−value* of 0.39 for the Liberia-Omsk path and 0.13 for the Reunion-Omsk path. The optimal fits in Marenko (1989b) were obtained for *shift* at about 0 to 48 hours, well within the search range used here. Thus, we attribute the apparent success in Marenko (1989b) to the use of the Poisson model.

Holding *shift* at 0 and varying *duration* from 4 to 120 hours gave *p-values* values of 0.35 for the Liberia-Omsk data and 0.21 for the Reunion-Omsk data.

Discussion

The two tantalizing results are the *p-value* = 0.02 obtained for the Liberia-Omsk data when using only earthquakes with $M \geq 4.5$ and the *p-value* = 0.05 for the Reunion-Omsk path with a maximum width of 1500 km. These results can be discounted for three reasons. First, for the Liberia-Omsk path the *p-value* increases again when increasing the minimum magnitude to 5.0. Second, in this section we have discussed the results for 22 different analyses using the one-step model. When doing many independent experiments, one expects 5% of them to have *p-value* ≤0.05 simply due to random chance. The 22 experiments discussed here are not truly independent but it is still not very surprising that two results have *p-value* ≤ 0.05. Third, even the FOA model used for these analyses underestimates the amount of clustering in the earthquake catalogs and thus also underestimates the *p-values*. Hence, if a different model with greater clustering was used we would expect all of these *p-values* to increase. This would further undermine the apparent success of these two results.

Marenko (1989b) showed 5 analyses. For the Reunion-Omsk data set he looked at $M \geq 4$ and $M \geq 5$. Also, for $M \geq 4$ he separated the data into the three depth ranges. For the Liberia-Omsk path he only show an analysis of the $M \geq 4$ and all depths combined. Each of these 5 analyses yielded *p-value* ≤ 0.01 That result is very unlikely and so the relationship between the anomalies and the earthquakes appeared real. However, their *p-values* were determined using the Poisson model which greatly under-estimates the true *p-values*.

A further problem with believing that this prediction technique works is that the values of *shift* and *duration* that yield R_d^{max} vary greatly depending on the data set used and the time period analyzed. If there was a physical process that produced these anomalies before earthquakes we might expect it to be similar for both paths and certainly would expect it to be similar for the two arbitrarily chosen time periods. Hence, the observed differences suggest that the results are due to a random process.

Conclusions

The goal of this study was to make an independent assessment of whether the data presented in Marenko (1989b) support the idea that phase anomalies observed in the VLF band are precursors to earthquakes. To do this we have proposed a method of parameterizing this relationship in terms of the time between anomalies and subsequent earthquakes (*shift* and *duration*). To evaluate this relationship we propose a measure of success that is the difference in the rate of earthquake occurrence measured during the prediction and other windows and maximized over a search of *shift* and *duration* (R_d^{max}). To estimate the statistical significance of observed values of R_d^{max} we have simulated the earthquake data using three models with increasing levels of clustering (the Poisson, empirical, and FOA models). And finally we have varied the available free parameters that were used to define the data set in order to test how robust the results are.

The location of the best result (R_d^{max}) with respect to *shift* and *duration* varies depending on the path and time period analyzed. Thus, no single relationship between the anomalies and the earthquakes has emerged. While regional differences in this proposed relationship are possible, it seems very unlikely that large differences should occur depending on arbitrarily chosen time periods. This suggests that the observed relationships are due to a random, rather than physical, process.

The statistical significance of the observed results are also low, especially when using a model that includes clustering in the earthquake data. As expected the methods that have less clustering produce lower *p–values*. Marenko (1989b) used only the Poisson method which has no clustering. In our tests using the Poisson model yielded *p–values* about 0.1 higher than using the FOA model. The one-step model still underestimates the real amount of clustering in the data. Thus, we conclude that the *p–values* determined by Marenko (1989b) were underestimated and contributed to his conclusion that the anomalies do precede the earthquakes.

Varying the magnitude, depth, and maximum distance from the central path used to select the earthquakes show that some of these parameters can be adjusted to obtain more significant results. However, the adjustment in magnitude produces unstable results. Out of 22 choices of parameters only two of the results have *p–values* below 0.05 and most have *p–values* greater than 0.1. This suggests that the two significant results demonstrate the dangers of data fitting by varying free parameters and do not demonstrate support for the proposed precursory relationship.

This leads to our conclusion that the observed phase anomalies are probably not earthquake precursors. The greatest difficulty in analyzing this data came from the many data dropouts; however, if future work on this topic is done we do not recommend collecting similar data of higher quality and again searching for a relationship. This might take a few years to complete. Instead, we note that these phase anomalies occur frequently and therefore making detailed electromagnetic and atmospheric observations along a path may quickly lead to a physical explanation for these anomalies. This physical explanation should then help us learn if these anomalies are caused by something in the crust related to earthquakes.

Acknowledgements

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Captions

Figure 1. A map showing the locations of the Liberia and Reunion Omega transmitters and the great circle path that connect them to the receiver in Omsk. Also shown are the earthquakes with $M \geq 4$ within 1000 km of the Liberia-Omsk path (crosses) and Reunion-Omsk path (circles).

Figure 2. Histograms of the start and end hours of the day (in GMT) for the Liberia-Omsk and Reunion-Omsk paths.

Figure 3. The cumulative distribution of the earthquakes along the Liberia-Omsk and Reunion-Omsk paths with respect to magnitude. The dots show the observed distributions and the line shows the least squares fit to the observations over the magnitude range shown below each figure. The *a* and *b* values for the lines are also shown below the figures.

Figure 4. Histograms of the inter-earthquake times for the events along the Liberia-Omsk and Reunion to Omsk paths. The more solid line is the observed data and the dashed line is the prediction of a Poisson model with the mean inter-earthquake time taken from the observed data.

Figure 5. Autocorrelation Functions for the earthquake interevent times along the Liberia-Omsk and Reunion-Omsk path. These functions are computed by first finding the earthquake interevent time series in which the abscissa is an integer index that increases one unit for each successive earthquake and the ordinal is the time between that earthquake and the next earthquake. Then the autocorrelation is computed for the earthquake interevent time series and the lag is the offset in terms of the integer abscissa. The horizontal dashed lines show 95% confidence thresholds for the autocorrelation values. These plots are done with the earthquake interevent times transformed using their empirical interevent time distribution to a normally distributed space.

Figure 6. The anomaly, data dropout, and earthquakes along each path are shown on a timeline. The anomalies and data dropouts are shown as horizontal line segments connecting their starting and ending times. The earthquakes are shown as vertical lines at their origin time with heights linearly proportional to their magnitudes. Tall vertical lines at the beginning and end of each timeline show the dividing points between successive lines.

Figure 7. A cartoon outlining the definition of prediction windows from *shift* to *shift+duration* hours after radio anomalies and unknown time periods due to data dropouts. The earthquakes are then compared to the prediction windows, unknown and other time periods.

Figure 8. Results for the Liberia-Omsk and Reunion-Omsk data sets. In the top color shaded figures, values of the rate difference R_d are displayed for various choices of *shift* and *duration*. The color scale ranges from blue for the lowest values through white to red for higher values, with a yellow square used to emphasize the highest level (R_d^{max}). The range of R_d values is shown below the plot. At the bottom are histograms of the R_d^{max} values obtained during the 1000 simulations of each data set. The black line shows results for the Poisson model, the green line for the empirical model, and the red line for the FOA model. The vertical black line shows the level of the highest value of R_d from the real data and is labeled with the *p−values* obtained

from the three earthquake simulation models.

Figure 9. The effect of choosing the time period analyzed is shown by comparing the results from figure 8 to results obtained by analyzing the first and second halves of the total time period. Each of the six plots shows values of the rate difference (R_d) shaded from blue for the lowest values to red for the largest, with a yellow square used to emphasize the highest (R_d^{max}). The range of R_d values is shown below each plot. The *p−value* obtained by using the FOA model is given above each plot. The range of R_d is given below each plot.

Figure 10. The effect of limiting the focal depth of the earthquakes to above or below 40 km is shown and compared to the results for all depths shown in Figure 8. Each of the six plots shows values of the rate difference (R_d) shaded from blue for the lowest values to red for the largest, with a yellow square used to emphasize the highest (R_d^{max}). The range of R_d values is shown below each plot. The *p−value* obtained by using the FOA model is given above each plot. The range of R_d is given below each plot.

Figure 11. The effect of changing the maximum distance between the great circle path and an earthquake used in the analysis is shown. The results for maximum distances of 500, 1000, and 1500 km are shown. The results for 1000 km are the same as from Figure 8. Each of the six plots shows values of the rate difference (R_d) shaded from blue for the lowest values to red for the largest, with a yellow square used to emphasize the highest (R_d^{max}). The range of R_d values is shown below each plot. The *p−value* obtained by using the FOA model is given above each plot. The range of R_d is given below each plot.

Figure 12. The effect of changing the minimum magnitude of the earthquakes used in the analysis is shown. The results for minimum magnitudes of 4.0, 4.5, and 5.0. The results for 4.0 are the same as from Figure 8. Each of the six plots shows values of the rate difference (R_d) shaded from blue for the lowest values to red for the largest, with a yellow square used to emphasize the highest (R_d^{max}). The range of R_d values is shown below each plot. The *p−value* obtained by using the FOA model is given above each plot. The range of R_d is given below each plot.

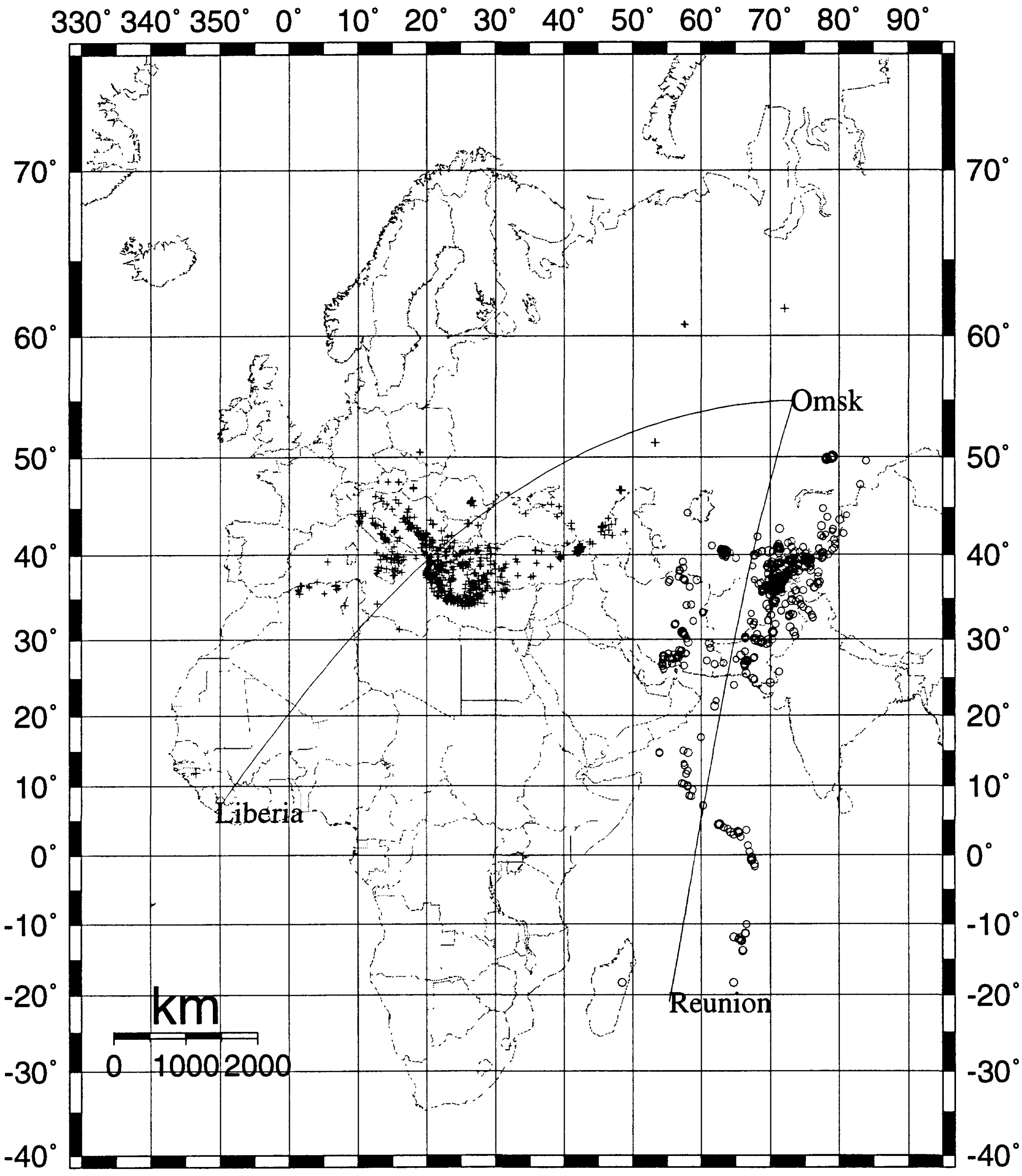

330° 340° 350° 0° 10° 20° 30° 40° 50° 60° 70° 80° 90°
70° 60° 50° 40° 30° 20° 10° 0° -10° -20° -30° -40°
Omsk
Liberia
Reunion
km
0 1000 2000

Figure 1

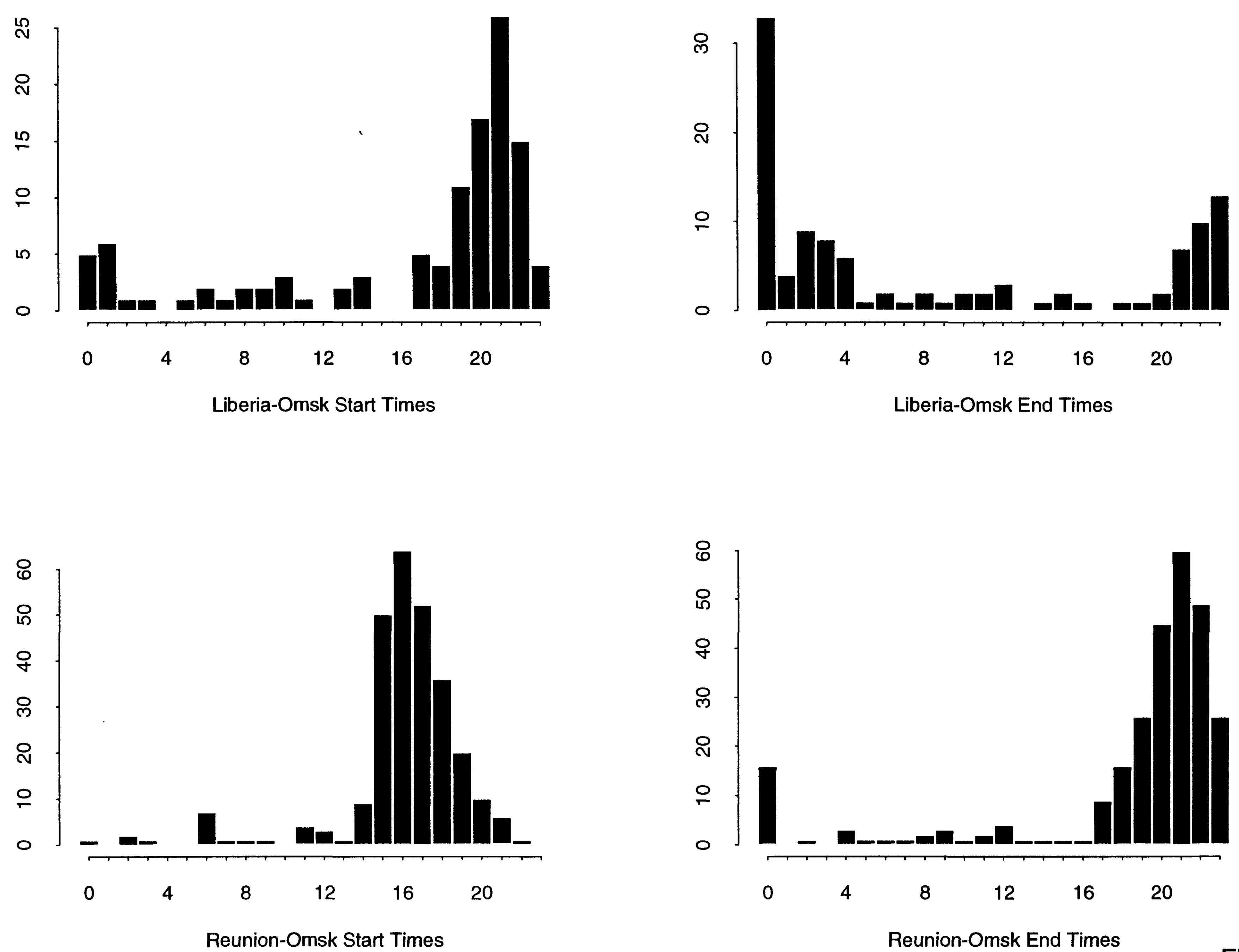

25
20
15
10
5
0
0
4
8
12
16
20
Liberia-Omsk Start Times
30
20
10
0
0
4
8
12
16
20
Liberia-Omsk End Times
60
50
40
30
20
10
0
0
4
8
12
16
20
Reunion-Omsk Start Times
60
50
40
30
20
10
0
0
4
8
12
16
20
Reunion-Omsk End Times

Figure 2

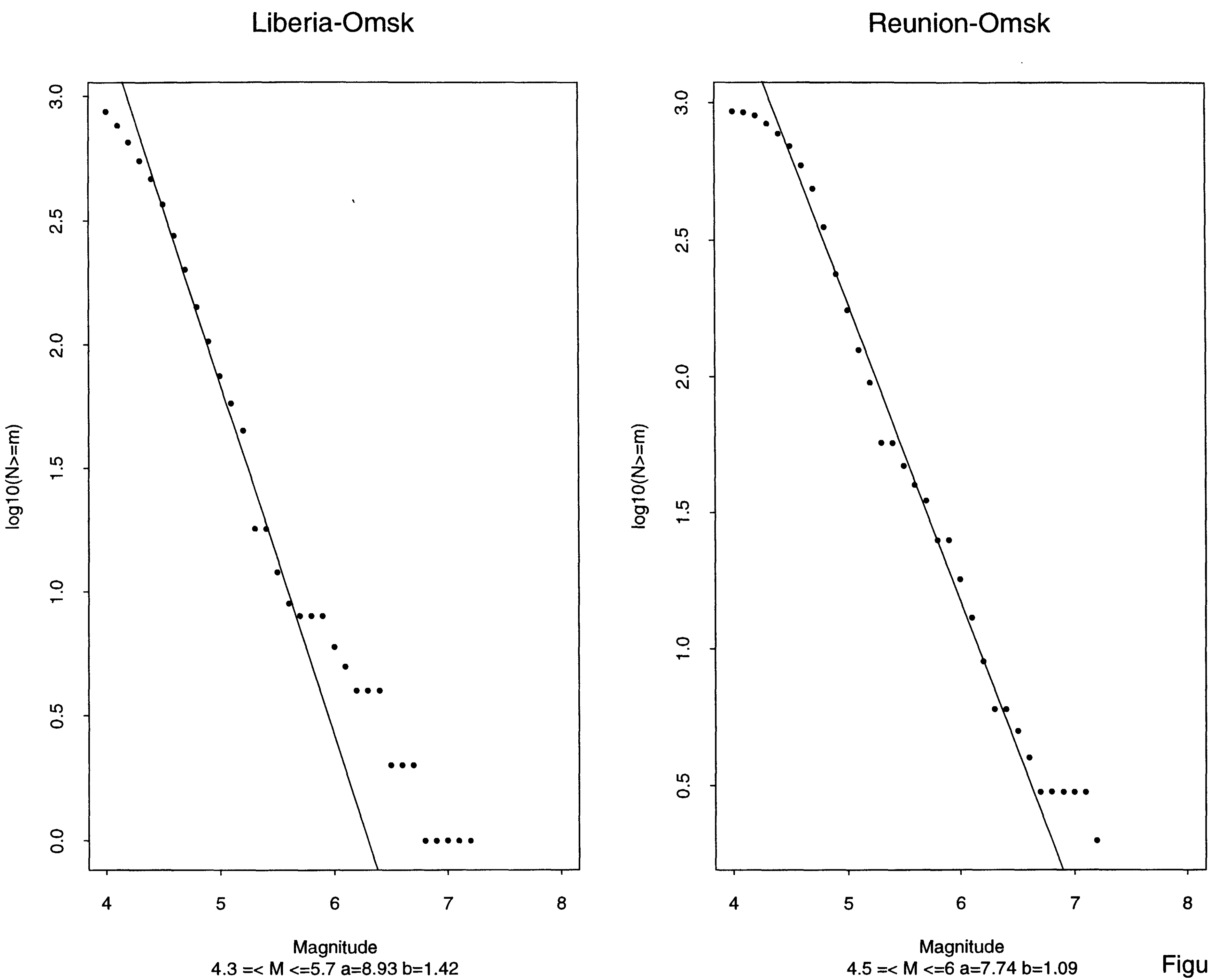

Liberia-Omsk
log10(N>=m)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
4
5
6
7
8
Magnitude
4.3 =< M <=5.7 a=8.93 b=1.42
Reunion-Omsk
log10(N>=m)
3.0
2.5
2.0
1.5
1.0
0.5
4
5
6
7
8
Magnitude
4.5 =< M <=6 a=7.74 b=1.09

Figure 3

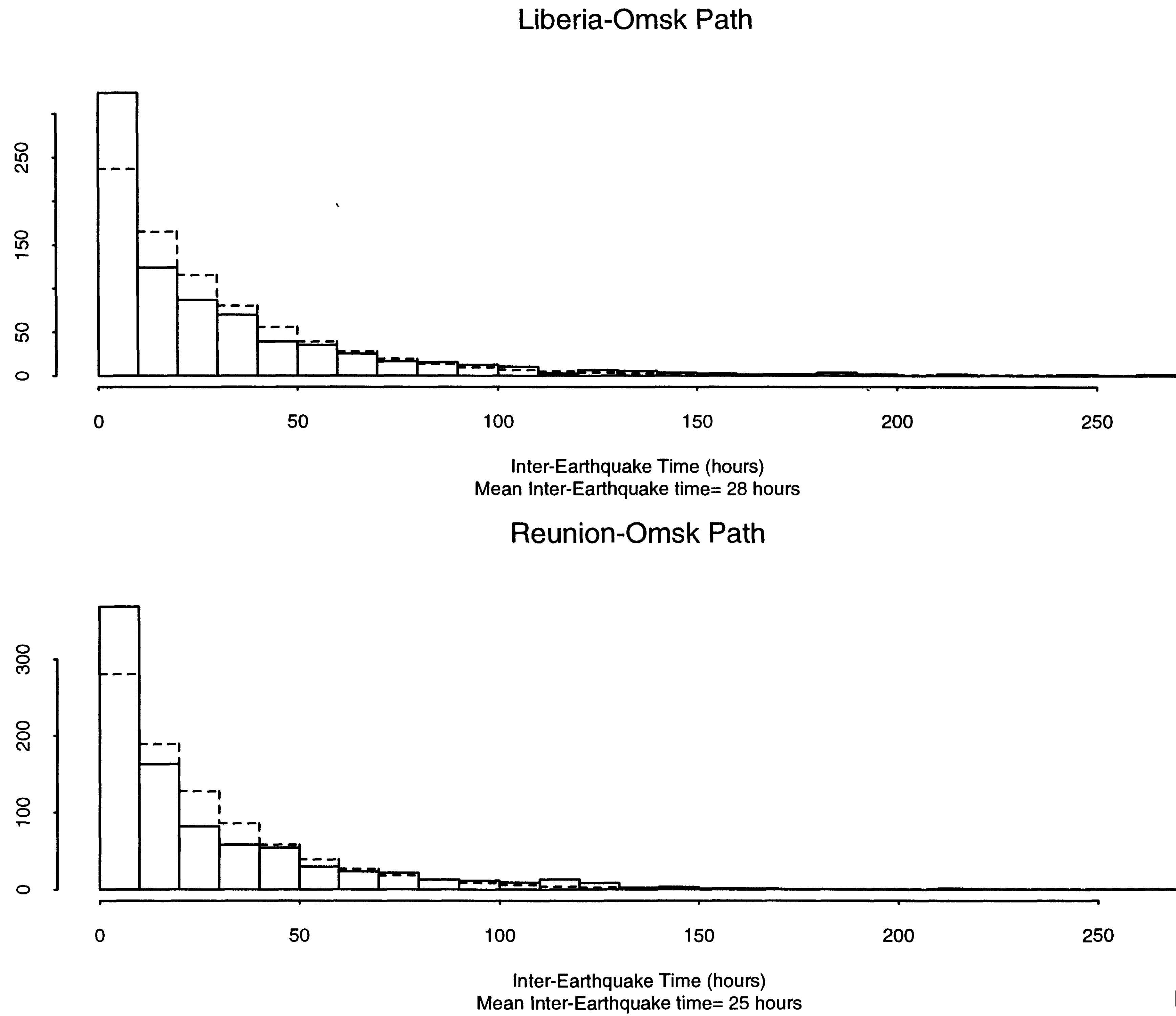
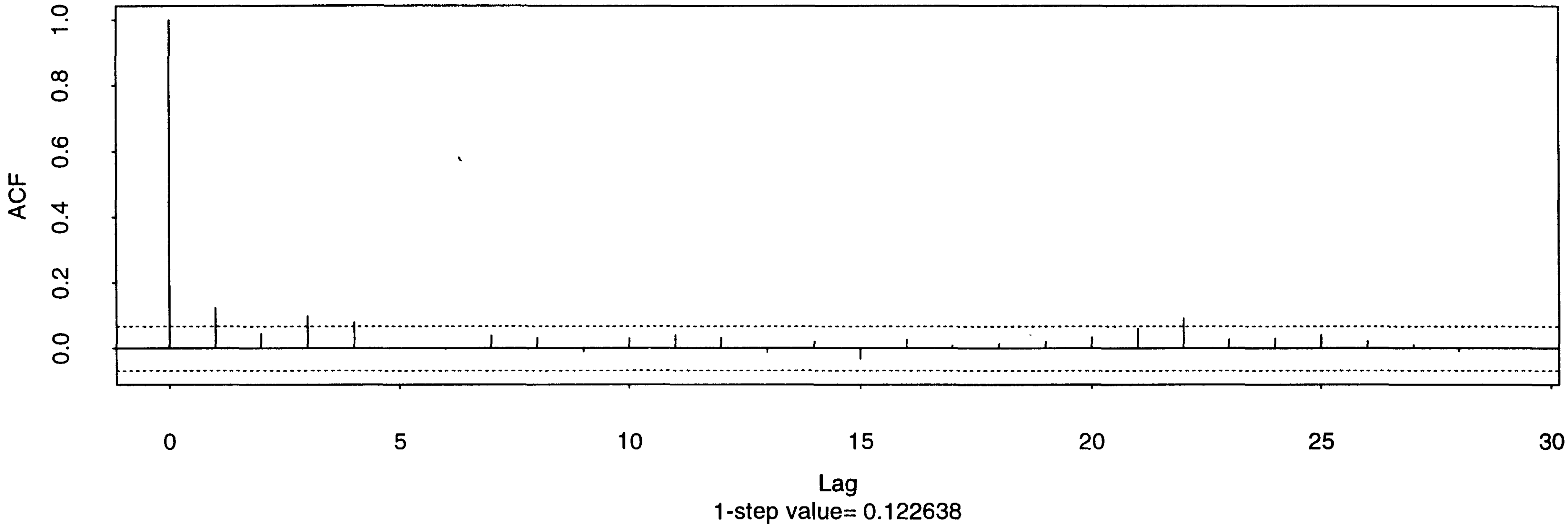

Liberia-Omsk Path
0
50
150
250
0
50
100
150
200
250
Inter-Earthquake Time (hours)
Mean Inter-Earthquake time= 28 hours
Reunion-Omsk Path
0
100
200
300
0
50
100
150
200
250
Inter-Earthquake Time (hours)
Mean Inter-Earthquake time= 25 hours

Figure 4

Series : Liberia-Omsk Interevent Values



Series : Reunion-Omsk Interevent Values

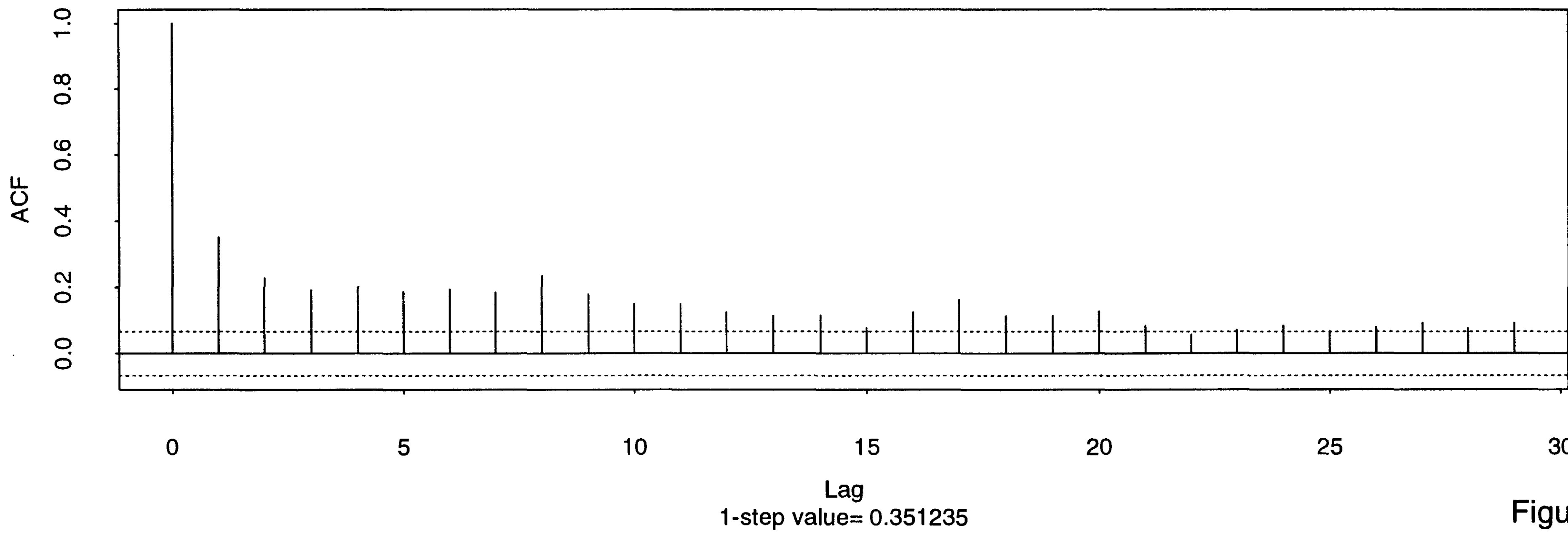


Figure 5

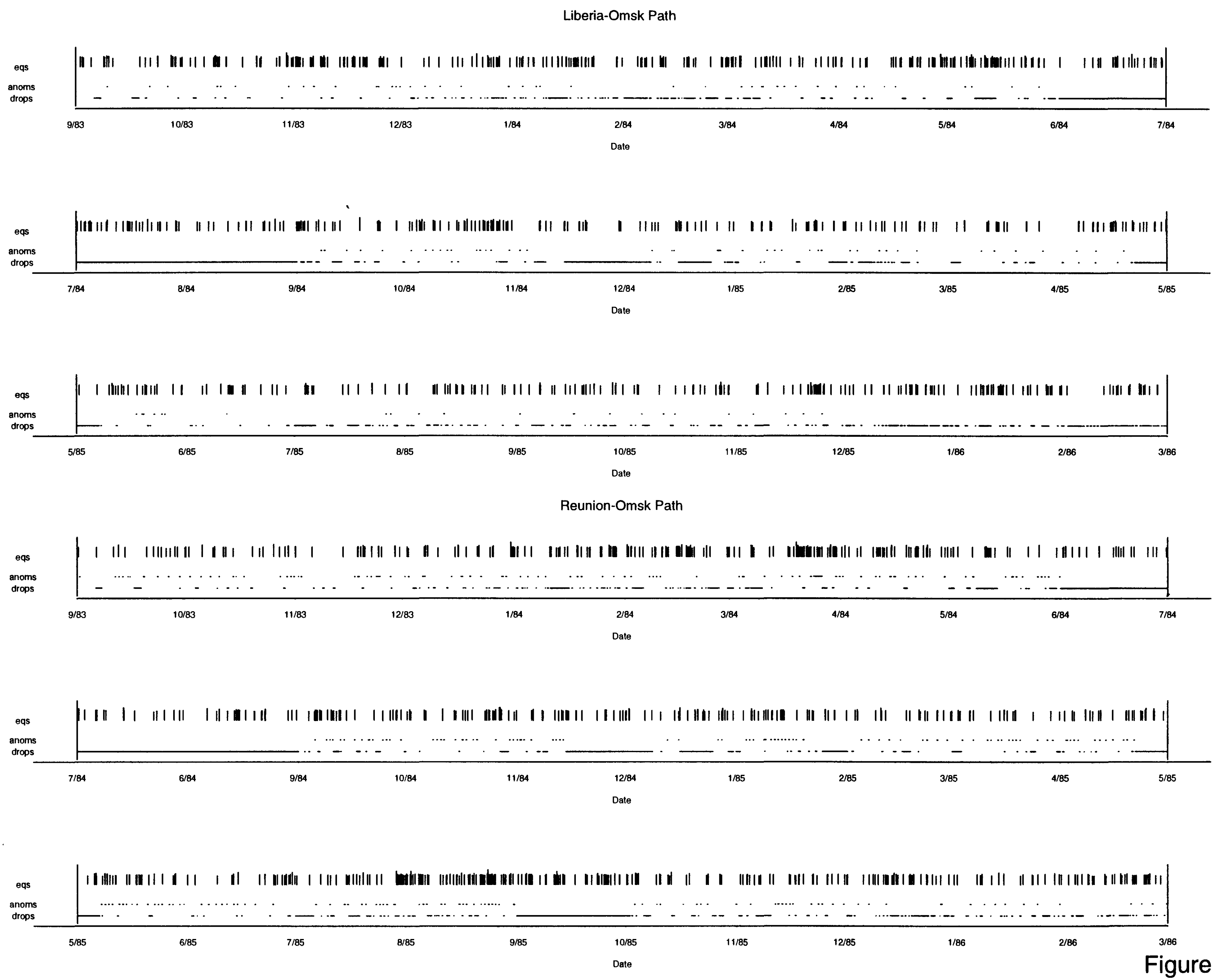

Liberia-Omsk Path
eqs
anoms
drops
9/83
10/83
11/83
12/83
1/84
2/84
3/84
4/84
5/84
6/84
7/84
Date
eqs
anoms
drops
7/84
8/84
9/84
10/84
11/84
12/84
1/85
2/85
3/85
4/85
5/85
Date
eqs
anoms
drops
5/85
6/85
7/85
8/85
9/85
10/85
11/85
12/85
1/86
2/86
3/86
Date
Reunion-Omsk Path
eqs
anoms
drops
9/83
10/83
11/83
12/83
1/84
2/84
3/84
4/84
5/84
6/84
7/84
Date
eqs
anoms
drops
7/84
6/84
9/84
10/84
11/84
12/84
1/85
2/85
3/85
4/85
5/85
Date
eqs
anoms
drops
5/85
6/85
7/85
8/85
9/85
10/85
11/85
12/85
1/86
2/86
3/86
Date

Figure 6

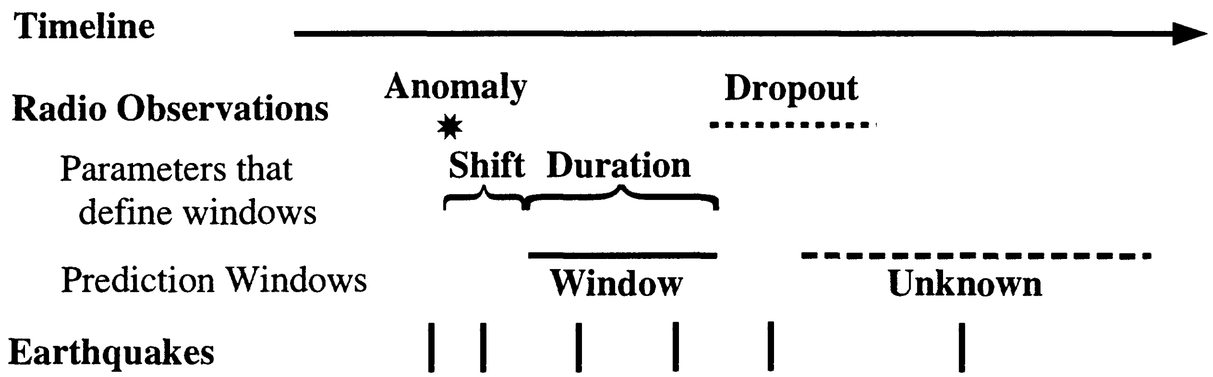
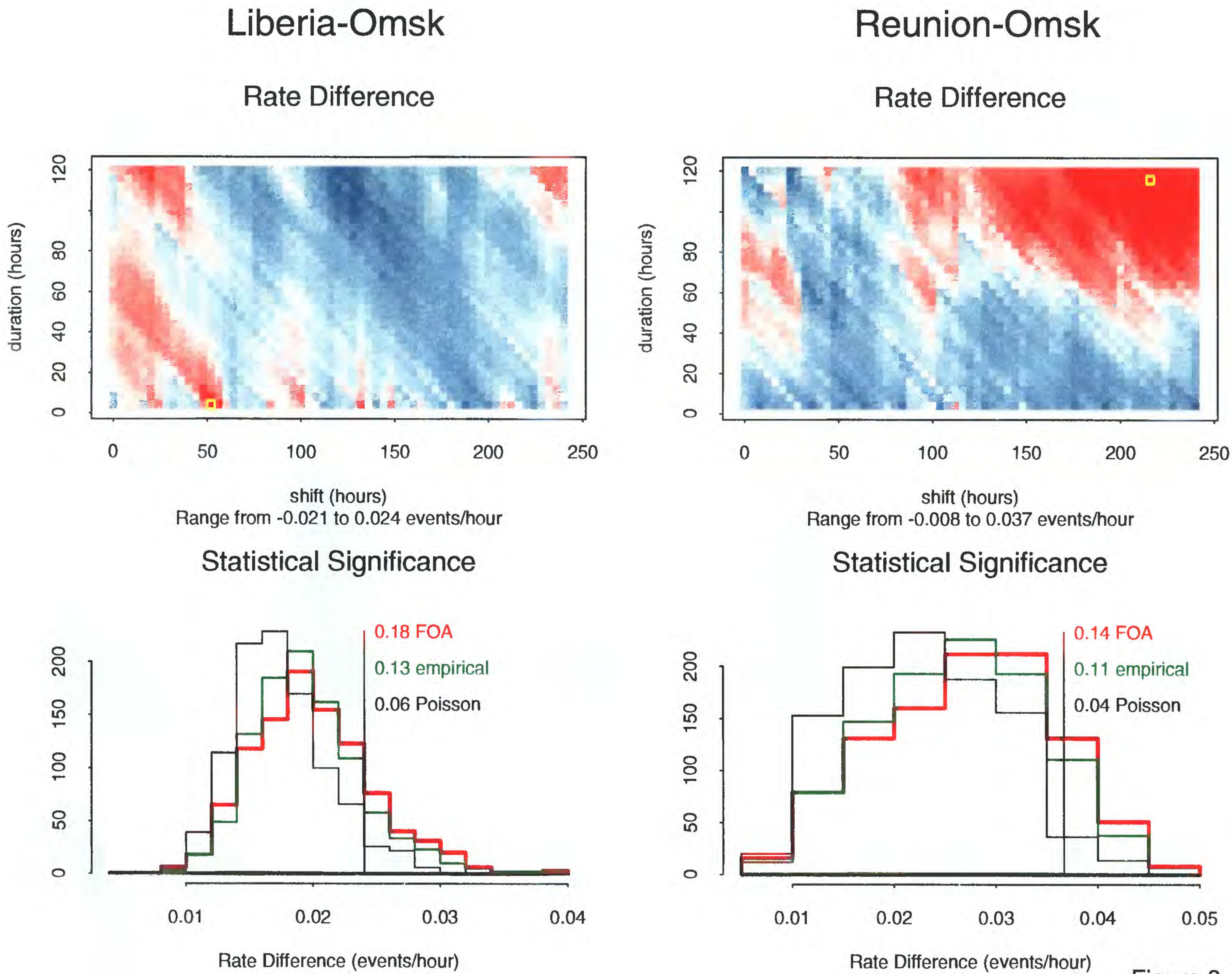

Timeline
Radio Observations
Anomaly
Dropout
Parameters that define windows
Shift
Duration
Prediction Windows
Window
Unknown
Earthquakes

Figure 7



Liberia-Omsk
Reunion-Omsk
Rate Difference
duration (hours)
shift (hours)
Range from -0.021 to 0.024 events/hour
Range from -0.008 to 0.037 events/hour
Statistical Significance
0.18 FOA
0.13 empirical
0.06 Poisson
0.14 FOA
0.11 empirical
0.04 Poisson
Rate Difference (events/hour)

Figure 8

Effect of Chosen Time Period

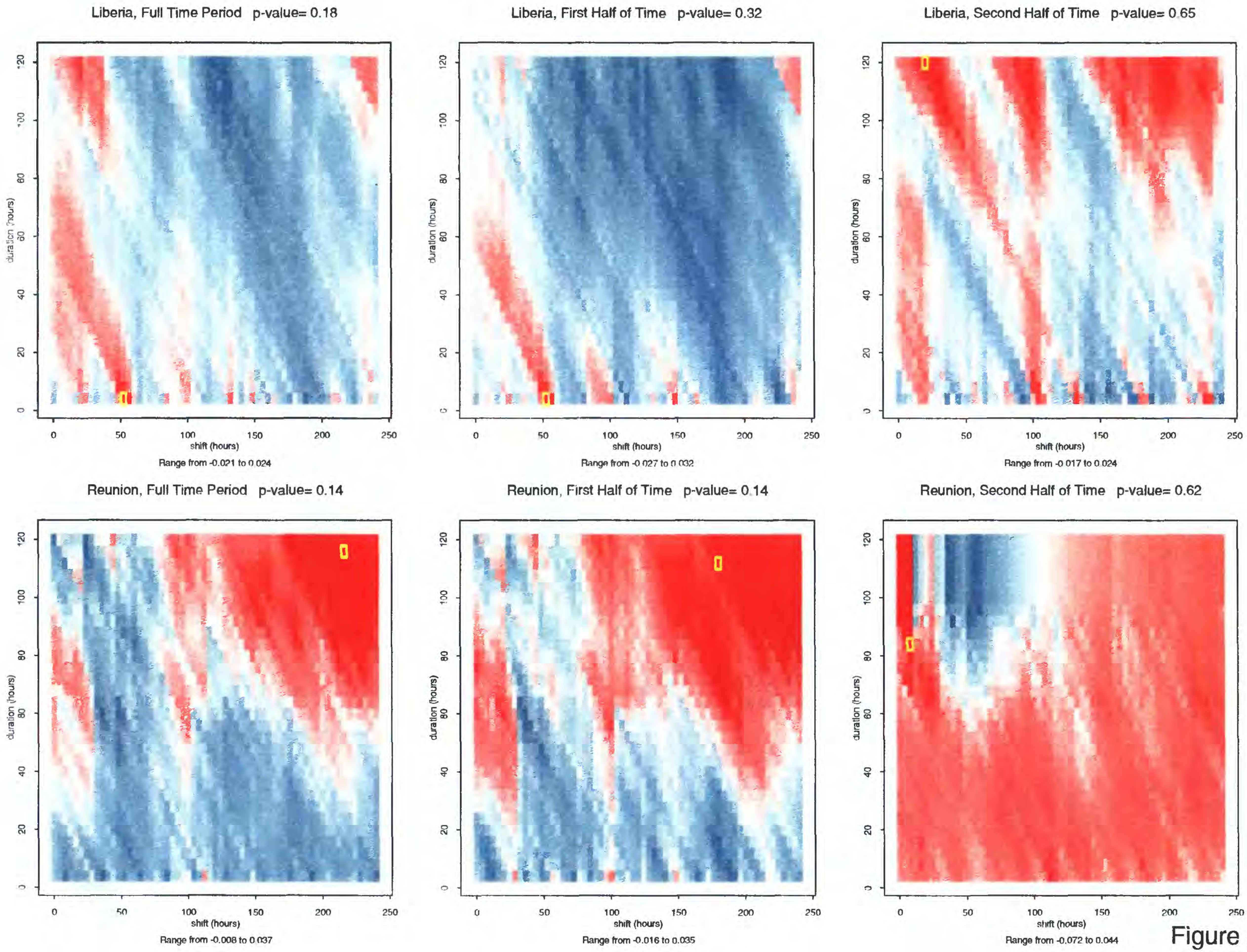


Figure 9

Effect of Focal Depth

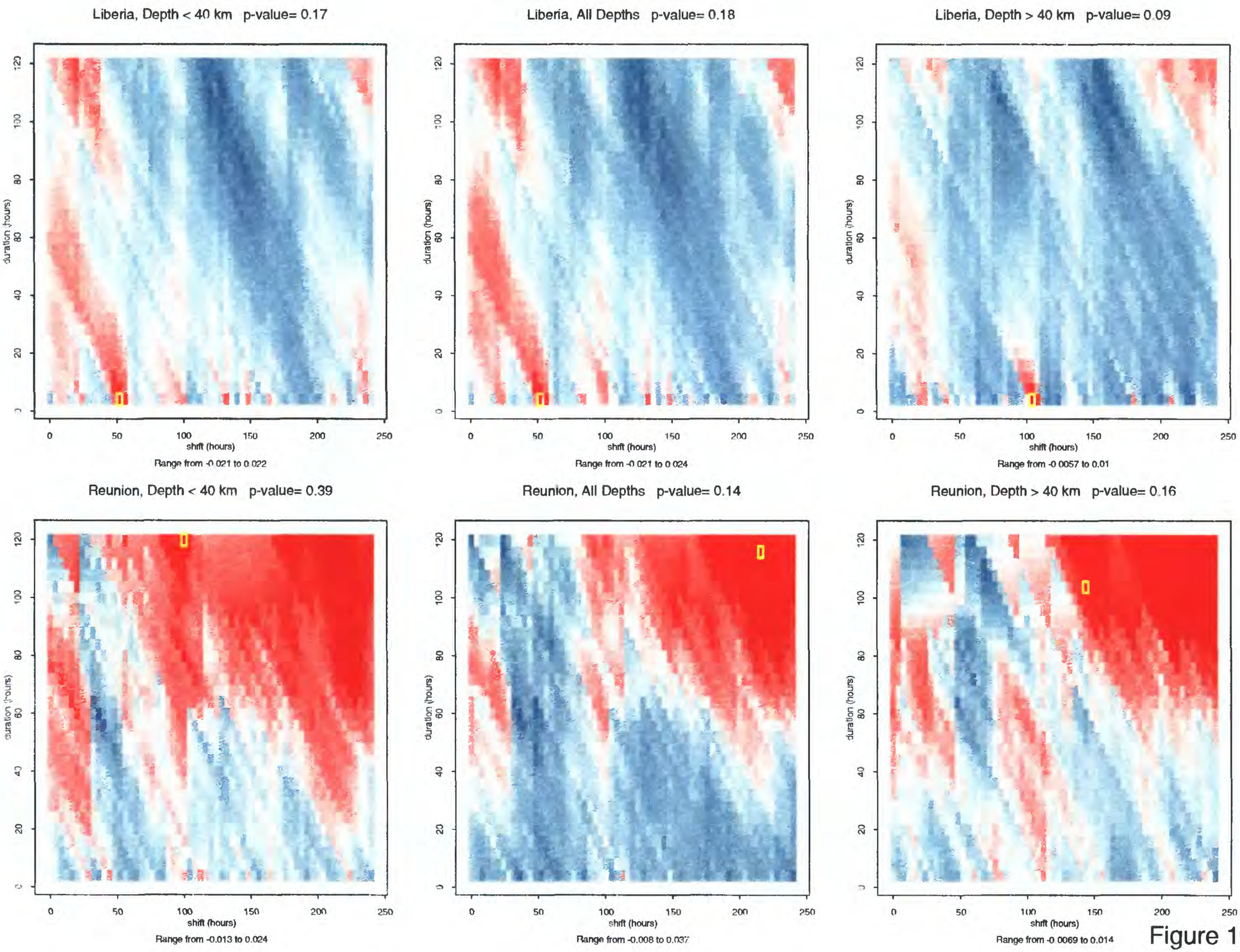


Figure 10

Effect of Maximum Distance from Path

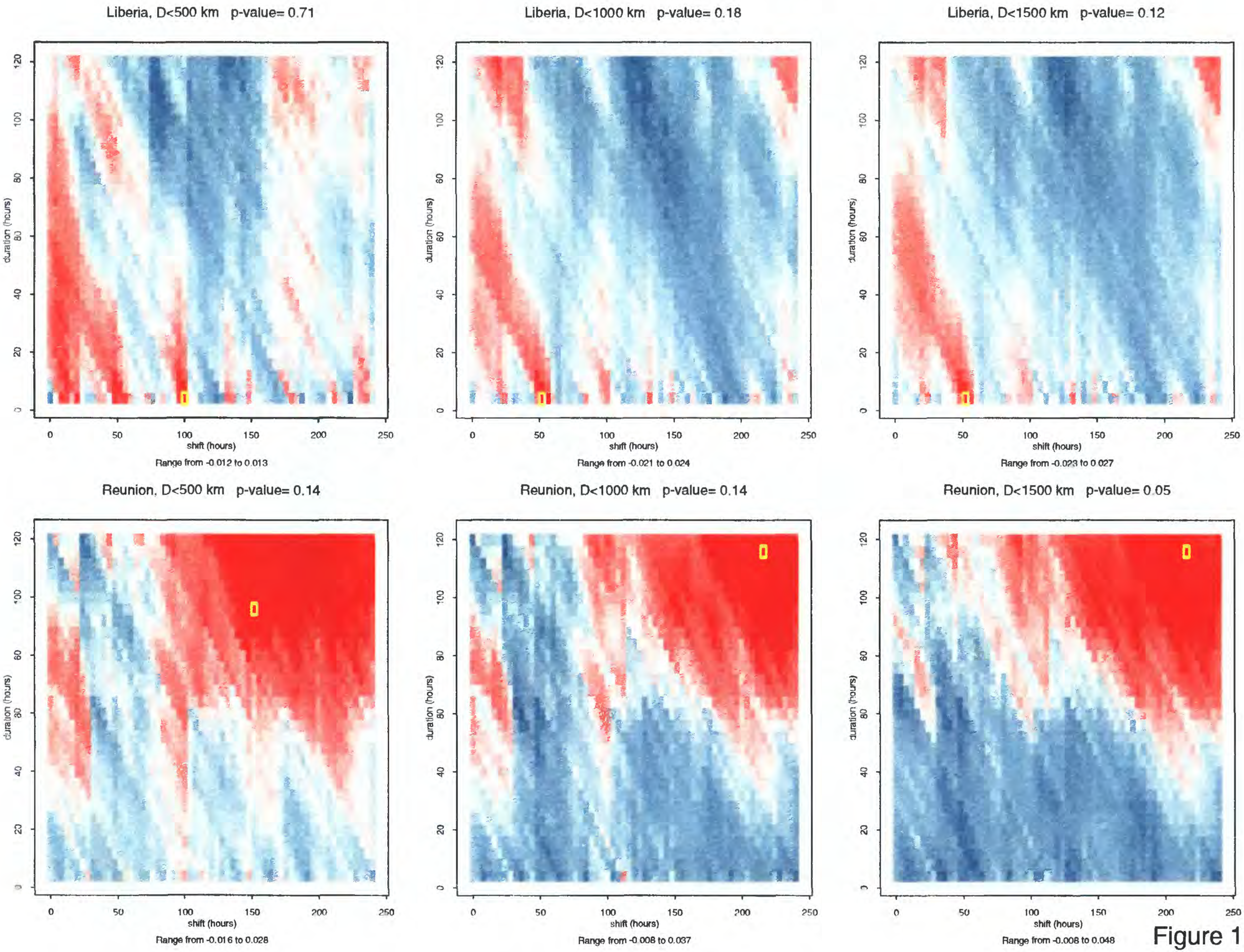


Figure 11

Effect of Minimum Magnitude

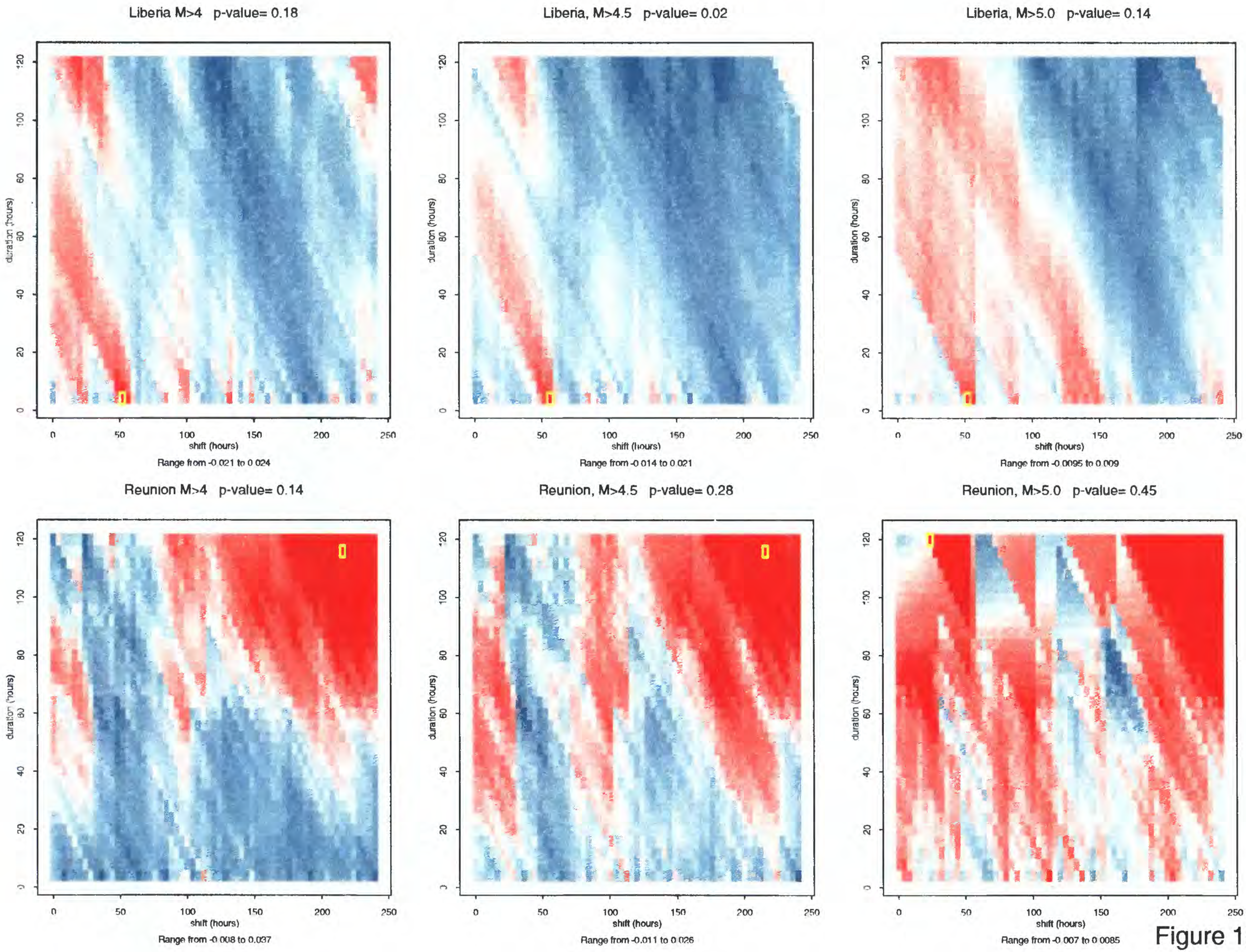


Figure 12