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Abstract

Earthquake magnitudes are generally determined by taking an average (most often, the arithmetic mean) of magnitudes calculated at many individual seismograph stations. While some variation in station magnitudes stems directly from the seismic source (for example, radiation pattern or directivity) conditions beneath the recording station also affect the calculated value. For example, soft soils tend to amplify the seismic signal resulting in an apparent magnitude that is higher than the true value. By analyzing the differences between the magnitude determined at a specific station and the average magnitude for a large number of earthquakes, a site correction for the station can be determined and then applied as part of the magnitude calculation. Station corrections have been determined for more than three hundred seismographs used in the calculations of magnitudes in eastern Canada. In most cases, the site corrections are small but several stations with significant corrections were identified. Magnitudes were recalculated applying the corrections. When the earthquake catalog is considered as a whole, the effect is negligible but there are many individual earthquakes for which it is significant. The remaining residuals after the application of the site corrections were further evaluated to determine whether they are dependent on parameters such as distance, azimuth or frequency. A consistent pattern of residuals with respect to distance is seen at a large number of stations spanning the region, suggesting that the attenuation relation used in magnitude calculations may need to be modified. In most regions azimuthal dependence is minimal but a few regions have been targeted for further study. Residuals are near zero for periods of ~0.02-~0.5 sec and then slowly increase with increasing period, raising questions about the validity of using the magnitude equation over a wider range of frequencies than that for which it was originally intended.

Introduction

Earthquake magnitude is typically calculated by taking an average (mean, median etc.) value of magnitudes determined at individual seismograph stations. Some variation from station to station is to be expected because of factors related to the earthquake source, such as radiation pattern or directivity. There may, however, also be stations that give consistently high or low magnitudes relative to the average. This difference should reflect the site conditions beneath the station but it could also be an indication that the instrument has not been properly calibrated or that there is an error in the instrument response file. Regional differences in attenuation may also play a role. Identifying these stations and applying an appropriate correction should result in more robust magnitudes. It also allows larger numbers of stations to be used to calculate magnitude as current practice in eastern Canada is to exclude individual station magnitudes that are significantly different from the mean.

This study was undertaken to determine the site corrections for seismograph stations that are used in magnitude calculations for earthquakes occurring in eastern Canada, defined here as east of 110°W. The stations examined are those that are used for the calculation of M_N (Nuttli, 1973, with modifications as proposed by Wetmiller and Drysdale, 1982 and discussed further in Bent and Greene, 2014, and Bent 2018a), which is the standard magnitude scale for eastern Canada. A similar study was undertaken several years ago (Bent, 2010) but, in subsequent years, a large number of new stations, both permanent and temporary, were deployed in eastern Canada. Additionally, larger data sets are now available for stations that were relatively new at the time of the previous study. Thus, an update is in order.

Note that the Canadian National Seismograph Network (CNSN; see Data and Resources) is currently in the midst of a major overhaul with most of the older stations being upgraded and a small number of new stations being installed. Preliminary corrections have been determined for stations that were upgraded prior to 30 June 2017 using data from 2017 through February 2018 but the bulk of this document focuses on longer running stations. A re-evaluation of the station corrections several years in the future after the new or upgraded stations have been running long enough to produce a reasonable sized data set is recommended. A discussion of the CNSN refreshment may be found at
http://www.earthquakescanada.nrcan.gc.ca/stndon/blog-en.php .

Individual station magnitudes may also be influenced by the path between the earthquake and station due to variations in Earth structure. For station corrections derived from a data set spanning a wide range of distances and azimuths, these variations should cancel each other and the station correction should be a true site correction. Variations in regional structure, however, could result in station corrections that are dependent on azimuth or distance or both, which could, in turn, influence the site correction if most of the data come from a narrow range of azimuths and/or distance. Station corrections may also be dependent upon the period at which the magnitude is calculated. These factors are investigated, results are presented and some suggestions for future investigations are brought forward.

Data Selection and Analysis

Magnitude data from eastern Canadian earthquakes from 2006-2016 whose preferred magnitude type was M_N and where magnitudes were available from five or more stations were evaluated to determine site corrections to be used with the M_N magnitude scale. Because M_N is used primarily in eastern Canada, a longitude cut-off of 110º W was used when selecting the earthquakes. Only those stations which were used in M_N calculations for those earthquakes were examined. Therefore, corrections for only a few western Canadian stations were determined in this study.

The list of stations (Table 1) includes some that are located in the United States and Greenland. They are included because they are routinely used in the analysis of Canadian earthquakes. It should be emphasized that the corrections for these stations are based only on those earthquakes that appear in the Canadian earthquake database and some caution should be exercised if applying them to earthquakes occurring elsewhere as the Canadian earthquakes recorded by these stations generally occur over a narrow range of azimuths and distance. As discussed in the introduction, this may result in a combined path-site correction. The same caution should be applied to Canadian stations, such as those in western Canada, that are near or beyond the boundaries of the earthquake data set.

A magnitude residual is defined as the difference (M(station)-M(event)) between the magnitude calculated at a specific station hereafter referred to as the station magnitude and the average magnitude for an earthquake hereafter referred to as the event magnitude. The station correction is the mean residual for a given station. When applied, it should be **subtracted** from the calculated station magnitude.

It is standard practice in the Canadian Earthquake Database (NEDB; see also Data and Resources section) to calculate magnitude to one decimal place, and it is a sensible choice for event magnitudes, which represent the mean value of many individual station magnitudes. The digital data now available, however, allow individual station magnitudes to be calculated with more precision. For the calculation stage of this project all magnitudes were recalculated to two decimal places. It is left to the user to decide how many significant digits to retain when applying the corrections. Standard deviations and 99% confidence internals based on the statistical T-test were also calculated. The T-test is used to measure the significance of the mean of a data set (residuals for individual stations) with respect to the overall population mean (event residuals- assumed to be 0). A t value based on the degrees of freedom and desired confidence level is obtained from a look-up table and the confidence internal is then defined as

$$\overline{X} \pm ts/\sqrt{n}$$

where $\overline{X}$ is the mean residual, t is the t value, s is the standard deviation and n is the number of measurements. There are n-1 degrees of freedom.

All of these values as well as the number of events used to determine the corrections are provided in Table 1. Note that many stations, particularly in the north, are used more often than it would appear from Table 1 but because there are often fewer than five station magnitudes available for small to moderate earthquakes in the north, not all earthquakes recorded by the station are included in this data set.

Static Corrections

The static correction for each station is defined as the mean residual for the entire data set without considering possible differences related to aziumuth, distance, period or any other factors. It should represent the site conditions beneath the station but could potentially incorporate errors in the instrument calibration. If most of the earthquakes recorded by a station come from a single source zone the apparent static correction could also reflect source-specific path or radiation pattern effects. Any corrections based on a very small number of data points should be used with caution as they may not represent the true station corrections. Readers are encouraged to consider the supporting information, such as number of events, standard deviation and 99% confidence width, in Table 1 to decide whether the correction for a particular station is well enough constrained for their needs.

For the most part the static station corrections summarized in Table 1 are small. That is, they are less than 0.2 magnitude units, or within the range of the magnitude uncertainty associated with most of the earthquakes in the study suggesting that, on average, including station corrections in magnitude calculations might not have a significant effect on the event magnitude. Tests discussing the effects of including the station corrections are discussed later in the section entitled “Impact of Station Corrections on Event Magnitudes”.

There are no strong regional trends in the static corrections (Figures 1 and 2) although there are a few weaker trends. There are a range of values for each region with the mean being close to zero. Stations in the Atlantic provinces and high Arctic are more likely to have negative (blue symbols) than positive corrections while the reverse is true for southern Ontario, but all regions are dominated by stations with corrections close to zero. Northern Ontario stations show the widest range of corrections with large differences sometimes observed between neighboring stations. In this region neighboring stations are separated by 10s to 100s of km and, thus, the nearest station to another is not necessarily close to it.

It is standard practice in eastern Canada to exclude individual station magnitudes that appear to be outliers or not close to the mean. Magnitudes calculated at distances (< 50 km) and periods (> 1.3sec) inappropriate to the M_N scale as applied in eastern Canada (see Bent, 2011 for further details) are automatically excluded by the location program (S. Hayek, personal communication). Otherwise, it is the analyst’s decision. For the current study, magnitudes excluded by the analyst were included but those automatically excluded because they were out of range were not used. For stations with large site corrections, the correction obtained is likely more representative of the true value if the excluded values are considered.

Excluding outlier magnitudes has long been the practice in eastern Canada but it is somewhat questionable. When there is a high degree of redundancy at a particular azimuth and distance it may make sense to leave out any readings that are clearly different from the average. When there is little or no redundancy the best course of action for dealing with an anomalous station magnitude is less clear. The normal variations in magnitude due strictly to radiation pattern can be quite significant. Directivity can also affect the apparent magnitude although it is generally only a significant factor for larger earthquakes. Furthermore, the magnitude residual pattern may provide information about the focal mechanism and/or directivity, which is lost if the magnitudes are excluded. It should be noted, however, that station magnitudes that are calculated and then rejected by the analyst are kept in the NEDB (see Data and Resources) and marked by an "X" to indicate that they were not used in the calculation of the event magnitude. When data from a station does not appear in the database, it is less clear whether the data could not be used or whether it was simply not evaluated, the latter option may occur on a regular basis when a station gains a reputation for giving magnitudes that are consistently higher or lower than the mean or if there were already several readings from stations at similar azimuths and distances.

Impact of Station Corrections on Event Magnitudes

To determine the effect of applying station corrections, the corrections were applied to each individual station magnitude. The mean event magnitude was recalculated and compared to the original catalog magnitude. The mean difference (corrected – catalog) is 0.005 with a standard deviation of 0.08 and is independent of magnitude (Figure 3), suggesting that, for the earthquake catalog as a whole, the application of station corrections has little effect on the final magnitudes. If the excluded stations are included, the difference between magnitudes with and without corrections applied is -0.015 ± 0.06, a somewhat greater effect but still relatively small. If the sign of the magnitude change is ignored and only the value considered, the effect of correcting for the site is still small but more significant, with a mean difference of 0.056 ± 0.56 relative to the catalog magnitude and 0.042 ± 0.046 relative to the mean value with the originally excluded stations included. This measurement may be a better indication of the effect of station corrections on individual earthquakes whereas considering the sign is probably a better reflection of the effect on the catalog as a whole.

Magnitude uncertainty in the NEDB is typically expressed as standard deviation. The mean standard deviation of the catalog magnitudes is 0.14± 0.08. When all station magnitudes (within the allowable distance-period range) are included the uncertainty is increased to 0.23 ± 0.10 reflecting the inclusion of outlier magnitudes. This value may be a better measure of the true scatter in the data. When the corrections are applied to the larger data set, the uncertainty is slightly decreased to 0.20 ± 0.08.

Despite the low impact the application of station corrections has on the earthquake catalog as a whole, the effect on many individual earthquakes is greater (Figures 3 and 4). Figure 4 shows that the events where the application of station corrections has the largest effect on event magnitude are generally those where the event magnitudes are calculated from small numbers of stations. The mean difference for events with 5-10 station magnitudes is on par with entire data set but the variation is much larger.

In choosing whether or how to implement station corrections there are several options. The two simplest being either to not use them or to apply them to all stations. The first option reflects current practice, which results in magnitudes that could be easily corrected being excluded from the magnitude calculation. Assuming the practice of excluding outlier magnitude continues, the second option would reduce the number of excluded stations. Although the corrections for most stations are negligible, global application of corrections would result in a consistent database. Some thought would have to be given regarding how to handle new stations and those stations for which the site correction is not well constrained. Other options would be to apply site corrections only for those events whose magnitudes were calculated from fewer than some predefined number of stations or for those events whose magnitudes include stations with a site correction greater than some predefined value. These two options would target the events where the application of site corrections would have the largest effect but not applying corrections uniformly could result in inconsistencies in the earthquake catalog and would put the onus of the users of the data to determine how a particular magnitude was calculated. Whatever option is used, it should be clearly documented especially if it differs from current practice. Ideally, users would be given the option of accessing a corrected or raw data set.

Site Effect or Instrument Calibration Error?

While the general assumption is that station corrections represent the site effects beneath the station, there is always a possibility that an instrument calibration error may be contributing to the correction. It cannot always be determined with certainty which is the case but the responses at a number of stations are examined in closer detail. These stations include sites occupied by more than one instrument and sites whose corrections are unusually large and/or significantly different from neighboring stations.

A small number of sites have been occupied by more than one instrument. The instruments may have been operating simultaneously. For example a short-period and broadband instrument may co-exist or a site may have been used to test new instruments at the same time a long-term instrument was operating. In other cases, the different instruments may not have run at the same time. For example, an older or faulty instrument might have been replaced with a newer one. If the correction truly represents the site response, one would expect the corrections to be the same or at least very similar for all instruments at that site.

At several sites hosting stations of the CNSN (HAL, LMN, MNT-MNTQ, OTT-TOTT-TOTT2) the difference between instruments is zero or negligible suggesting these are true site corrections. At other stations more variation is seem among the instruments occupying the sites. Potential issues involving DPQ, FFC and YKW3 are addressed in the discussion of stations with large site corrections.

GAC and the test instruments at the same site GAX1-GAX6 show a wide variety of corrections. GAC_BHZ and GAC_EHZ, which were long running instruments, both have negative corrections derived from large data sets, suggesting that a negative correction is appropriate to the site but leaving room for further refinement. GAC_HHZ has a positive correction, but it was derived from only four events. Re-evaluating this instrument at a future date with a larger data set may reveal whether the difference was an artefact of a small data set or whether there is a potential instrument calibration problem. Stations GAX1-GAX6 were test instruments whose corrections were derived from relatively small data sets. Most had negative corrections, somewhat consistent with the longer running instruments. The high positive corrections at GAX2 and GAX3 may be instrument calibration errors and are discussed later.

The instruments MCA3_HHZ and MCA3_EHZ have significantly different corrections. To the two decimal places shown in Table 1, stations MCA1, MCA2, MCA4 and MCA5 appear to be in the same location but they actually occupy different sites within the same small community. Most have positive corrections suggesting that the 0.0 correction for MCA3-EHZ might be a calibration issue. All MCA1-5 corrections were derived from small data sets.

The corrections for LMQ_BHZ and LMQ_HHZ are both positive but differ by a bit more than a factor of two. Both are well constrained and determined from large data sets. The difference could be caused by a calibration problem at one station but could possibly result from another factor such as magnitudes being measured at different frequencies.

Standard deviations for instrumental event magnitudes in eastern Canada are typically 0.1-0.3 magnitude units although the possible range is much wider. Stations for which the absolute value of the station correction for M_N is 0.3 or greater and based on a minimum of 5 readings are discussed below. More information about the number of readings and uncertainties associated with these stations may be found in Table 1.

Some effort was made to find reasonable explanations why these stations have high corrections. For long running or permanent stations it may be worthwhile to expend more effort to fully understand the underlying reason. For temporary stations, it may be sufficient to note that there is a large site correction. Many of the stations with high positive corrections are located on soft soil, glacial deposits or fill, which may amplify the signal. The stations ALGO, BSPQ, BRCO, DREO, DRWO, GASG, MGDQ, MSNO, ORHO, OTRO, PKRO and TORO fall into this category (CNSN, 2018; S. Hayek and I. Asudeh, personal communication). Stations MCA2 and MCA5 in southwestern New Brunswick show high positive corrections. MCA5 is on glacial till; the site conditions beneath MCA2 are not confirmed but noise plots show that it was consistently the noisiest of the MCA stations, suggesting it may be on soil (S. Halchuk, personal communication). Stations RD01, RD02 and RD03 in southern Ontario are likely on soft soils but this has not been confirmed.

The high residual for DPQ_HHZ may be a combination of site and instrument effects. Its correction of +0.34 was based on measurements from only 17 events. The EHZ instrument at the same site, whose correction of +0.15 was based on more than 1400 events is also significantly positive but nevertheless notably smaller.

Several other stations with high positive corrections (ATKO, BANO, EPLO, LATQ, LDIO, SVNB), however, are situated, or least purported to be, on bedrock (CNSN, 2018; S. Hayek and I. Asudeh, personal communication) and the reason for their high residuals is less obvious. Instrument miscalibrations are a possibility but have not been proven. All of the stations were noted as having high positive residuals in the earlier study by Bent (2010) except SVNB, which did not exist at that time.

The reason for the high residual of +0.30 for FFC_BHZ is not clear. The short-period (SHZ) instrument has a negative correction of -0.11. Both are based on small data sets. The difference could indicate an instrument calibration problem at one or both but differences in the data set (frequency, distance etc.) could also be making a contribution. Nor has it been established whether the high correction at VDBQ is related to site conditions or an instrument calibration error. This station was installed as a temporary site to monitor aftershocks of the 2010 Val-des-Bois earthquake.

Station EYMN in the United States is a bedrock station with a high negative correction. This station has been used for earthquakes covering a wide distance range and is consistently underestimating the magnitudes suggesting that there is an instrument response problem although a significant difference in geology at the site relative to the overall path could be contributing to the effect. NCB is also in the United States. Its correction is based on a relatively large number of individual magnitudes and should therefore be reliable. An instrument miscalibration or incorrect response file is highly likely but not proven.

Stations GAX2, GAX3 and GAX5 were all test instruments in or near the same vault as GAC. The high corrections and difference between the various instruments are suggestive of calibration errors or incorrect response files but there were some variations in instrument set-ups that might contribute to differences in mean residuals. GAX2 was located in the tunnel leading to the GAC vault. GAX3 was a post hole instrument. GAX5 was located in the same vault as GAC and along with GAX4 and GAX6 was part of a self-noise test. It is also noted that the correction for these 3 stations were based on fewer than 20 individual magnitudes and the 99% confidence intervals of between 0.2 and 0.4 magnitude units from the mean are relatively large.

Stations D59A, E55A and F55A were all temporary stations that were part of the US Transportable Array (USTA, see Data and Resources). Their corrections are based on relatively small numbers of magnitude readings. It has been this author's experience that great care was taken to ensure that the USTA instruments were well-calibrated and that the response files were correct although a calibration error cannot be completely ruled out. Less effort was put into deploying stations on bedrock as the number of stations in the array was very large and keeping the station spacing as uniform as possible was a higher priority than site conditions. Photos on the USTA website (see Data and Resources) suggest that D59A and E55A are on soil. It is more difficult to ascertain the site conditions at F55A from the photo.

The number of stations with high negative corrections is relatively small. In addition to those already discussed are ELNB, MUMO and YKW3_EHZ. YKW3_EHZ is a mystery. The BHZ instrument at the same site also has a negative correction but less significant. The EHZ correction was based on a larger data set and, in theory, should be more reliable. The Bent (2010) paper showed both having similar corrections to each other (-0.14 BHZ and -0.18 EHZ). The broadband instrument was replaced in 2015, which might effect that component but there was no change of instrumentation for the EHZ component as far as I have been able to ascertain. High attenuation might explain negative residuals. There is some evidence that the Appalachian region may have lower attenuation than the Canadian Shield. Many stations near ELNB, which lies within the Appalachians, also have negative, albeit lower amplitude corrections. MUMO lies well within the Shield. Bent (2010) also noted a high negative residual for that station. It could be the result of an instrument miscalibration but this has not been proven.

Parameter Dependent Residuals

Building on the static corrections, variations in magnitude residual as a function of azimuth, distance and period were also evaluated. Only those stations with more than one hundred magnitude residuals were used for this part of the analysis. In all cases the individual station magnitudes were corrected by applying the static station correction discussed in the previous section and summarized in Table 1. Magnitude residuals discussed in the following sections are thus second order residuals not accounted for by the site correction. The intent of this section is not necessarily to explain the underlying reasons for any parameter dependences but to determine whether they exist and, if so, make recommendations for future research to better understand them and their effects. Many of the dependencies observed and discussed below appear to be widespread and are, therefore, more likely to be a result of internal practice, inadequacies in the magnitude formula or variations in structure. Thus there seems to be no justification for the use of complex or parameter-dependent station corrections but there is room for improvement in how magnitudes are calculated in eastern Canada.

Distance

Station corrections were applied to all stations in Table 1 whose corrections were derived from one hundred or more data points and then plotted as a function of azimuth and distance (Figures 5i-xciii). Azimuthal variations will be discussed in a subsequent section. Note that Figures 5i-xciii show distances to 1000 km. M_N may be calculated to distance of ~3000 km but the data set beyond 1000 km is relatively sparse and not shown. It was, however, included in the calculations. While there is scatter at any given station and variation between stations, there are a few fairly ubiquitous trends with respect to distance. For the most part the residuals appear to be positive at shorter distances and negative at distances greater than ~400 km. Particularly clear examples may be seen at stations BANO (Figure 5xiii), DPQ (Figure 5xxv), GGN (Figure 5xxx), LMN (Figure 5li), MOQ (Figure 5lviii), PLVO (Figure 5lxxi) and SMQ (Figure 5lxxix). Many stations also appear to have negative residuals over a narrow range of distances close to 50 km. This effect is clearly seen at stations DPQ (Figure 5xxv), GGN (Figure 5xxx), HKNB (Figure 5xxxv), LMN (Figure 5li), MNT-MNTQ (Figure 5lvii), NATG (Figure 5lxii), OTT (Figure 5lxv), PKME (Figure 5lxviii), PKRO (Figure 5lxix), SADO (Figure 5lxxvi) and WCNB (Figure 5lxci).

The distance dependence of the residuals was demonstrated by combining the data for several regional groups of stations. The data were then windowed and the mean value and 99% confidence interval for each window determined. The groups and stations included in each group are as follows: Charlevoix (Figure 6a; A11, A16, A21, A54, A61, A64, LMQ), Lower St. Lawrence (Figure 6b, CNQ, GSQ, ICQ, SMQ), Melville Island (Figure 6c; AP3N, GIFN, ILON, KUGN, SRLN), southern New Brunswick (Figure 6d; ELNB, GGN, HKNB, LMN, SRNB, SVNB, WCNB), southern Ontario (Figure 6e; ACTO, BANO, PECO, PKRO, PLIO, TYNO, WLVO) and the Western Quebec Seismic Zone (Figure 6f; ALFO, GAC, GRQ, MNT, MNTQ, MRHQ, ORIO, OTT, PEMO, TRQ). The windows used were 50-60 km, 60-100 km, 100-150 km, continuing in 50 km increments to 1000 km, 1000-1100 km and then continuing in 100 km increments to 1500 km.

The mean values are generally negative in the 50-60 km range, positive to 250 km, close to zero from 250-400 km and then largely negative beyond 400 km. The fact that a similar residual pattern is seen at all or at least most stations suggests that the problem is likely not a distance dependence in the station corrections but that the attenuation relation used in the magnitude scale does not adequately reflect the true attenuation in eastern Canada. The same pattern is seen when the data sets from the six groups are combined (Figure 7). The 99% confidence intervals suggest that the differences are statistically significant on the whole and to distances of 400-500 km regionally. Beyond that, the regional results are equivocal likely due to the small size of the data sets.

The results of this analysis are consistent with those made by Bent (2018a) as part of a larger investigation of magnitudes in eastern Canada. The M_N scale is based on the Lg phase. At 50 km the difference in residuals may reflect that the phase in question is Sg and not a true Lg. It was also noted by Bent (2018a) that if the M_N scale was extended to shorter distances, the magnitudes obtained were close to those determined at stations at the appropriate distance range but smaller, on average, by 0.1-0.2 magnitude units.

Azimuth

Figures 5i-5xciii show that, on the whole, the variations in residuals after the station corrections have been applied are not strongly dependent on azimuth but there are a few stations that do show a dependence: A11 (Figure 5i), BATG (Figure 5xiv), GAC (Figure 5xxix), MNT-MNTQ (Figure 5lvii), PECO (Figure 5lxvi) and PKME (Figure 5lxviii). In some cases the azimuthal trend extends across wide distance ranges and in other cases it is confined to a narrower range of distances.

Azimuthal variations are most likely caused by path and/or radiation pattern effects and thus would be expected to be similar at nearby stations, in which case combining the data from several stations may highlight the pattern and reduce the uncertainty. To evaluate azimuthal dependence more objectively, data from the same groups of stations discussed in the preceding section on distance analysis were binned in 30º azimuthal windows and the mean residual was determined. The calculations were performed twice with the mid-point of the window shifted by 15º to help ensure that the choice of window did not influence the outcome. Note that when working with stations it is more common to use back azimuth (station to event direction) than azimuth (event to station direction). However, because the database is event oriented, azimuth is more readily available and was used for this part of the analysis.

The results for most regions were equivocal (Figures 8a-f). That is, although some azimuthal variations were observed, the 99% confidence interval for the azimuth in question, overlapped with the that of the overall mean for the same region. However, azimuthal variations in the Western Quebec Seismic Zone (Figure 8f) appear to be statistically significant. The same is true for some azimuths for the southern Ontario (Figure 8e) and Lower St. Lawrence (Figure 8b) groups of stations. As part of a larger study on best practices for magnitude calculations, Bent (2018b) is looking at the effect on how individual station magnitudes are combined to determine the event magnitude. One factor under investigation, is the effect treating all magnitudes equally versus averaging over azimuthal windows to avoid oversampling at some azimuths relative to others. The results of the current study suggest that the three regions discussed above would be good test cases for the broader study.

Period

With a few exceptions, no strong correlation was noted between residual and period (Figures 9a-v and 10). Although the M_N scale was intended to be used at periods of close to 1 sec (Nuttli, 1973) in practice it is used at much higher frequencies (Figures 9a-v and 10; also see comments in Bent, 2011 and Bent and Greene, 2014). The database will be dominated by those higher frequencies and therefore the residuals alone will not indicate whether the event magnitude is equivalent to an M_N calculated with stricter attention to Nuttli's (1973) formulation.

Plotting the residuals as a function of both distance and period for individual stations whose corrections were derived from 500 or more data points (Figures 9a-v) suggests that the distance dependence is generally more significant than any potential frequency dependence. However, at periods greater than ~0.5-1.0 sec there is a tendency toward higher positive residuals. This effect can be seen most clearly at stations A61 (Figure 9a), ALFO (Figure 9b), BATG (Figure 9d), ICQ (Figure 9m), PEMO (Figure 9q), PLVO (Figure 9r), SADO (Figure 9s) and VLDQ (Figure 9v). This observation is supported by calculating and plotting the mean residual as a function of period (Figure 10) using the combined data set from the regional groupings discussed in several preceding sections.

An observation of concern stemming from this part of the study and the previous (Bent, 2010) is that many magnitudes are being calculated at periods close to the sample rate of the instruments, typically 100 samples per second (sps) for EH and HH instruments and 40 sps for BH (see Table 1). These magnitudes may not be reliable indications of the true size of the earthquake and may, in some cases, represent noise spikes rather than true signal. Bent (2010) noted that the magnitude calculation program had been modified to reject any magnitudes calculated at periods less than 0.1 sec. Further investigation has shown that this is not the case. The change was recommended but never implemented.

New Stations

As noted in the introductory section, the CNSN is currently in the midst of a renewal. Preliminary site corrections were determined for twenty-six stations that were operational on or before 30 June 2017. Other than the time period covered, the data selection criteria and processing procedures followed were the same as described in the "Data Selection and Analysis" section. The earthquakes used to analyze this data set occurred between 1 January 2017 and 1 March 2018. The mean residuals and supporting information are summarized in Table 2. For the most part, the residuals are similar to those for the same or closest station in Table 1, suggesting that these are true site corrections. There are seven stations where the old and new corrections differ by 0.1 magnitude units or more: RESN, TOTT2, GGN, LMN, KGNO, MNTQ, SAKN. It is worth noting, however, that, because of the relatively small data set, the 99% confidence widths are generally much larger than those in Table 1. In the case of SAKN, the original correction was based on only two data points and should not be considered reliable. A difference from a previous instrument at the same site could be an indication of a calibration problem with one of the instruments, but it is also possible that with a larger data set any discrepancies will be resolved.

Conclusions

Station magnitude corrections have been established for seismograph stations used in the calculation of M_N magnitude in eastern Canada. For the most part, the corrections are within the typical standard deviation for event magnitudes in this region although there are some stations for which the corrections are significant. In most cases the large corrections can be tied to the local site conditions although there are others for which the reason is not apparent. For example, many of the stations with high positive corrections are location on soft soils. An evaluation of magnitude residuals as a function of several other parameters was carried out. On average, azimuthal variations are not statistically significant although there are a few regions, such as the Western Quebec Seismic Zone, where further investigation is warranted. At periods of ~0.02-0.30 seconds, where most of the magnitude measurements are made, the mean residuals are close to 0.0. As the period increases beyond that there is a steady increase in the residual. Variations to distance are fairly systematic and suggest that the attenuation relation used to calculate magnitude may be incorrect and should be re-evaluated. In particular, it is noted that residuals tend to be negative at distances of ~50 km and greater than ~400 km. Recalculating event magnitudes with the station corrections applied show that the difference is generally negligible but that there are some events where the effect is significant. Applying the corrections to those stations for which the correction is large may result in data from those stations not being routinely discarded in the future and provide better azimuthal coverage for earthquakes in some regions.

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Data from the New England and Danish seismograph networks (see Data and Resources) were also made freely available.

Data and Resources

Earthquake epicenters, origin times and magnitudes were obtained from the Canadian National Earthquake Database (NEDB)

http://www.earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bulletin-en.php

This study makes use of magnitudes from data freely provided by the following networks:

The Canadian National Seismograph Network (CNSN)

http://www.earthquakescanada.nrcan.gc.ca/stndon/index-en.php

The New England Seismograph Network (NESN)

http://aki.bc.edu/index.htm

The US Transportable Array (USTA)

http://www.usarray.org/researchers/obs/transportable

The Danish Seismograph Network (stations in Greenland)

http://seis.geus.net/seismic_service.html

All links verified 3 April 2019.

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Table 1
Station Site Corrections

Station	**Component**	**Latitude (°N)**	**Longitude (°W)**	**# events**	**mean residual**	**standard deviation**	**99% confidence width**
A11	HHZ	47.24	70.20	228	-0.21	0.25	0.043
A16	HHZ	47.47	70.01	329	0.00	0.22	0.030
A21	HHZ	47.70	69.69	487	0.02	0.22	0.026
A54	HHZ	47.46	70.41	484	0.04	0.20	0.024
A61	HHZ	47.69	70.09	517	-0.05	0.17	0.019
A64	HHZ	47.83	69.89	479	-0.04	0.18	0.021
ACKN	HHZ	64.99	110.87	1	-0.30		
ACTO	HHZ	43.61	80.06	193	0.26	0.17	0.032
AKVQ	BHZ	60.81	78.19	154	-0.08	0.21	0.044
ALDO	HHZ	45.62	74.88	80	-0.13	0.18	0.053
ALFO	HHZ	45.62	74.88	902	-0.13	0.20	0.017
ALGO	HHZ	45.95	78.05	424	0.74	0.17	0.021
ALLY	BHZ	41.65	80.14	7	-0.17	0.31	0.434
AP3N	BHZ	69.46	89.46	127	0.01	0.18	0.042
ARVN	BHZ	61.10	94.07	135	0.01	0.16	0.036
ATKO	HHZ	48.82	91.16	39	0.33	0.56	0.243
BACQ	HHZ	49.29	68.16	79	0.07	0.18	0.054
BANO	HHZ	45.02	77.93	508	0.53	0.24	0.028
BASO	HHZ	44.01	81.66	128	0.09	0.18	0.042
BATG	HHZ	47.28	66.06	567	0.12	0.28	0.030
BCLQ	HHZ	46.93	71.17	273	0.03	0.17	0.027
BECQ	HHZ	46.34	72.48	37	-0.14	0.26	0.116
BELQ	HHZ	47.40	78.69	287	-0.05	0.19	0.029
BINY	BHZ	42.20	75.99	62	-0.12	0.21	0.071
BLBQ	HHZ	47.43	70.52	1	1.10		
BMRO	HHZ	44.60	81.22	158	-0.01	0.26	0.054
BOXN	BHZ	63.85	109.72	2	-0.10	0.28	
BRCO	HHZ	44.24	81.44	72	0.44	0.21	0.066
BSCQ	HHZ	48.12	69.72	59	-0.05	0.16	0.056
BSPQ	HHZ	47.44	70.51	9	0.71	0.15	0.168
BUKO	HHZ	45.44	79.40	461	0.10	0.19	0.023
BULN	BHZ	66.40	93.13	345	-0.04	0.17	0.024

BWLO	HHZ	44.12	81.14	158	0.06	0.22	0.046
CB31	BHZ	69.13	105.11	95	0.10	0.18	0.049
CDKN	BHZ	64.23	66.34	46	-0.04	0.13	0.052
CHEG	HHZ	46.81	60.67	444	0.06	0.20	0.025
CHGQ	HHZ	49.91	74.37	86	0.02	0.18	0.051
CLRN	BHZ	70.47	68.59	75	0.10	0.20	0.061
CLWO	HHZ	44.45	80.30	207	0.13	0.16	0.029
CMBN	BHZ	65.69	64.45	49	-0.02	0.17	0.065
CNQ	EHZ	49.30	68.07	884	0.03	0.19	0.016
CODG	HHZ	47.84	59.25	14	0.04	0.48	0.386
COKN	HHZ	63.27	108.76	6	-0.03	0.14	0.230
COWN	BHZ	65.27	111.19	6	0.02	0.39	0.642
CRLO	EHZ	46.04	77.38	1439	-0.05	0.16	0.011
CTLN	BHZ	64.43	116.02	13	-0.22	0.22	0.186
D50A	BHZ	47.17	79.84	2	-0.15	0.49	
D52A	BHZ	46.98	78.41	2	0.00	0.28	
D53A	BHZ	47.08	77.70	6	-0.10	0.17	0.280
D54A	BHZ	47.15	76.66	6	-0.20	0.21	0.346
D57A	BHZ	47.02	73.89	2	0.25	0.35	
D58A	BHZ	47.10	73.89	5	-0.02	0.13	0.268
D59A	BHZ	47.01	71.84	7	0.63	0.24	0.336
D60A	BHZ	46.91	70.92	25	-0.29	0.19	0.106
DAQ	EHZ	47.96	71.24	878	0.00	0.21	0.020
DELO	HHZ	44.52	77.62	487	0.10	0.17	0.020
DHRN	BHZ	67.03	119.51	4	-0.12	0.17	0.496
DMCQ	HHZ	48.96	72.07	241	0.01	0.20	0.034
DPQ	EHZ	46.68	72.78	1418	0.15	0.21	0.014
DPQ	HHZ	46.68	72.78	17	0.34	0.08	0.057
DRCO	HHZ	43.88	78.70	4	0.25	0.13	0.380
DREO	HHZ	43.87	78.70	12	0.69	0.20	0.179
DRLN	BHZ	49.26	57.50	64	-0.10	0.37	0.123
DRWO	HHZ	43.87	78.73	21	0.48	0.19	0.118
E46A	BHZ	46.37	84.31	1	0.20		
E48A	BHZ	46.48	82.17	1	1.00		
E51A	BHZ	46.53	79.49	1	-0.40		
E52A	BHZ	46.29	78.66	1	-0.70		
E53A	BHZ	46.38	77.66	7	0.07	0.11	0.154
E54A	BHZ	46.43	77.19	7	0.01	0.07	0.098
E55A	BHZ	46.45	76.06	16	0.53	0.22	0.162

E58A	BHZ	46.37	73.28	10	0.14	0.19	0.195
E60A	BHZ	46.37	71.45	3	0.23	0.15	0.860
E61A	BHZ	46.43	70.49	12	-0.06	0.23	0.206
EEO	EHZ	46.64	79.08	780	-0.03	0.16	0.015
EFO	EHZ	43.09	79.31	157	-0.06	0.19	0.040
ELFO	HHZ	43.19	81.32	133	0.27	0.17	0.038
ELGO	HHZ	43.68	80.44	5	-0.02	0.13	0.268
ELNB	HHZ	45.85	65.15	173	-0.39	0.25	0.050
EPLO	HHZ	49.67	93.73	27	0.47	0.52	0.278
ERPA	BHZ	42.12	79.99	59	-0.04	0.26	0.090
EUNU	BHZ	80.05	86.42	4	-0.60	0.47	1.373
EYMN	BHZ	47.95	91.46	20	-1.28	0.73	0.467
F51A	BHZ	45.93	79.92	2	-0.10	0.00	
F55A	BHZ	45.83	76.35	21	0.60	0.23	0.143
F57A	BHZ	45.81	74.69	22	0.29	0.17	0.103
F58A	BHZ	45.87	73.81	6	0.28	0.15	0.247
F59A	BHZ	45.85	72.78	4	0.20	0.27	0.789
F60A	BHZ	45.97	71.95	5	-0.12	0.13	0.268
FCC	BHZ	58.76	94.09	131	-0.16	0.28	0.064
FFC	SHZ	54.73	101.98	15	-0.11	0.19	0.146
FFC	BHZ	54.73	101.98	7	0.30	0.32	0.448
FL31	BHZ	54.72	102.00	2	0.05	0.21	
FNBB	BHZ	58.89	123.01	2	0.00	0.00	
FORQ	HHZ	48.75	69.11	76	0.07	0.20	0.061
FRB	BHZ	63.75	68.55	330	0.02	0.21	0.030
FRNY	BHZ	44.83	73.59	204	-0.09	0.21	0.032
G54A	BHZ	45.40	78.09	15	0.02	0.21	0.161
G55A	BHZ	45.25	76.72	1	0.00		
G57A	BHZ	45.10	74.99	21	-0.19	0.17	0.106
G60A	BHZ	45.10	72.33	11	-0.03	0.21	0.201
GAAQ	HHZ	49.28	63.24	39	0.21	0.40	0.174
GAC	EHZ	45.70	75.48	1163	-0.21	0.22	0.017
GAC	BHZ	45.70	75.48	536	-0.12	0.28	0.031
GAC	HHZ	45.70	75.48	4	0.23	0.36	1.051
GALN	BHZ	64.12	117.31	3	-0.30	0.35	2.010
GASG	HHZ	48.95	66.12	496	0.55	0.15	0.017
GAX1	HHZ	45.70	75.48	36	-0.13	0.20	0.091
GAX2	HHZ	45.70	75.48	17	0.59	0.34	0.241
GAX3	HHZ	45.70	75.48	9	0.30	0.19	0.213

GAX4	BHZ	45.70	75.48	3	-0.07	0.32	1.834
GAX5	BHZ	45.70	75.48	6	-0.30	0.24	0.395
GAX6	BHZ	45.70	75.48	6	-0.22	0.30	0.494
GBLN	BHZ	64.20	112.99	2	-0.25	0.35	
GBN	HHZ	45.41	61.51	151	-0.07	0.42	0.089
GDLN	BHZ	62.02	105.99	6	0.02	0.10	0.165
GGN	BHZ	45.12	66.84	438	0.03	0.30	0.037
GIFN	BHZ	69.99	81.64	319	-0.07	0.19	0.028
GLWN	BHZ	64.73	109.33	6	-0.08	0.17	0.280
GRQ	EHZ	46.61	75.86	1227	-0.05	0.16	0.012
GSQ	EHZ	48.91	67.11	698	-0.23	0.18	0.018
GTO	EHZ	49.75	86.96	106	0.01	0.23	0.059
H53A	BHZ	44.57	78.58	5	-0.20	0.12	0.247
HAL	EHZ	44.64	63.59	30	0.00	0.32	0.160
HAL	HHZ	44.64	63.59	59	0.03	0.24	0.083
HANN	HHZ	45.88	66.77	62	-0.22	0.32	0.108
HC2P	HHZ	46.43	63.76	1	0.20		
HC3P	HHZ	46.42	63.74	1	-0.10		
HC4P	HHZ	46.41	63.67	1	0.00		
HFRN	BHZ	60.86	109.28	2	0.00	0.28	
HGVO	HHZ	42.96	80.13	8	-0.06	0.14	0.173
HKNB	HHZ	45.98	65.38	153	0.15	0.26	0.055
HPLN	BHZ	66.35	115.32	5	0.08	0.15	0.309
HRV	BHZ	42.51	71.56	32	0.29	0.36	0.175
HSMO	HHZ	47.37	79.67	82	0.07	0.25	0.073
I51A	BHZ	43.80	81.02	2	-0.10	0.00	
ICQ	BHZ	49.52	67.27	610	-0.01	0.27	0.028
ILKN	BHZ	64.22	115.13	1	0.00		
ILON	BHZ	69.37	81.82	501	0.03	0.16	0.018
ILULI	HHZ	69.21	51.10	9	-0.17	0.60	0.671
INK	BHZ	68.31	133.53	1	-0.30		
INUQ	BHZ	58.45	78.12	160	0.06	0.22	0.045
IVKQ	BHZ	62.48	77.91	170	-0.01	0.22	0.044
J52A	BHZ	43.24	80.48	3	0.10	0.17	0.974
JERN	BHZ	66.02	111.47	12	0.03	0.18	0.161
JFWS	BHZ	42.91	90.25	4	0.05	0.13	0.380
JOSN	BHZ	63.16	91.54	175	0.04	0.16	0.032
K50A	BHZ	42.77	82.62	2	0.10	0.00	
K52A	BHZ	42.78	80.71	1	0.10		

KAJQ	HHZ	58.69	65.93	41	-0.08	0.24	0.101
KAPO	BHZ	48.45	82.51	176	-0.04	0.24	0.047
KASO	HHZ	53.53	88.64	5	-0.06	0.24	0.494
KB10	HHZ	45.40	76.18	174	0.03	0.17	0.034
KB2O	HHZ	45.39	76.16	1	0.20		
KB30	HHZ	45.38	76.15	4	0.35	0.06	0.175
KB4O	HHZ	45.37	76.16	1	0.30		
KB60	HHZ	45.39	76.17	3	0.30	0.10	0.573
KGNO	BHZ	44.23	76.49	314	0.02	0.16	0.023
KILO	HHZ	48.50	79.72	159	-0.11	0.20	0.410
KJKQ	HHZ	55.28	77.75	41	0.05	0.17	0.072
KLBO	HHZ	45.35	80.21	283	0.08	0.20	0.031
KNDN	BHZ	63.42	109.20	3	-0.33	0.25	1.432
KNGQ	HHZ	61.58	71.95	66	0.06	0.22	0.072
KRSQ	HHZ	60.02	69.99	2	-0.30	0.42	
KUGN	BHZ	68.09	90.06	220	-0.03	0.20	0.035
KUKN	BHZ	67.82	115.09	11	0.07	0.19	0.182
KULLO	HHZ	74.58	57.22	27	-0.21	0.32	0.171
KUQ	EHZ	58.11	68.41	162	-0.02	0.19	0.039
L50A	BHZ	42.04	82.81	3	0.00	0.10	0.570
LAIN	BHZ	69.11	83.54	205	-0.03	0.19	0.034
LATQ	HHZ	47.38	72.78	79	0.78	0.23	0.068
LBNH	BHZ	44.24	71.93	279	-0.09	0.26	0.040
LDIO	HHZ	49.92	89.60	6	0.83	0.43	0.708
LDSQ	HHZ	45.71	76.35	7	0.00	0.27	0.380
LESQ	HHZ	48.32	69.41	59	-0.12	0.18	0.062
LG4Q	EHZ	53.63	74.10	247	-0.07	0.22	0.118
LINO	HHZ	44.35	78.78	11	0.12	0.18	0.172
LMN	BHZ	45.85	64.81	385	-0.21	0.34	0.045
LMN	HHZ	45.85	64.81	3	-0.20	0.30	1.719
LMQ	BHZ	47.55	70.33	473	0.06	0.21	0.025
LMQ	HHZ	47.55	70.33	201	0.14	0.18	0.033
LONY	BHZ	44.62	74.58	343	-0.09	0.22	0.031
LRQ1	EHZ	50.67	63.23	1	0.30		
LRQ2	EHZ	50.65	63.28	1	0.20		
LSQ1	EHZ	45.79	76.15	17	0.10	0.11	0.078
LSQQ	HHZ	49.06	76.98	54	0.10	0.27	0.098
LUPN	BHZ	65.74	111.26	1	0.00		
MADG	HHZ	47.27	61.69	17	-0.06	0.31	0.220

MALG	HHZ	45.79	63.32	34	0.12	0.23	0.108
MALO	HHZ	50.02	79.76	146	-0.04	0.29	0.063
MATQ	HHZ	49.76	77.64	111	-0.09	0.18	0.045
MCA1	HHZ	45.59	67.33	7	0.17	0.29	0.406
MCA2	HHZ	45.59	67.31	14	0.60	0.29	0.233
MCA3	HHZ	45.59	67.34	9	0.24	0.21	0.235
MCA3	EHZ	45.59	67.34	6	0.00	0.30	0.490
MCA4	HHZ	45.60	67.33	8	0.20	0.37	0.458
MCA5	HHZ	45.60	67.33	9	0.54	0.42	0.470
MCKN	BHZ	64.20	110.21	3	-0.17	0.31	0.178
MCMN	BHZ	63.30	92.30	73	0.03	0.14	0.043
MCNB	HHZ	45.60	67.32	25	0.08	0.36	0.201
MEDO	HHZ	43.16	78.45	186	0.03	0.20	0.038
MGDQ	HHZ	45.72	75.49	6	0.42	0.07	0.115
MIV	EHZ	44.07	73.53	1	2.20		
MKVL	HHZ	55.09	59.18	10	0.09	0.35	0.360
MLON	BHZ	63.97	109.90	3	-0.23	0.15	0.860
MNQ	EHZ	50.53	68.77	541	0.01	0.21	0.023
MNT	BHZ	45.50	73.63	186	-0.07	0.27	0.052
MNTQ	HHZ	45.50	73.63	173	-0.07	0.17	0.034
MOQ	EHZ	45.31	72.25	766	-0.10	0.18	0.017
MPPO	HHZ	44.77	76.27	257	0.08	0.18	0.029
MRHQ	HHZ	45.89	74.21	232	-0.07	0.19	0.032
MRYN	BHZ	71.33	79.38	40	0.04	0.25	0.107
MSNO	HHZ	51.29	80.62	16	0.83	0.28	0.206
MUMO	HHZ	52.61	90.39	6	-0.35	0.57	0.938
NANL	HHZ	56.54	61.69	22	-0.11	0.24	0.145
NANO	HHZ	50.35	86.97	66	-0.09	0.27	0.088
NATG	HHZ	50.29	62.81	387	0.04	0.32	0.042
NCB	BHZ	43.97	74.22	84	-1.96	0.32	0.092
NMSQ	HHZ	51.71	76.02	62	0.10	0.23	0.078
NSKO	HHZ	52.20	87.93	6	0.27	0.30	0.494
NUNN	BHZ	65.21	91.08	363	0.11	0.22	0.030
ORHO	HHZ	45.46	75.54	42	0.75	0.23	0.096
ORIO	HHZ	45.45	75.51	401	-0.02	0.16	0.021
OTRO	HHZ	50.18	81.63	19	0.59	0.30	0.192
OTT	HHZ	45.39	75.72	320	0.03	0.22	0.320
OTT	EHZ	45.39	75.72	280	0.02	0.21	0.033
PCAQ	HHZ	49.73	62.94	39	0.09	0.28	0.122

PECO	HHZ	43.93	76.99	404	0.10	0.19	0.024
PEMO	HHZ	45.68	77.25	1080	0.21	0.23	0.018
PINU	HHZ	72.70	77.97	62	0.28	0.27	0.091
PKLO	HHZ	51.15	90.04	76	-0.04	0.28	0.085
PKME	BHZ	45.26	69.29	384	0.10	0.28	0.037
PKRO	HHZ	43.96	79.07	150	0.44	0.25	0.053
PLIO	HHZ	41.75	82.63	106	0.02	0.21	0.054
PLVO	HHZ	45.04	77.08	1187	0.21	0.21	0.016
PMAQ	HHZ	49.83	64.33	51	-0.03	0.44	0.165
PNPO	HHZ	48.60	86.29	88	0.05	0.30	0.084
PTCO	HHZ	42.88	79.31	8	0.04	0.17	0.210
QCQ	EHZ	46.78	71.28	195	-0.09	0.19	0.035
QILN	BHZ	66.65	86.37	469	-0.01	0.21	0.025
RD01	EHZ	43.41	79.84	20	0.54	0.22	0.141
RD02	EHZ	43.32	79.88	16	0.40	0.24	0.177
RD03	EHZ	43.18	79.94	20	0.75	0.30	0.192
RD04	EHZ	43.15	79.70	17	0.25	0.24	0.170
RES	BHZ	74.69	94.90	147	-0.27	0.30	0.065
RLKO	HHZ	51.07	93.76	4	-0.15	0.58	1.694
ROMN	BHZ	64.32	118.02	3	0.33	0.25	1.432
RSPO	HHZ	46.07	79.76	221	0.01	0.22	0.038
SADO	BHZ	44.77	79.14	743	0.02	0.23	0.022
SADQ	HHZ	46.75	71.54	5	0.22	0.30	0.618
SAKN	HHZ	56.54	79.23	2	0.40	0.28	
SCHQ	BHZ	54.83	66.83	163	-0.08	0.25	0.051
SEDN	BHZ	63.25	91.28	358	0.01	0.18	0.025
SFJD	BHZ	67.00	50.62	14	-0.36	0.93	0.749
SILO	HHZ	54.48	84.91	147	-0.09	0.28	0.060
SJNN	HHZ	47.60	52.68	12	0.16	0.13	0.117
SMCQ	HHZ	46.67	72.06	1	0.40		
SMLN	BHZ	68.59	91.94	74	-0.09	0.18	0.055
SMQ	EHZ	50.22	66.70	769	0.03	0.20	0.027
SNKN	BHZ	56.54	79.23	4	0.12	0.13	0.380
SNLN	BHZ	62.83	107.61	8	0.01	0.14	0.173
SNPN	BHZ	63.52	110.91	4	0.15	0.44	1.285
SNQN	BHZ	56.54	79.23	28	-0.04	0.27	0.141
SOLO	EHZ	50.02	92.08	65	-0.12	0.21	0.069
SRLN	BHZ	68.55	83.32	258	-0.04	0.18	0.029
SRNB	HHZ	45.83	65.64	153	0.01	0.26	0.050

STCO	HHZ	43.21	79.17	76	0.16	0.22	0.067
STFQ	HHZ	46.55	71.54	1	-0.10		
STLN	BHZ	67.31	92.98	219	-0.09	0.19	0.033
STUQ	HHZ	46.30	73.09	75	0.25	0.28	0.086
SUNO	HHZ	46.64	81.34	76	0.11	0.19	0.058
SVNB	HHZ	46.16	64.88	100	0.40	0.26	0.068
TBO	EHZ	48.65	89.41	66	-0.17	0.26	0.085
TIGG	HHZ	47.00	64.00	25	0.06	0.42	0.235
TIMO	BHZ	48.47	81.30	46	-0.02	0.25	0.099
TOBO	HHZ	45.23	81.52	172	-0.08	0.20	0.040
TORO	HHZ	43.61	79.34	62	0.72	0.23	0.078
TOTT	HHZ	45.39	75.72	8	0.06	0.07	0.087
TOTT2	HHZ	45.39	75.72	3	0.03	0.06	0.344
TRQ	EHZ	46.22	74.56	1280	-0.03	0.14	0.010
TULEG	BHZ	76.54	68.82	31	-0.28	0.19	0.094
TYNO	HHZ	43.10	79.87	96	0.28	0.21	0.056
ULM	BHZ	50.25	95.88	22	-0.15	0.30	0.181
VABQ	HHZ	45.90	75.61	502	0.01	0.16	0.018
VDBQ	HHZ	45.93	75.57	12	0.74	0.20	0.179
VIMO	HHZ	52.82	83.75	174	0.03	0.23	0.045
VLDQ	BHZ	48.11	77.45	572	-0.14	0.22	0.024
WAGN	BHZ	65.88	89.44	296	0.08	0.19	0.029
WBHL	HHZ	52.90	66.87	7	-0.04	0.21	0.294
WBO	EHZ	45.00	75.28	1199	-0.08	0.17	0.013
WCNB	HHZ	45.65	65.51	155	-0.01	0.26	0.054
WEMQ	HHZ	53.05	77.97	27	-0.06	0.29	0.155
WEMQ	BHZ	53.05	77.97	73	-0.02	0.19	0.059
WHFN	BHZ	62.56	107.09	9	-0.14	0.18	0.201
WLVO	HHZ	43.92	78.40	266	0.07	0.19	0.030
YBKN	BHZ	64.32	96.00	152	0.04	0.15	0.032
YKW3	EHZ	62.56	114.74	78	-0.31	0.22	0.066
YKW3	BHZ	62.56	114.74	8	-0.09	0.16	0.198
YOSQ	HHZ	52.87	72.20	81	0.03	0.19	0.056
YRTN	BHZ	62.81	92.11	67	0.09	0.23	0.074

Table 2
Preliminary Site Corrections for New Stations

Date upgraded	Site	# events	mean residual	standard deviation	99% confidence interval	old station
2016-08-01	RESN	10	-0.06	0.32	0.3289	-0.27
2016-08-03	TOTT	10	-0.05	0.15	0.1542	0.03 (OTT.HHZ)
2016-08-03	TOTT2	6	0.17	0.10	0.1646	0.03 (OTT.HHZ)
2016-08-10	A11	25	-0.20	0.27	0.1510	-0.21
2016-08-11	A16	41	-0.04	0.19	0.0802	0.00
2016-08-16	A54	40	0.02	0.16	0.0685	0.04
2016-09-27	GGN	62	0.14	0.34	0.1148	0.03
2016-09-28	LMN	60	-0.05	0.51	0.1753	-0.21
2016-10-04	A21	64	0.00	0.42	0.1400	0.02
2016-10-06	LMQ	53	0.18	0.33	0.1212	0.14 (LMQ.HHZ)
2016-10-07	A61	48	-0.01	0.32	0.1240	-0.05
2016-10-08	A64	45	-0.01	0.16	0.0642	-0.04
2016-11-01	WBO	84	-0.05	0.15	0.0431	-0.08
2016-11-03	VLDQ	56	-0.14	0.19	0.0677	-0.14
2016-11-23	GAC	93	-0.14	0.26	0.0709	-0.12 (GAC.BHZ)
2016-11-25	GRQ	93	0.00	0.23	0.0600	-0.05
2016-12-02	ORIO	55	0.01	0.22	0.0792	-0.02
2016-12-08	KGNO	11	0.17	0.17	0.1624	0.02
2017-02-16	MNTQ	31	0.07	0.19	0.0938	-0.07
2017-03-25	SAKN	11	0.11	0.23	0.2198	0.40
2017-04-21	HAL	7	-0.01	0.32	0.4484	0.03 (HAL.HHZ)
2017-06-04	KIPQ	53	-0.03	0.20	0.0735	-0.03 (EEO)
2017-06-06	SUBO	19	-0.02	0.15	0.0991	0.11 (SUNO)
2017-06-09	KAPO	17	0.05	0.23	0.1629	-0.04
2017-06-11	GTO	40	0.02	0.21	0.0899	0.01
2017-06-14	KILO	19	-0.08	0.16	0.1057	-0.11

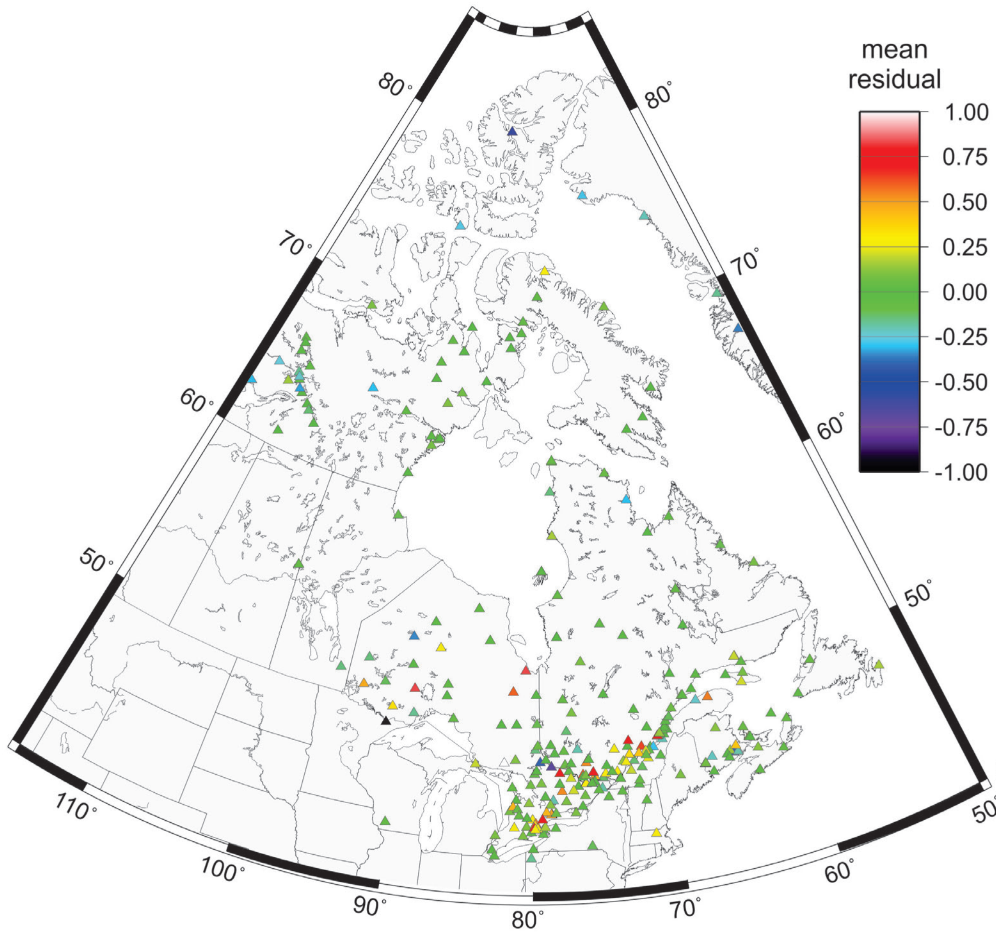


Figure 1: Map showing mean residuals or station corrections for seismograph stations used in this study. Negative residuals mean that the station magnitudes are lower than the mean event magnitudes and positive that they are higher. The residual is measured in magnitude units. Note that a small number of points may plot at the same locations when a station has been occupied by two or more instruments.

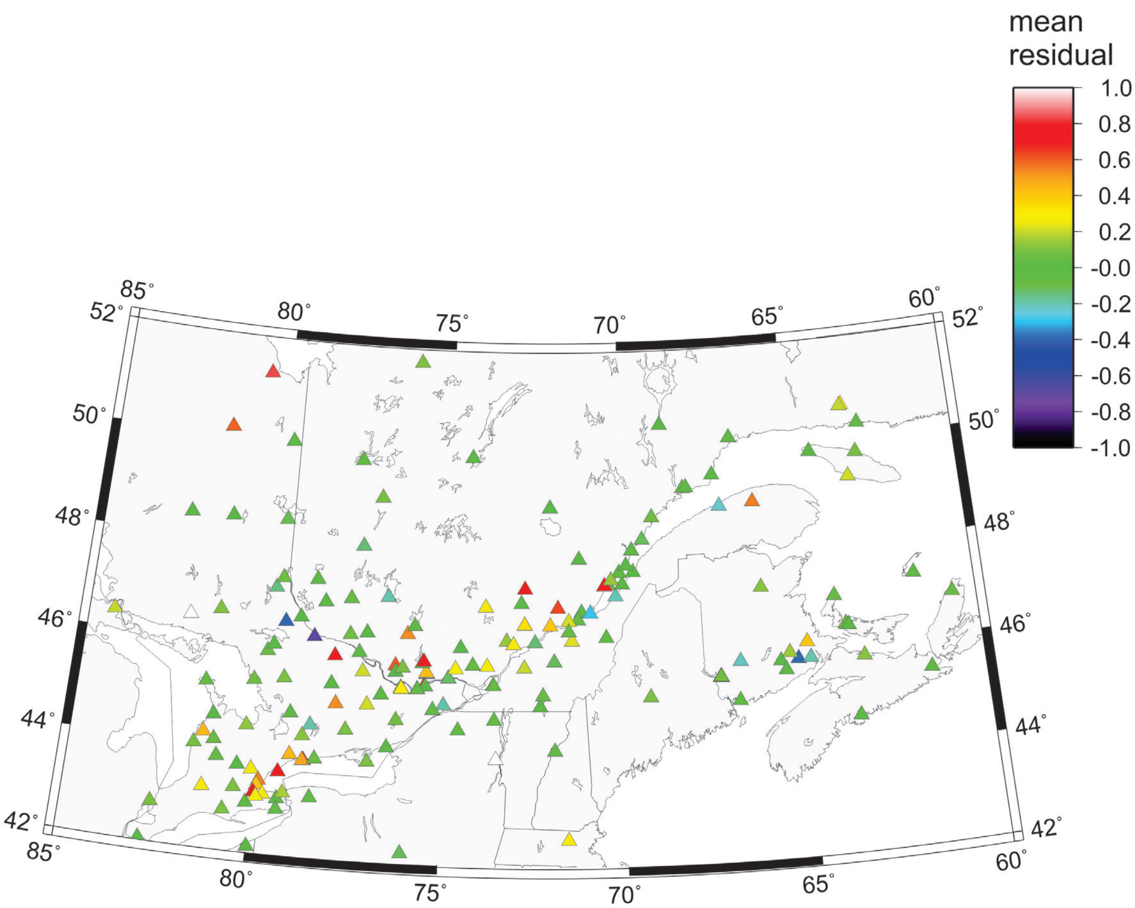


Figure 2: Map of station corrections focused on southeastern Canada. Same format as previous figure.

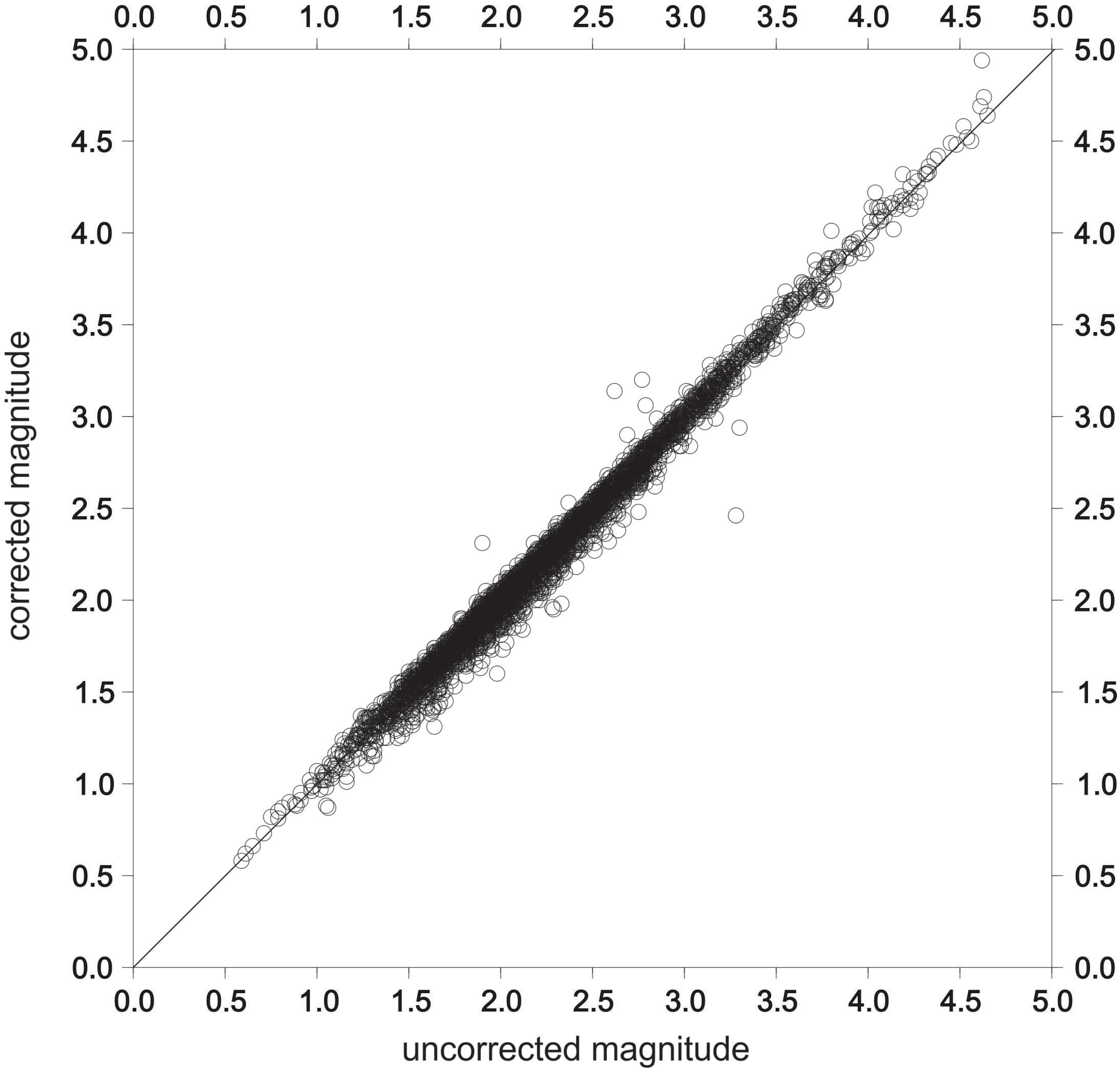


Figure 3: Comparison of magnitudes with (y-axis) and without (x-axis) station corrections applied. The diagonal line shows a 1:1 correspondence. Note that many points may plot at the same locations.

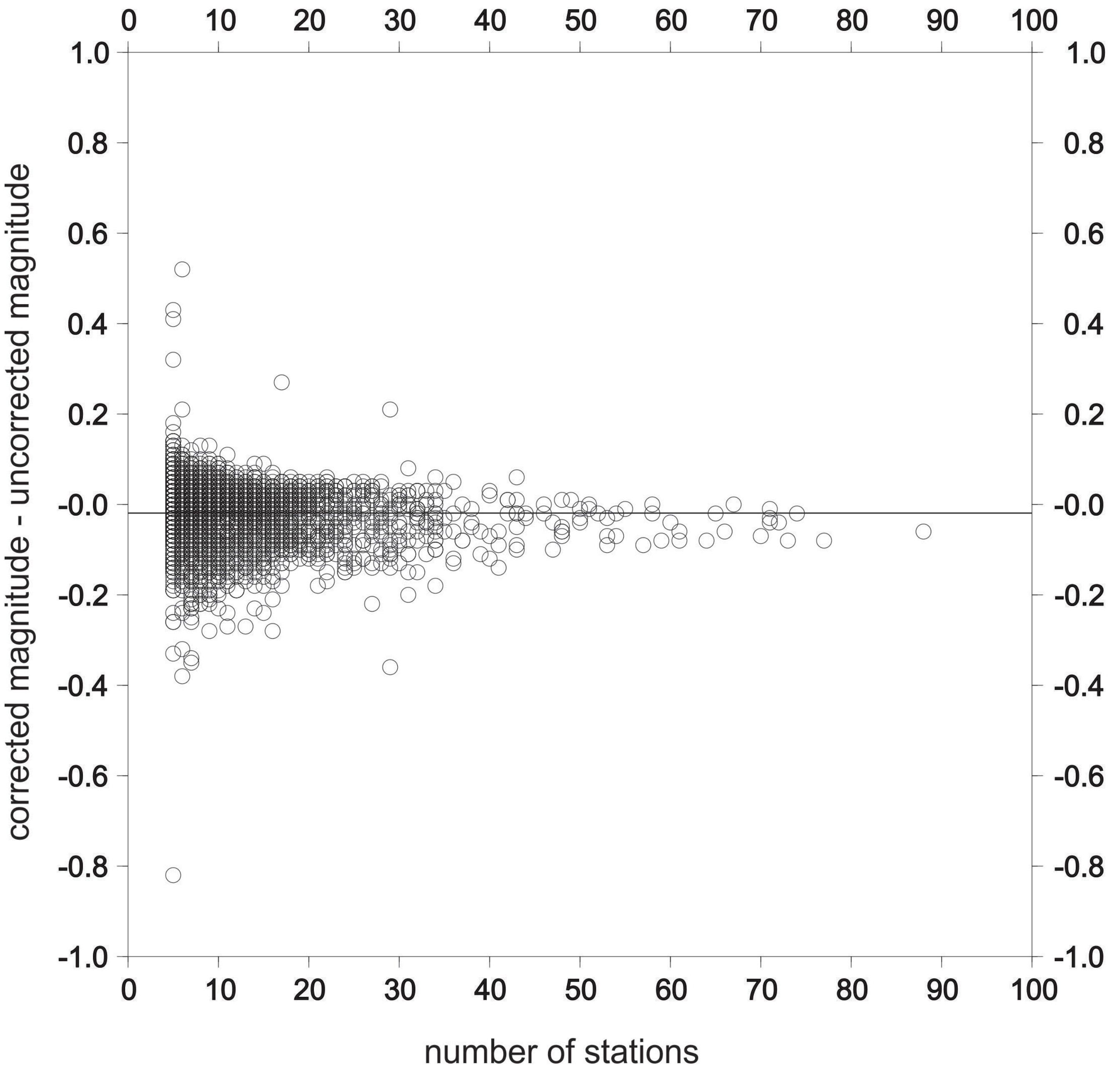


Figure 4: The difference between station corrected and non-corrected magnitudes vs. the number of stations used to calculate the magnitude. The horizontal line shows the mean difference. Note that many points may plot at the same locations.

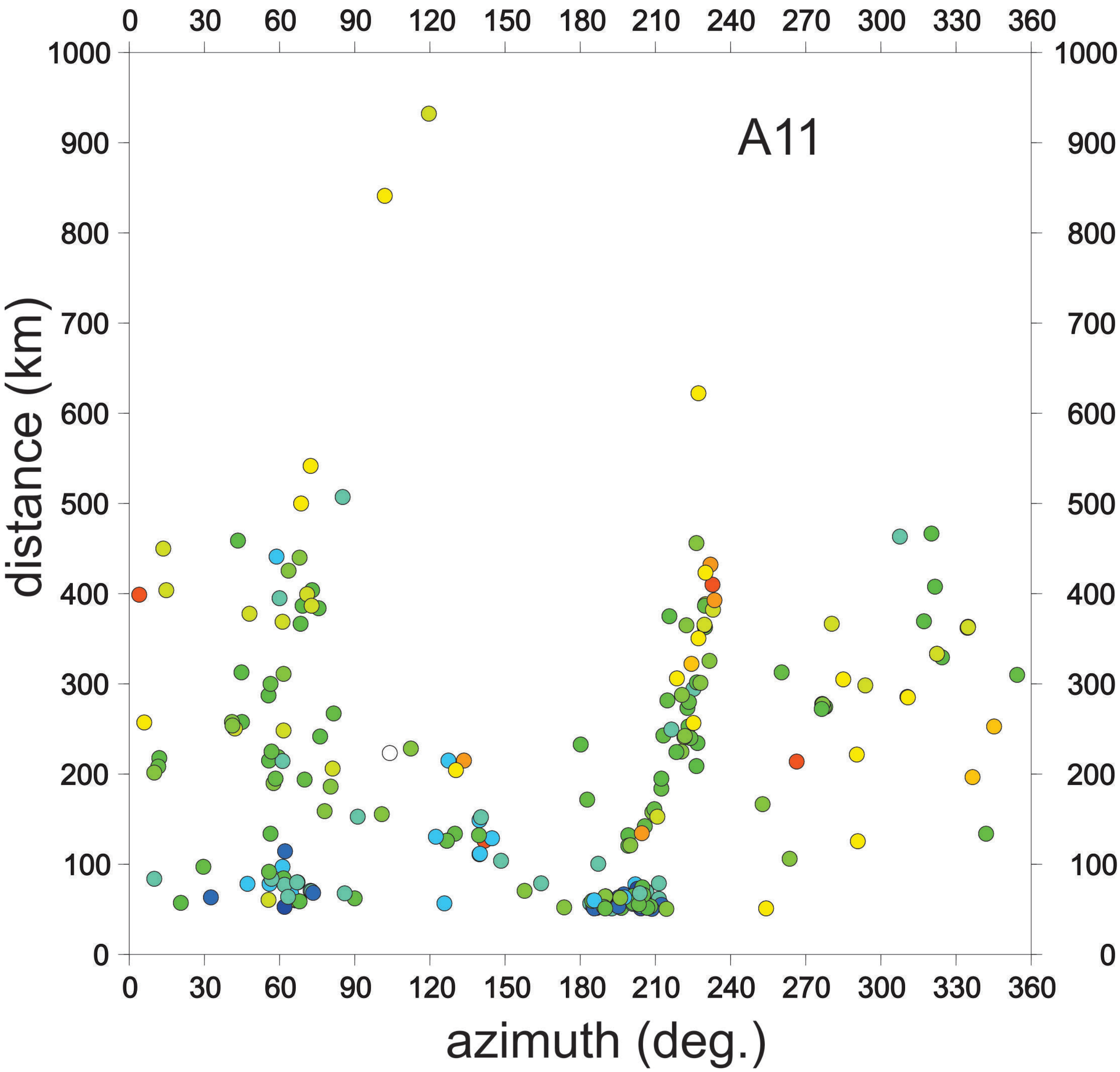
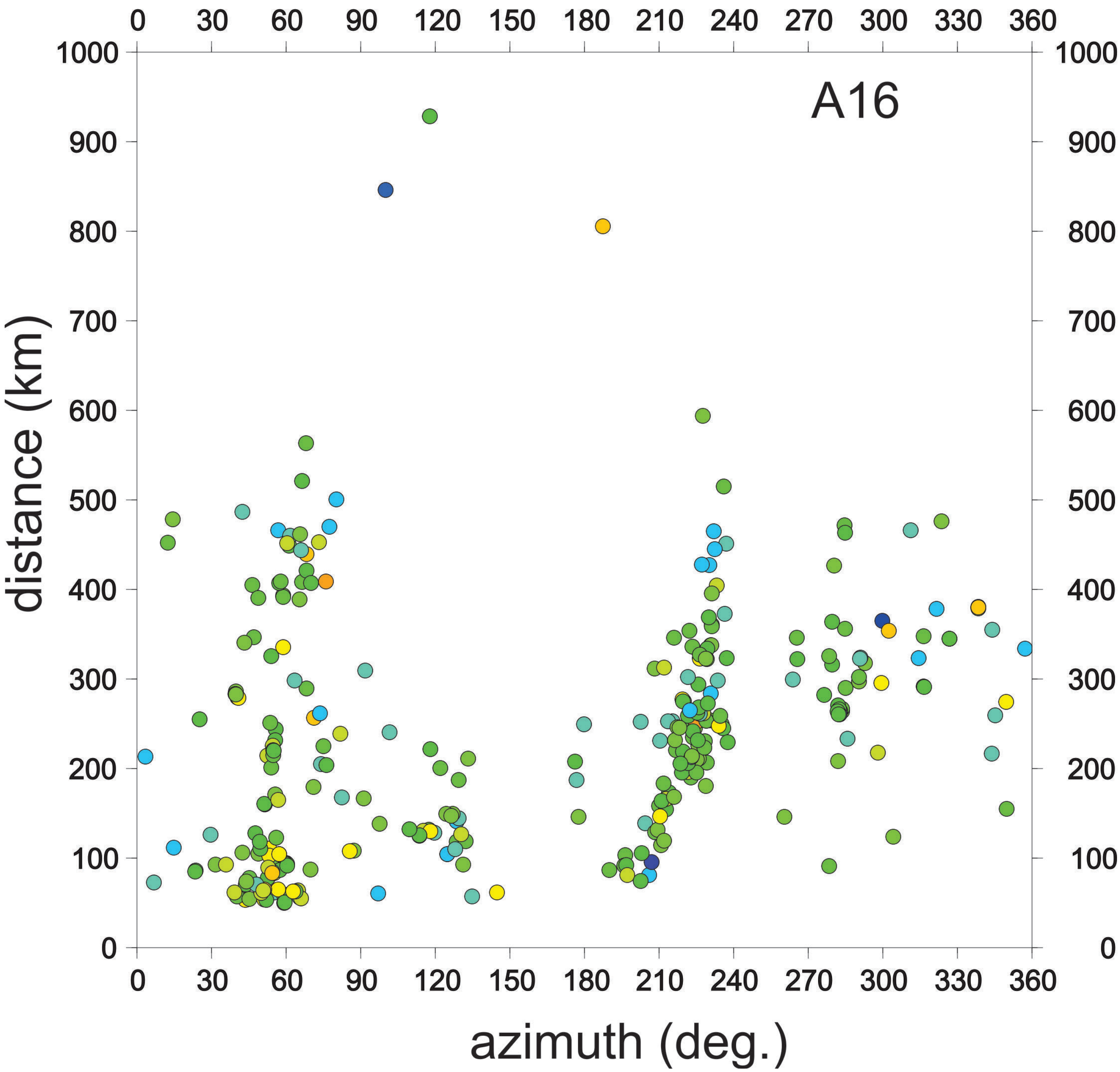

A11
distance (km)
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
0
100
200
300
400
500
600
700
800
900
1000

Figure 5i



A16
distance (km)
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
0
100
200
300
400
500
600
700
800
900
1000

Figure 5ii

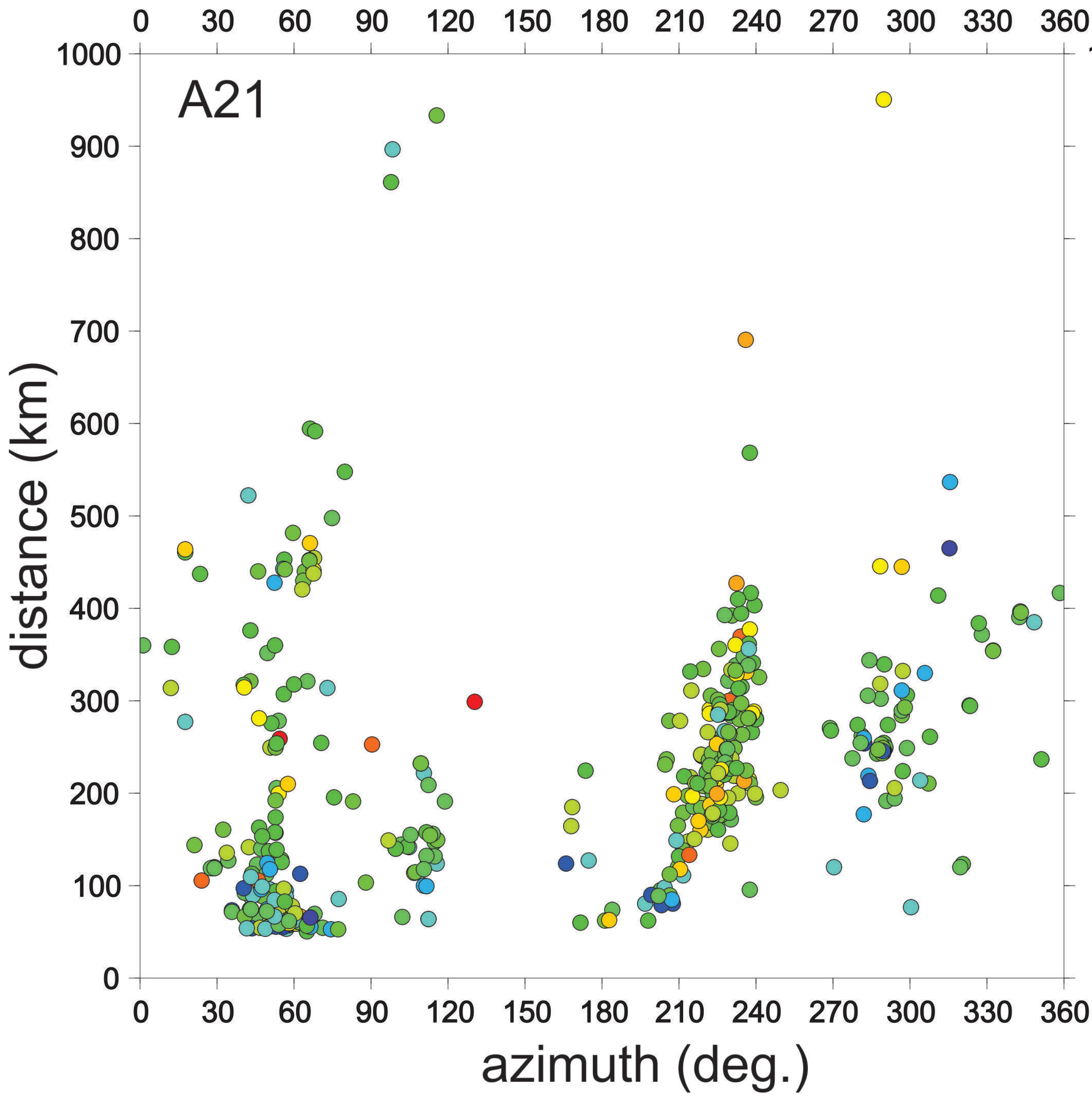
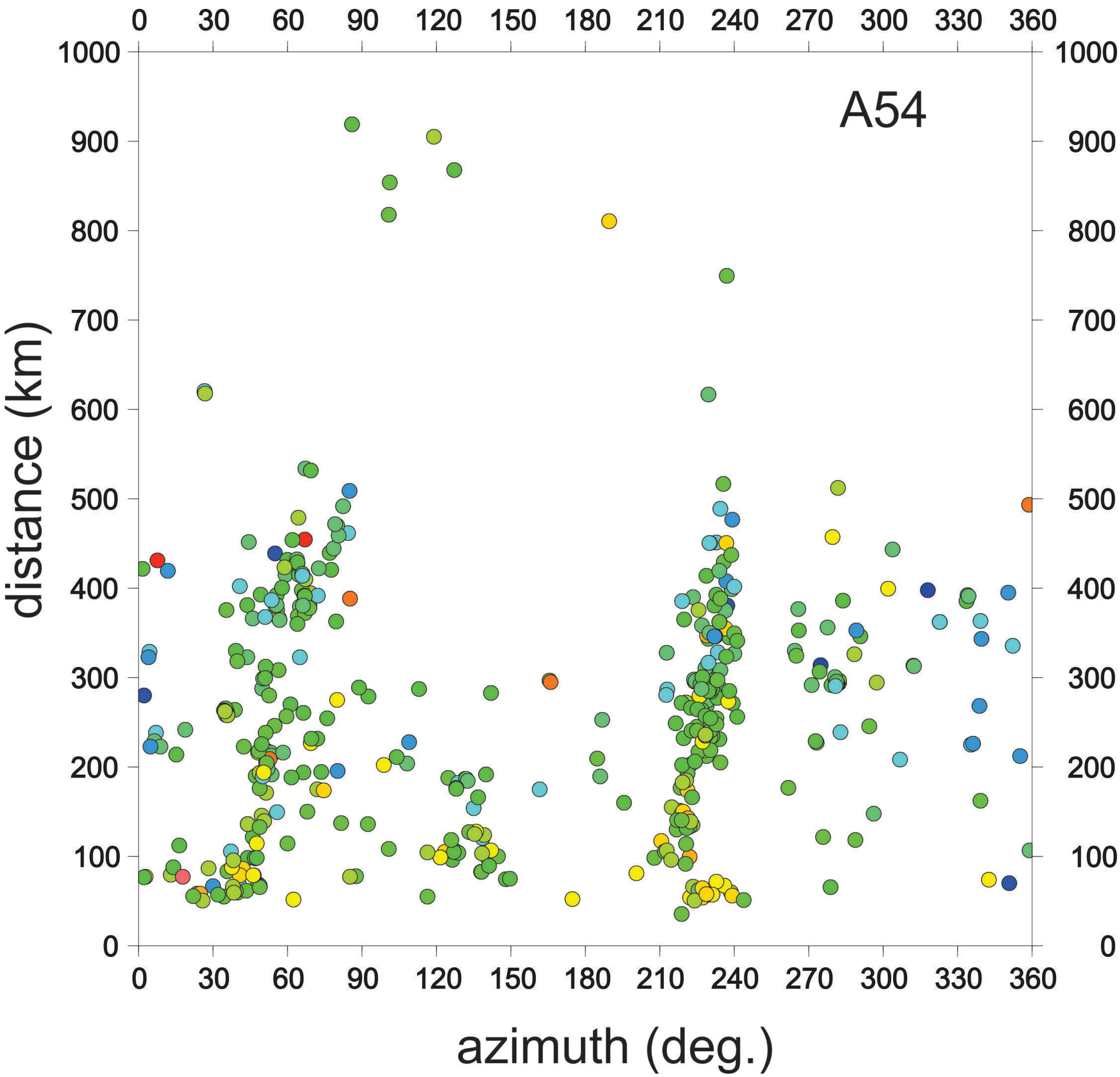

A21
distance (km)
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
0
100
200
300
400
500
600
700
800
900
1000

Figure 5iii



A54
distance (km)
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
0
100
200
300
400
500
600
700
800
900
1000

Figure 5iv

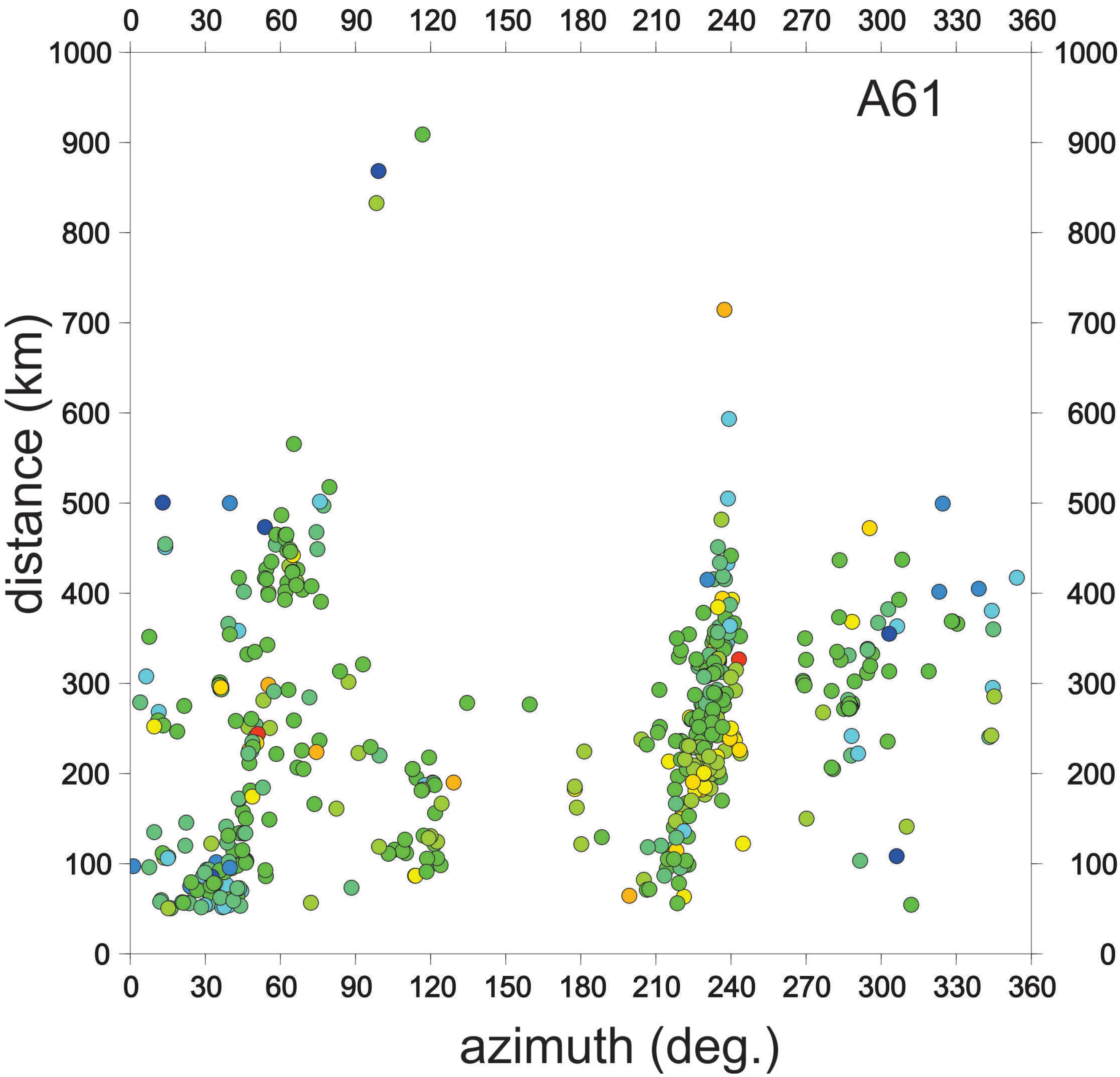

A61
distance (km)
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
0
100
200
300
400
500
600
700
800
900
1000

Figure 5v

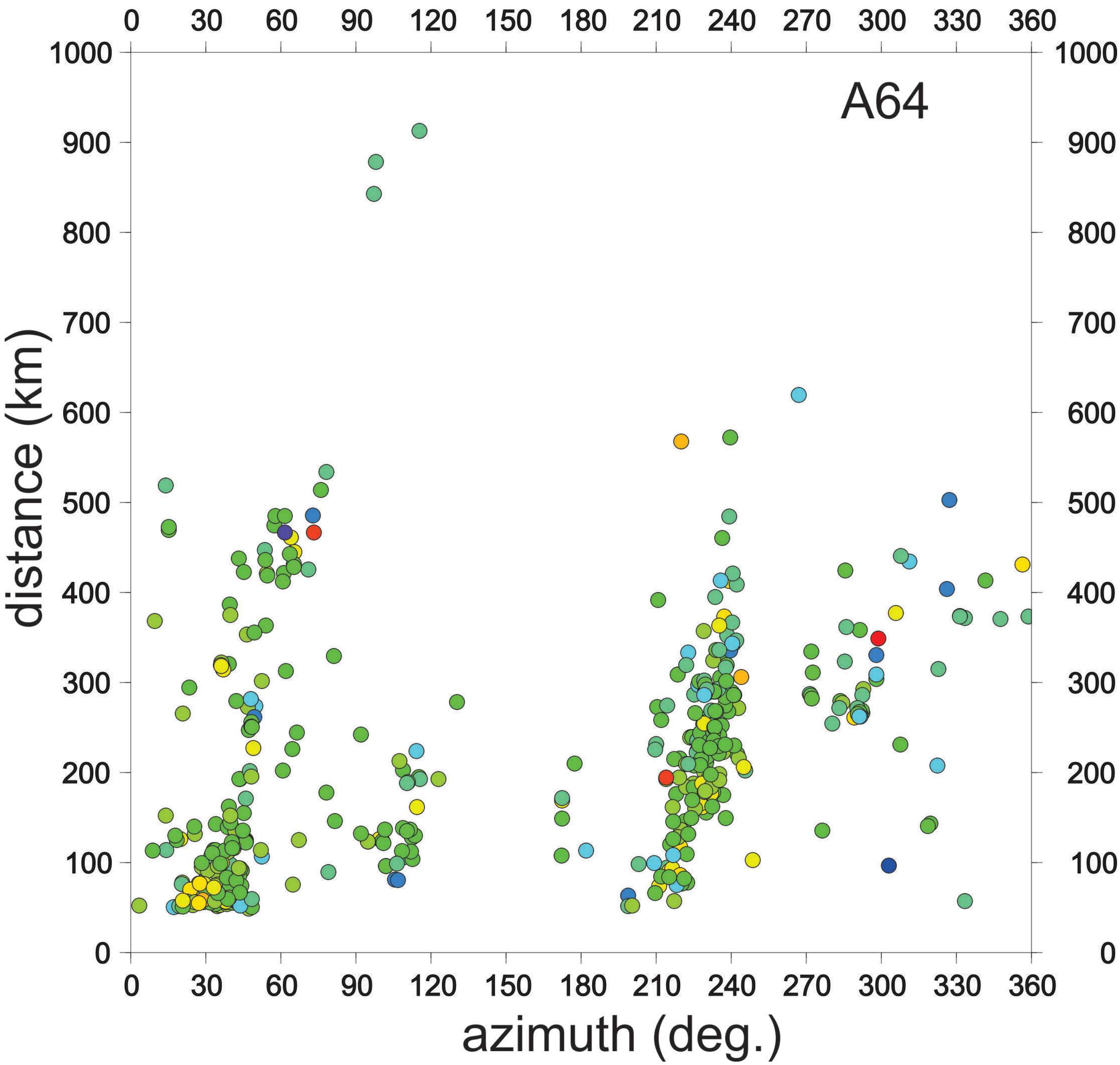

A64
distance (km)
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
0
100
200
300
400
500
600
700
800
900
1000

Figure 5vi

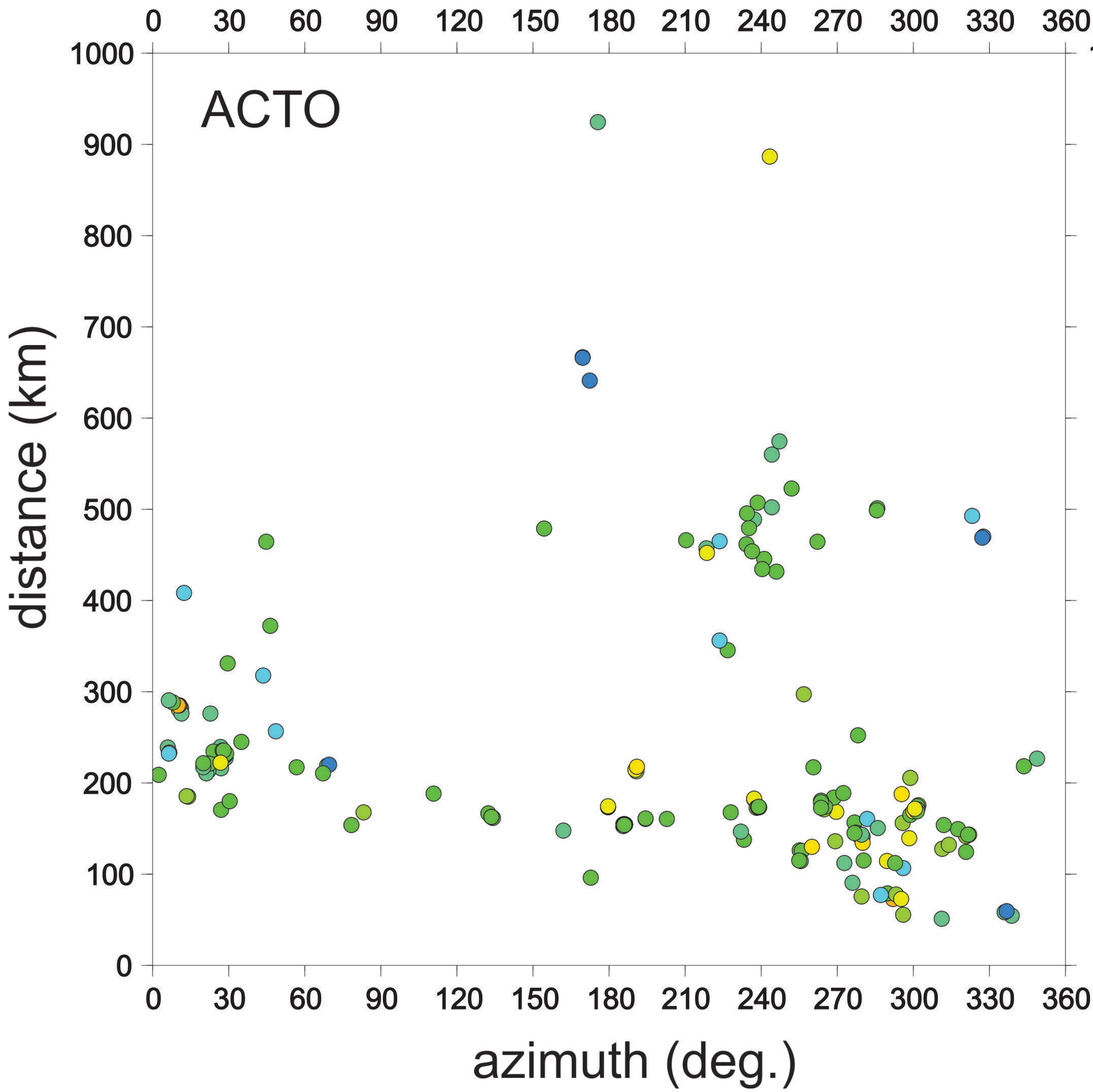

ACTO
distance (km)
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
0
100
200
300
400
500
600
700
800
900
1000

Figure 5vii

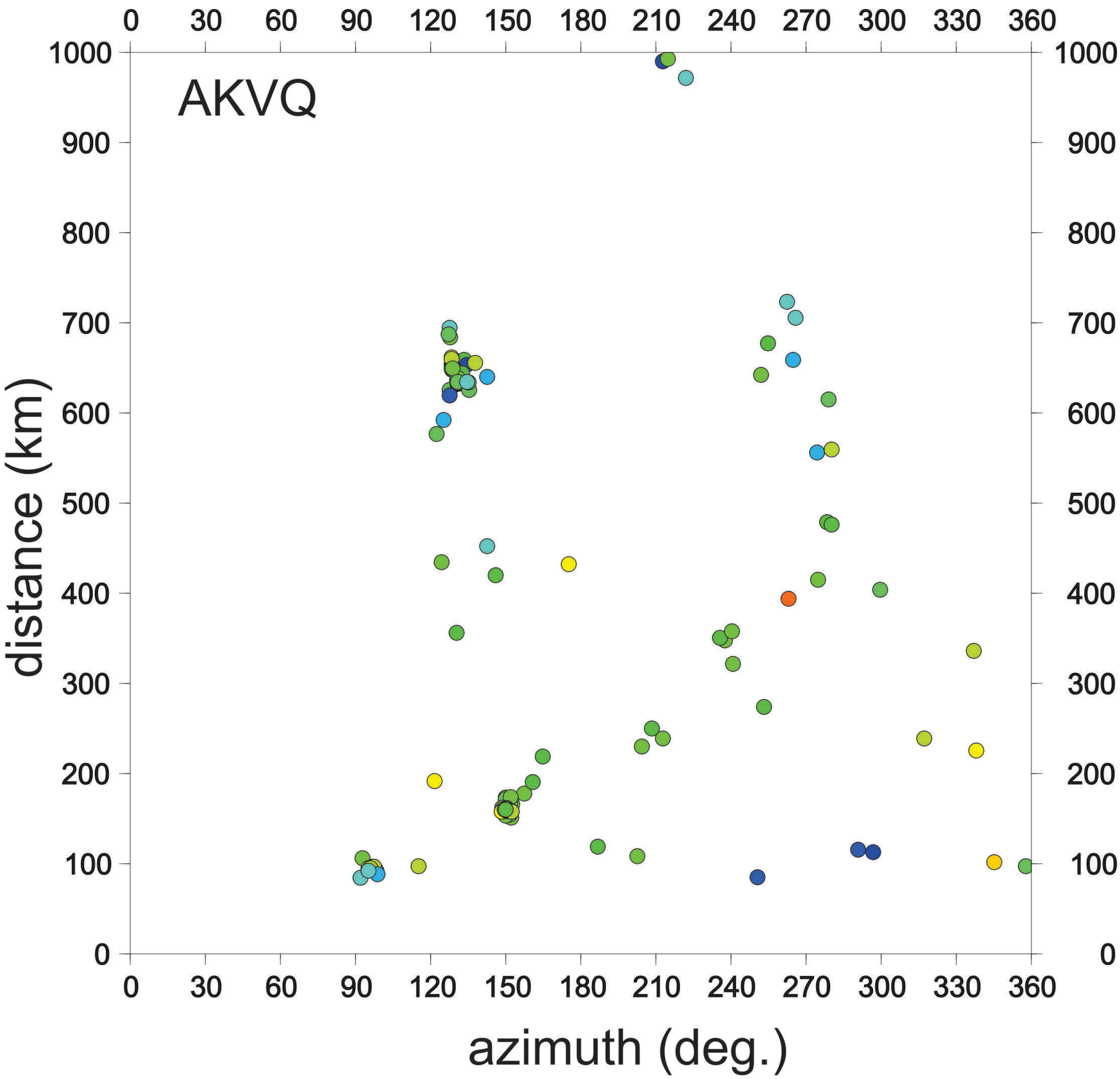


Figure 5viii

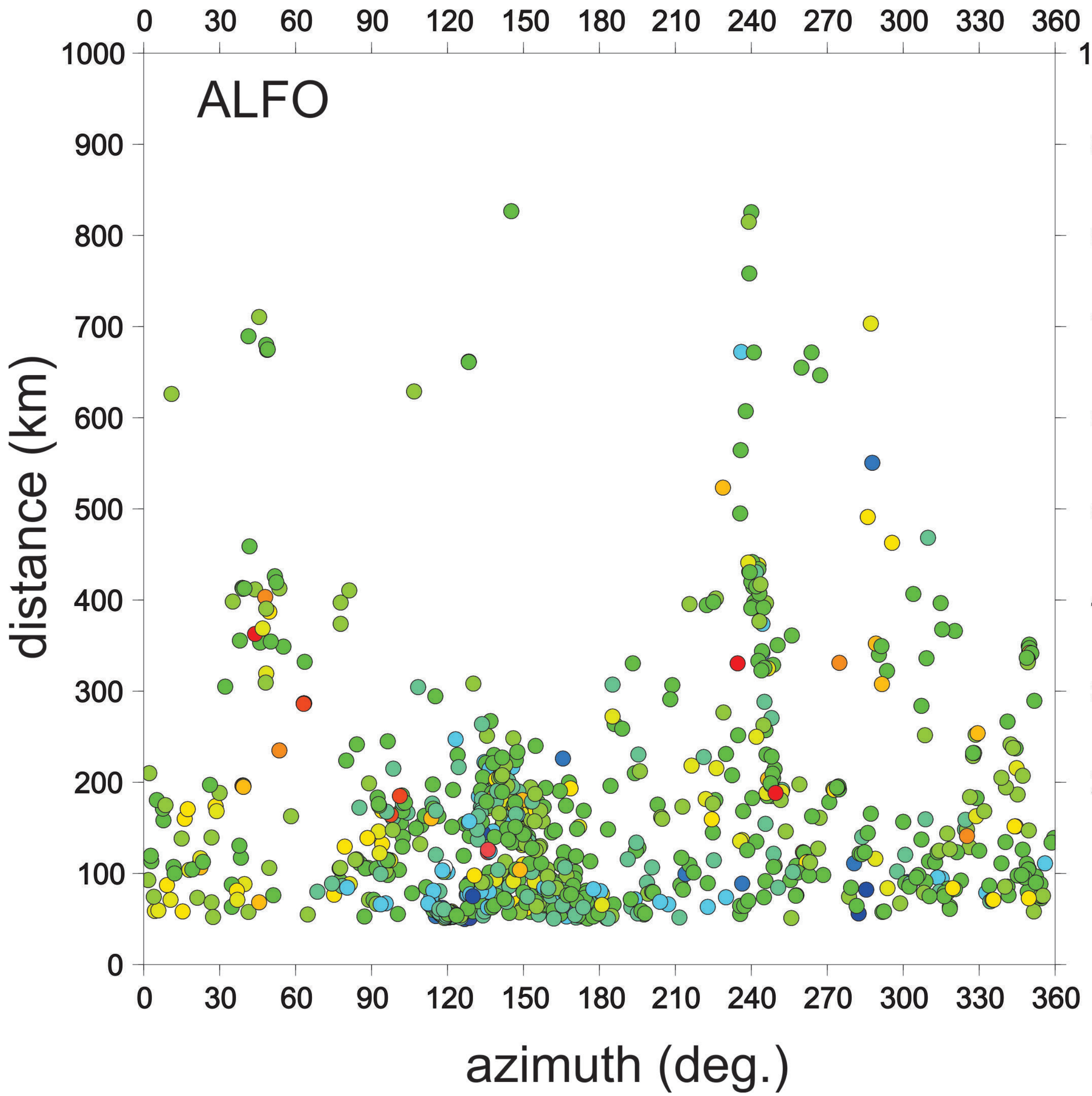

ALFO
distance (km)
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
0
100
200
300
400
500
600
700
800
900
1000

Figure 5ix

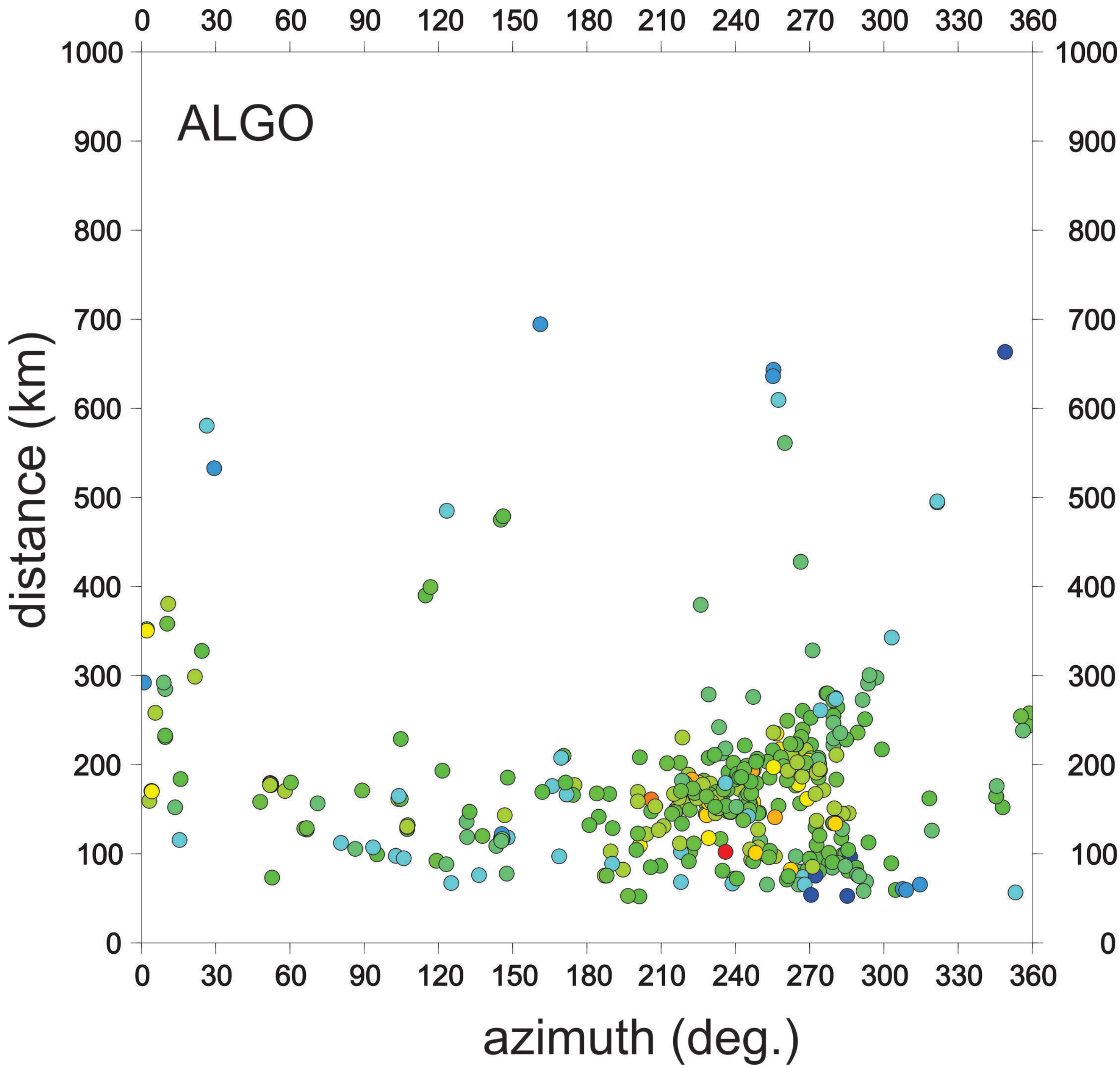

ALGO
distance (km)
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
1000
900
800
700
600
500
400
300
200
100
0

Figure 5x

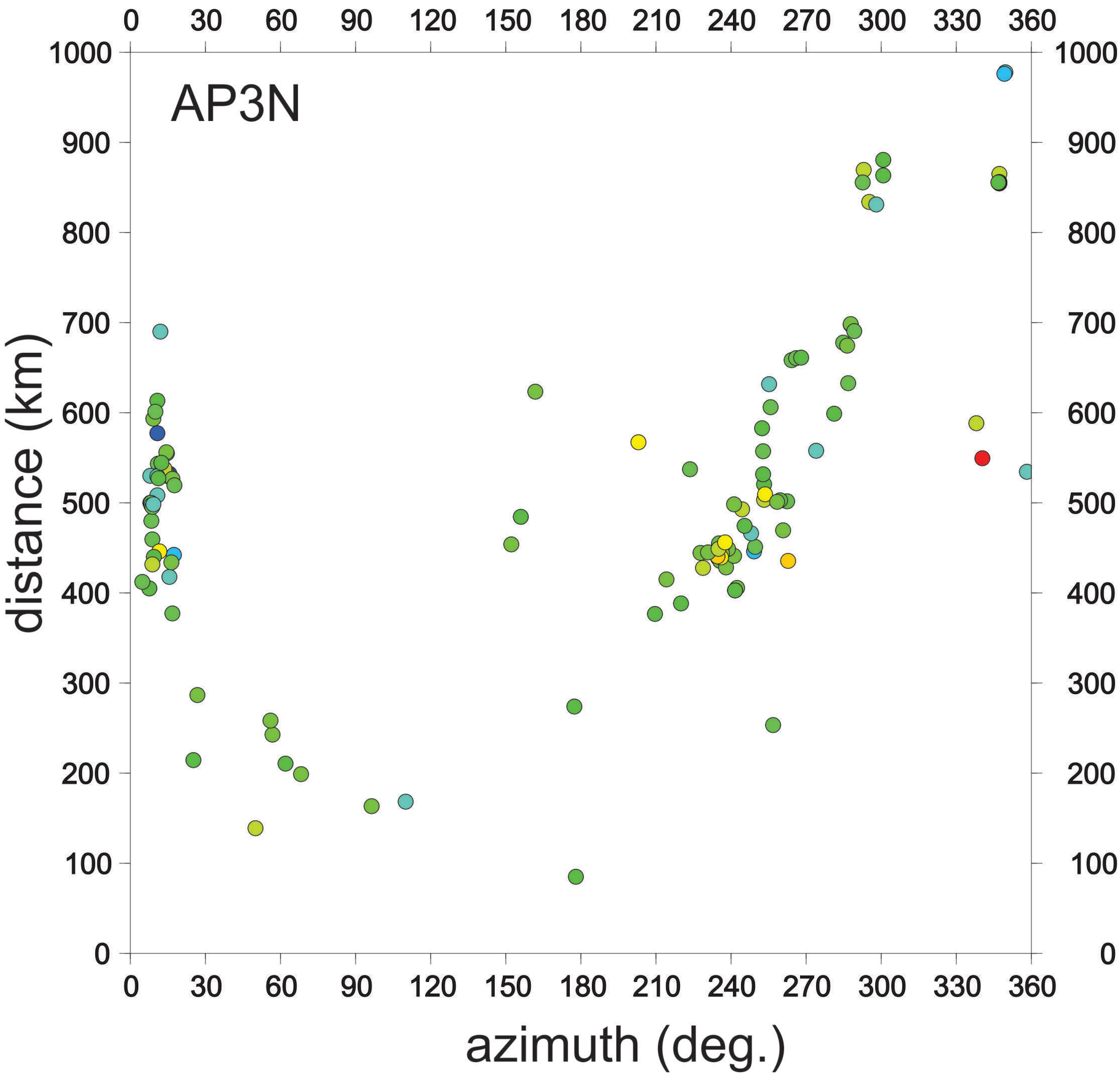

AP3N
distance (km)
azimuth (deg.)
0 30 60 90 120 150 180 210 240 270 300 330 360
0 100 200 300 400 500 600 700 800 900 1000

Figure 5xi

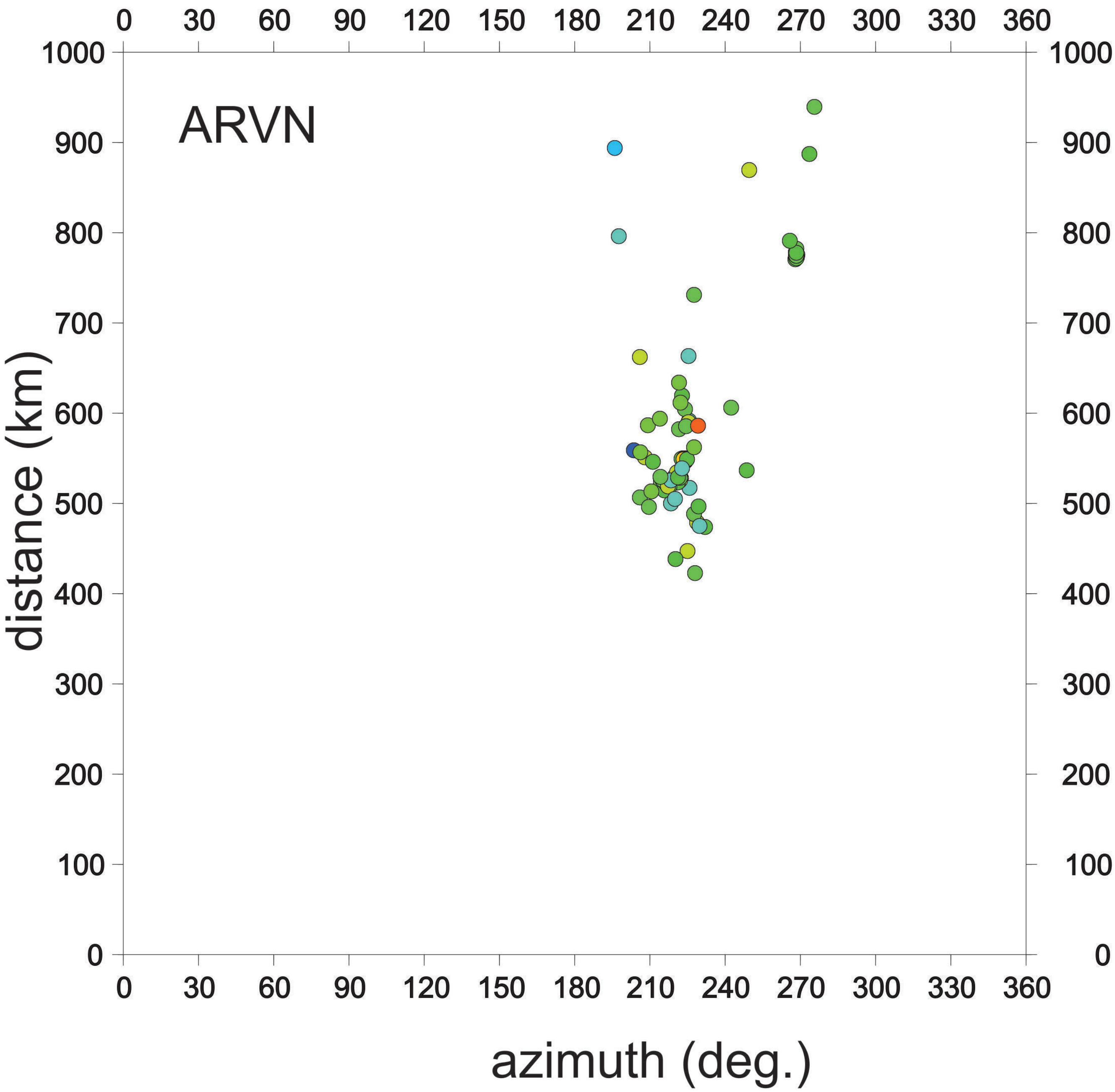

ARVN
distance (km)
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
0
100
200
300
400
500
600
700
800
900
1000

Figure 5xii

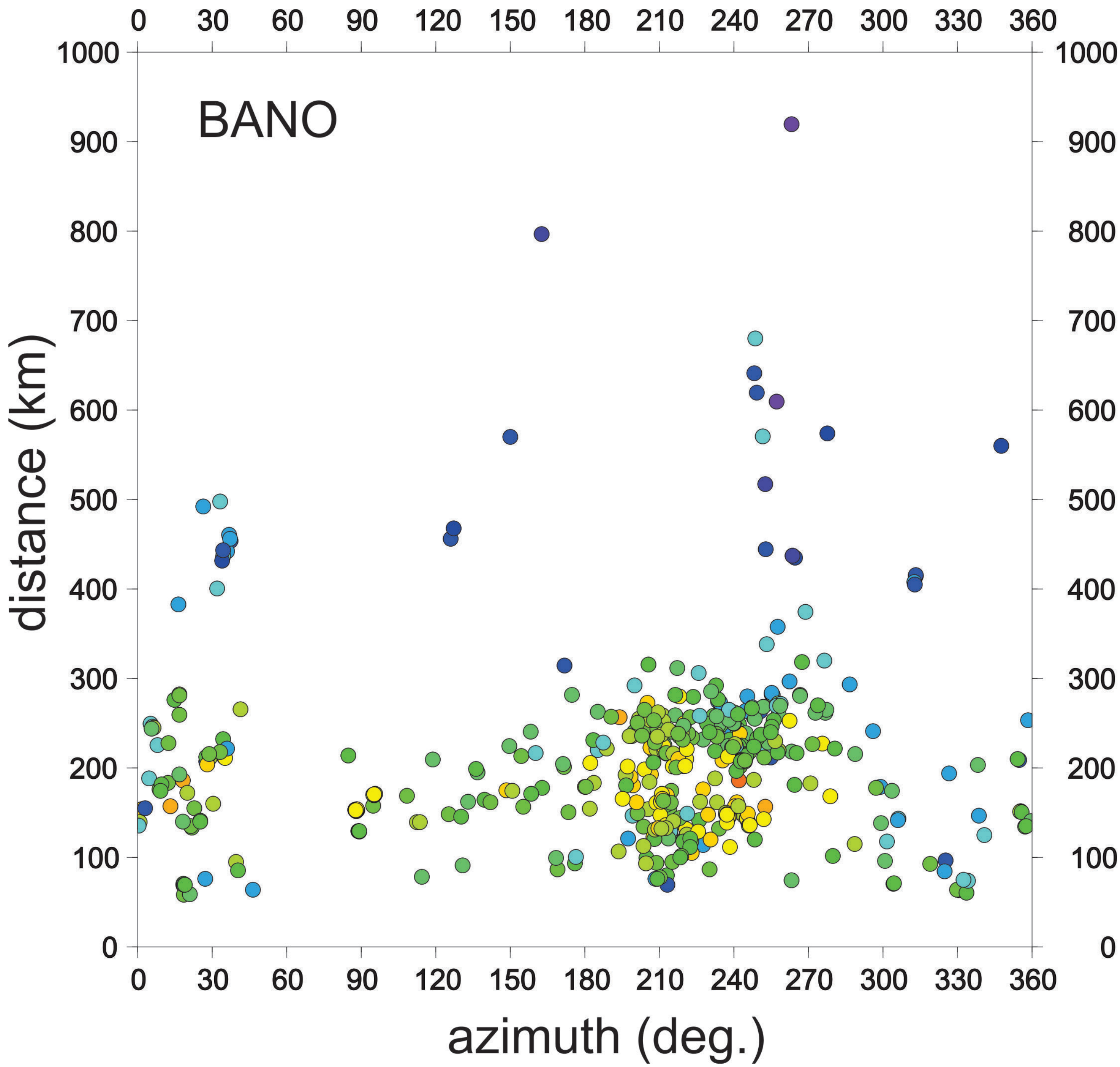
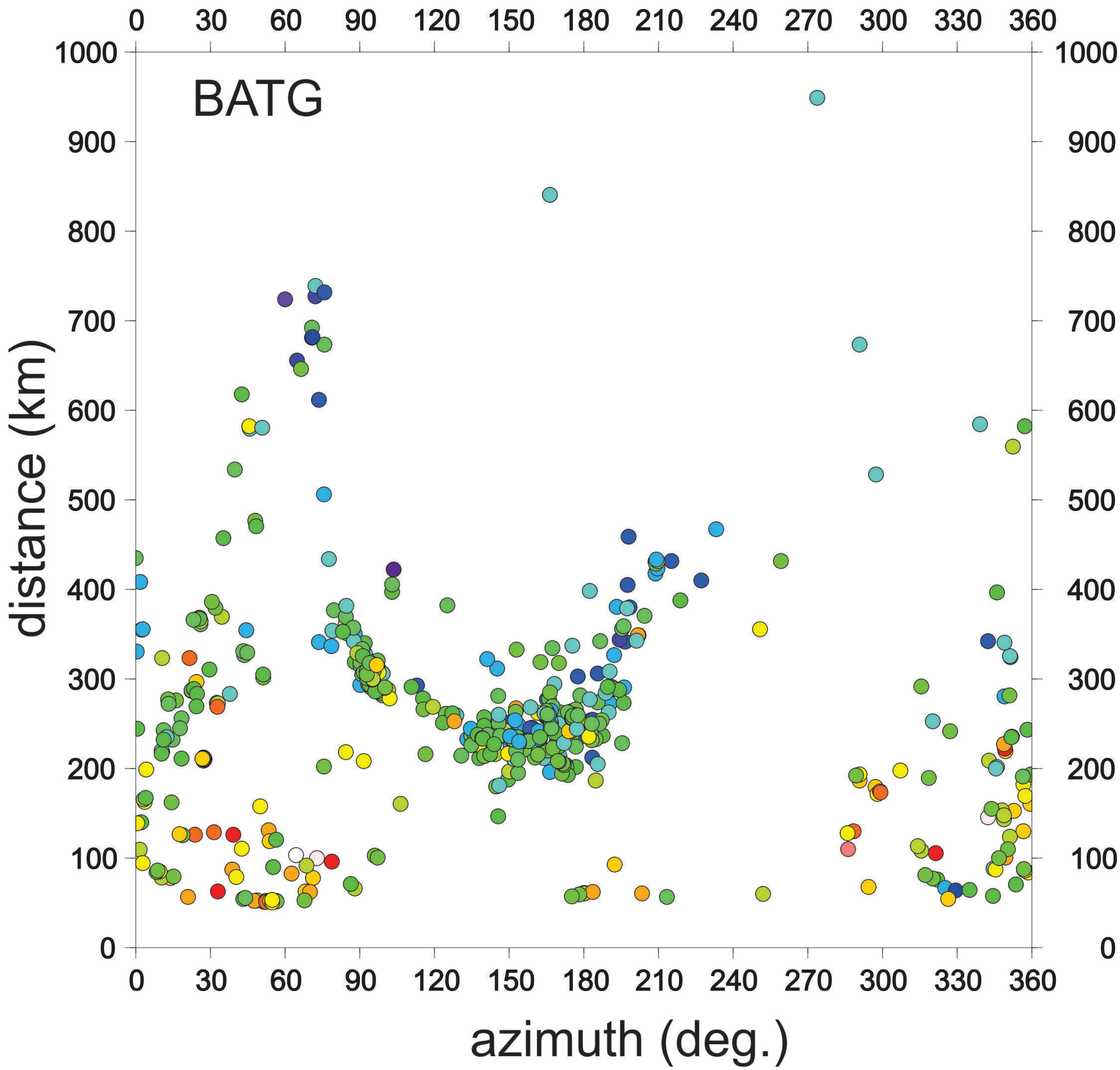


Figure 5xiii


BATG
distance (km)
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
0
100
200
300
400
500
600
700
800
900
1000
Figure 5xiv

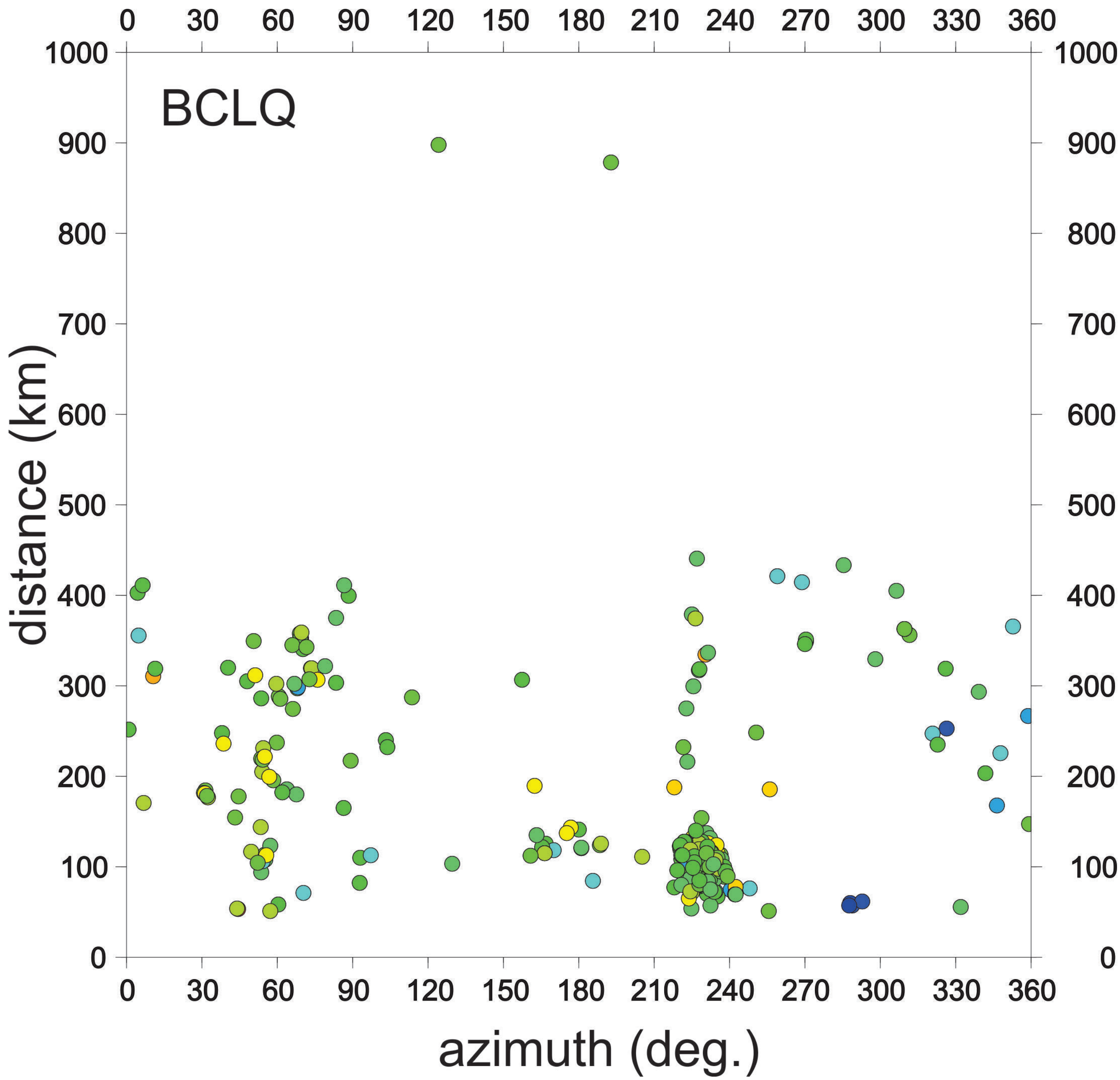

BCLQ
distance (km)
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
0
100
200
300
400
500
600
700
800
900
1000

Figure 5xv

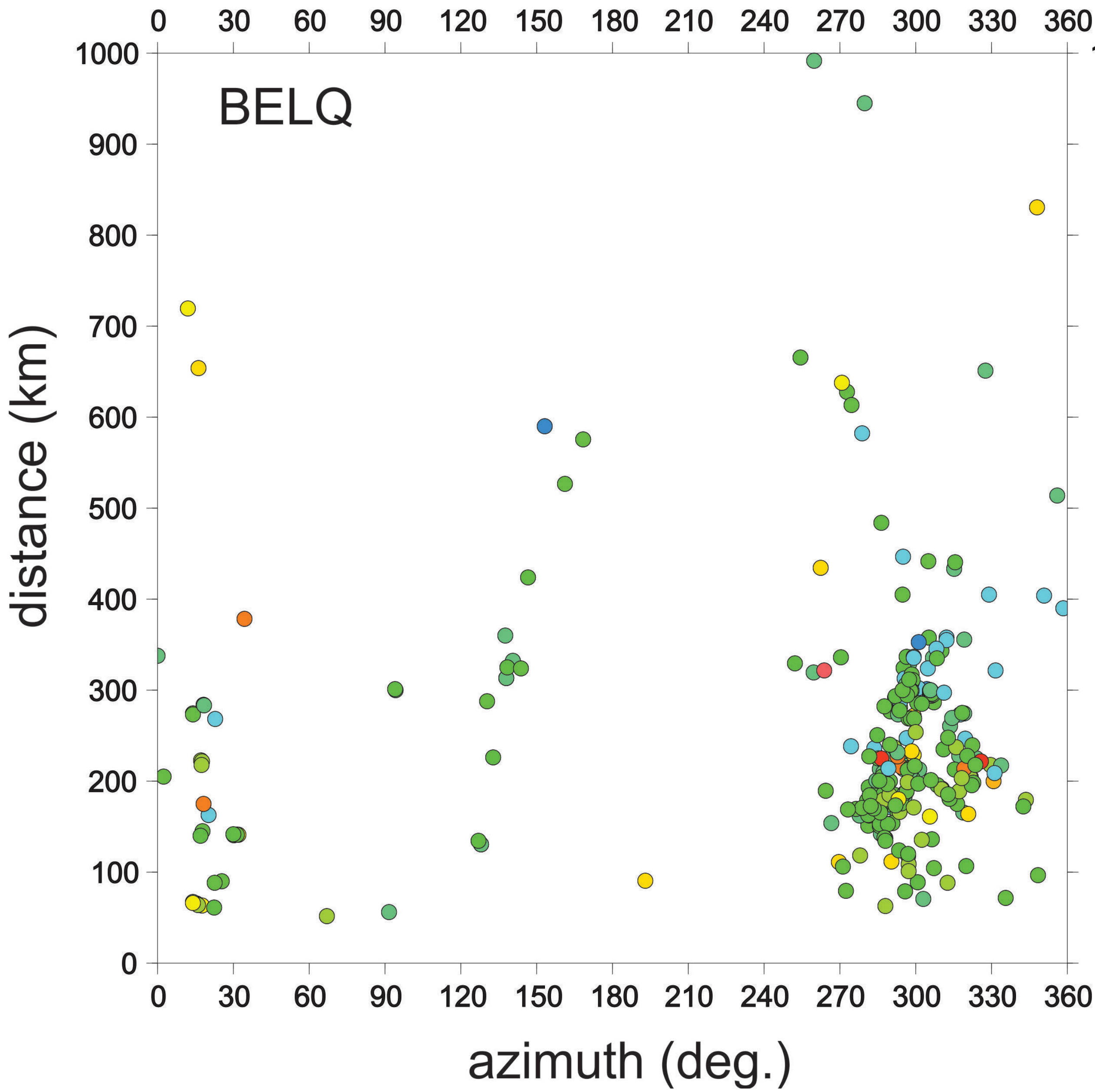

BELQ
distance (km)
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
0
100
200
300
400
500
600
700
800
900
1000

Figure 5xvi

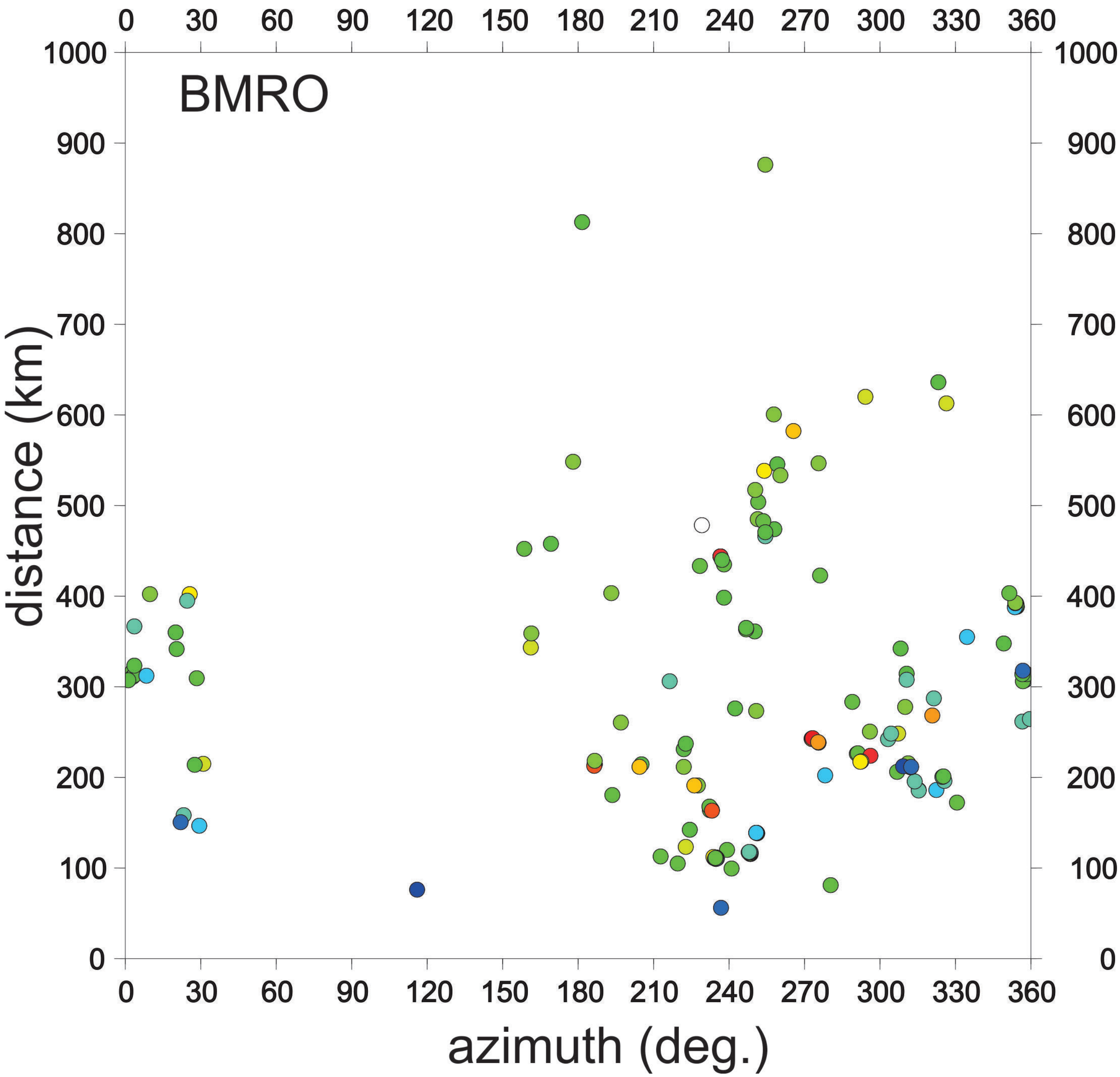


Figure 5xvii

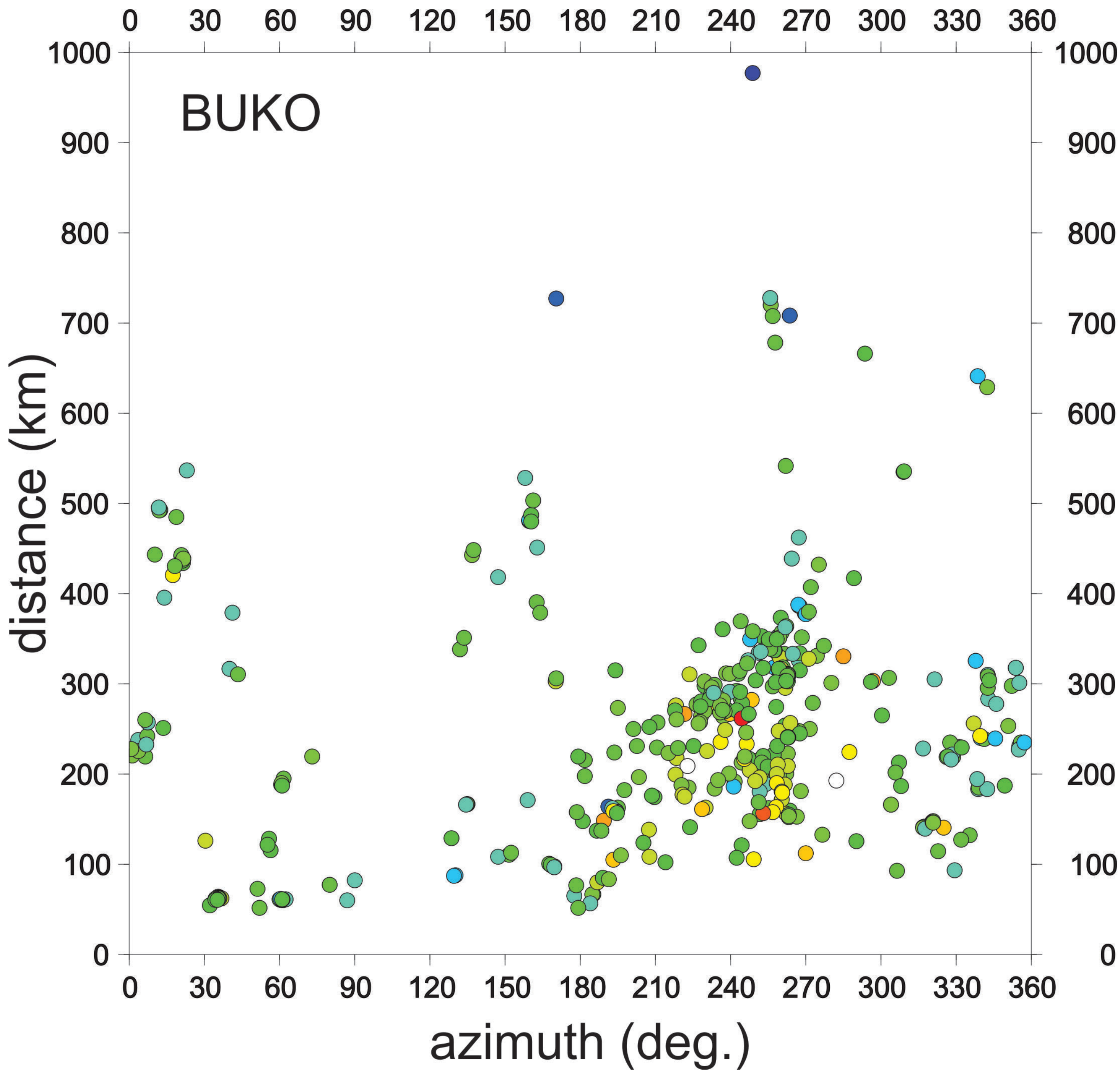


Figure 5xviii

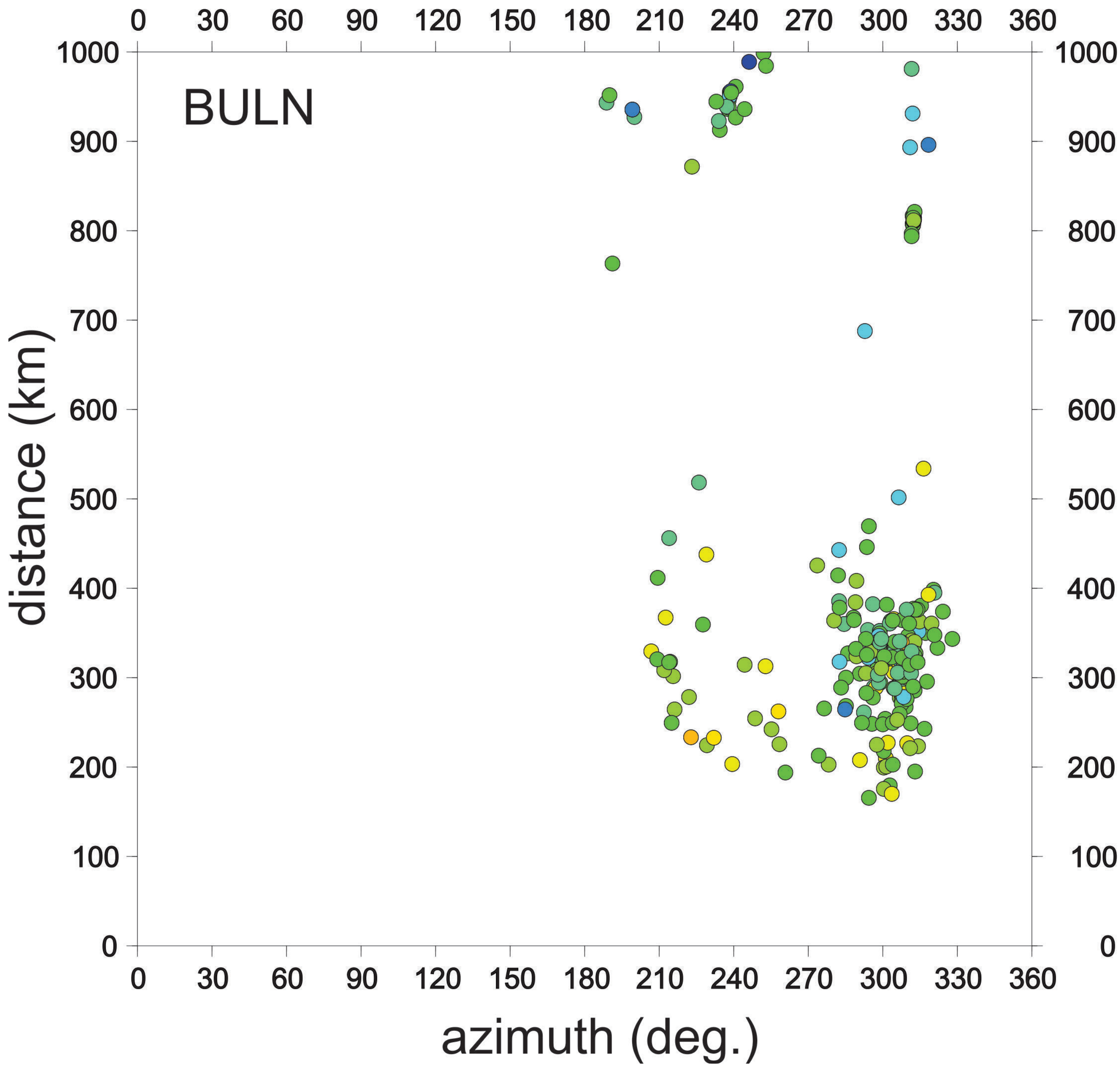

BULN
distance (km)
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
0
100
200
300
400
500
600
700
800
900
1000

Figure 5xix

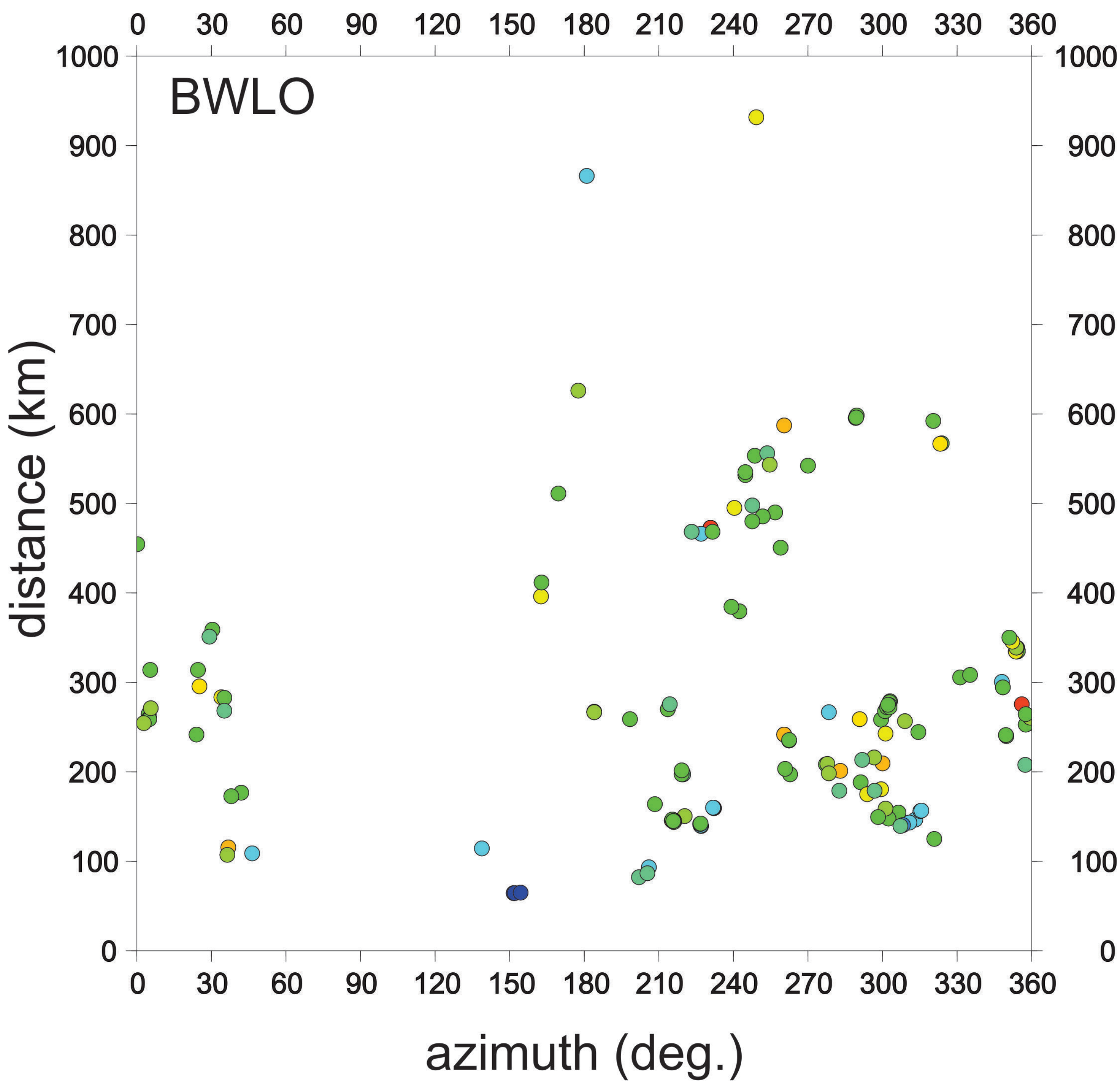
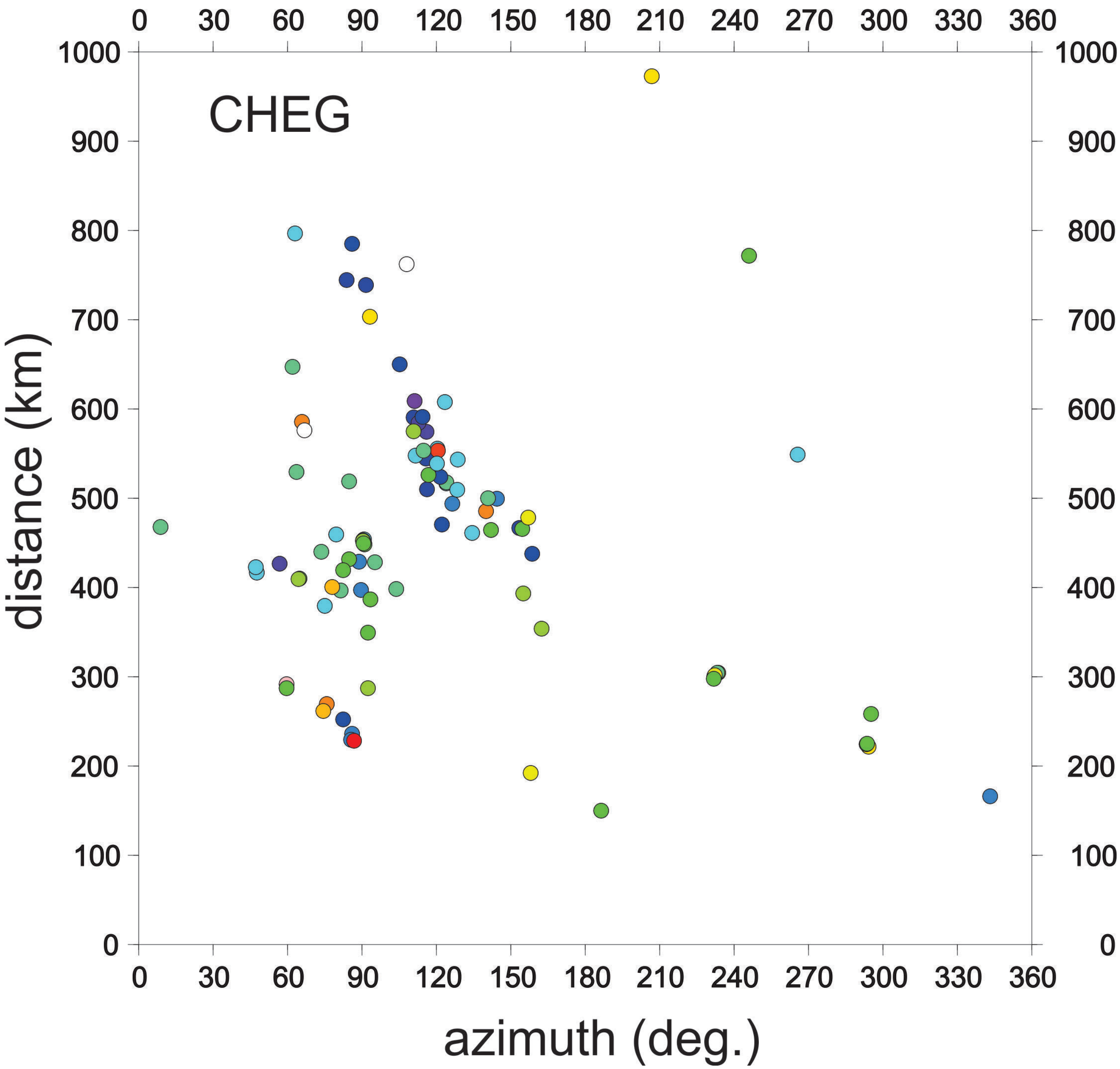

BWLO
distance (km)
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
0
100
200
300
400
500
600
700
800
900
1000

Figure 5xx



CHEG
distance (km)
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
1000
900
800
700
600
500
400
300
200
100
0

Figure 5xxi

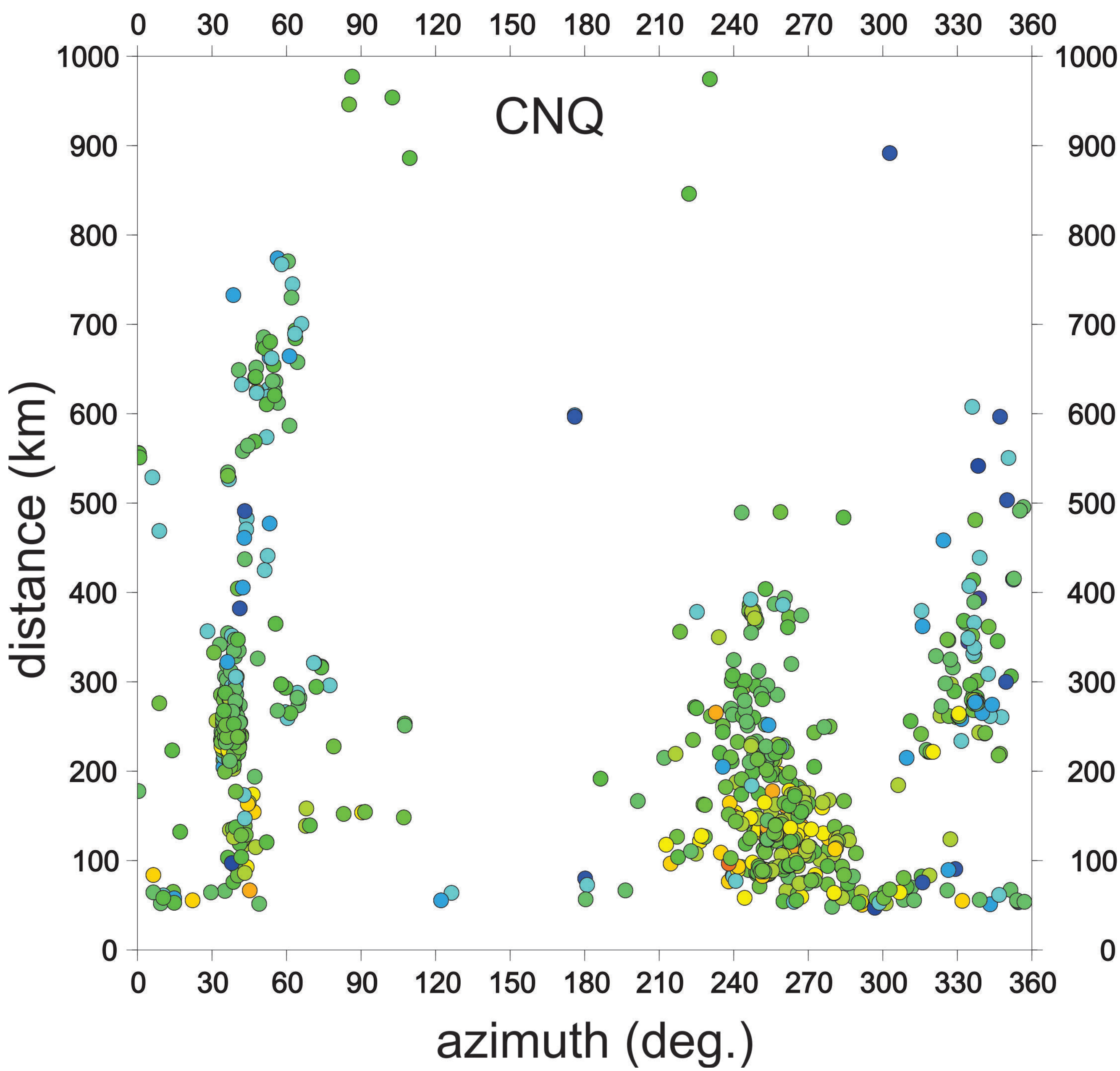


Figure 5xxii

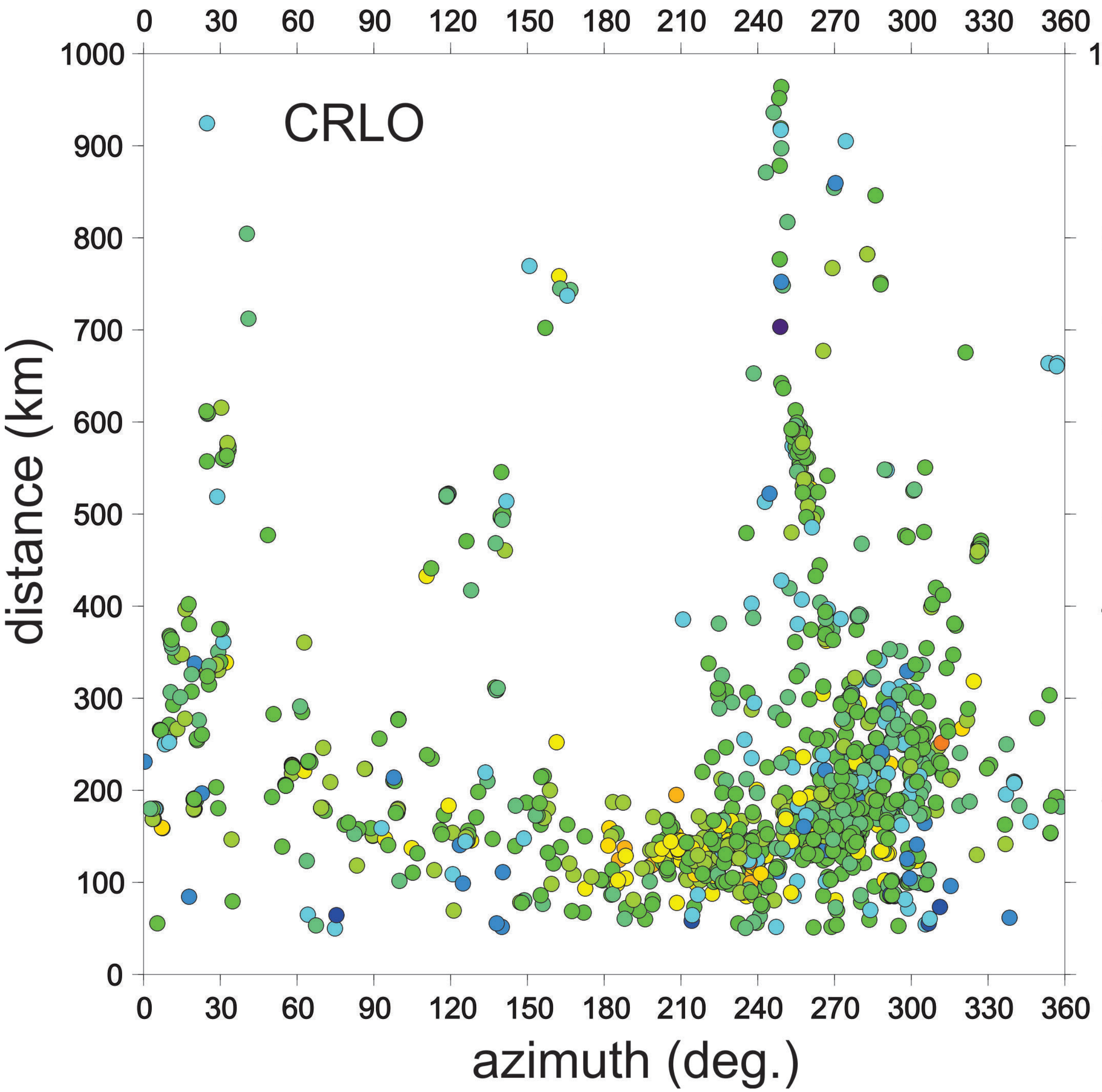


Figure 5xxiii

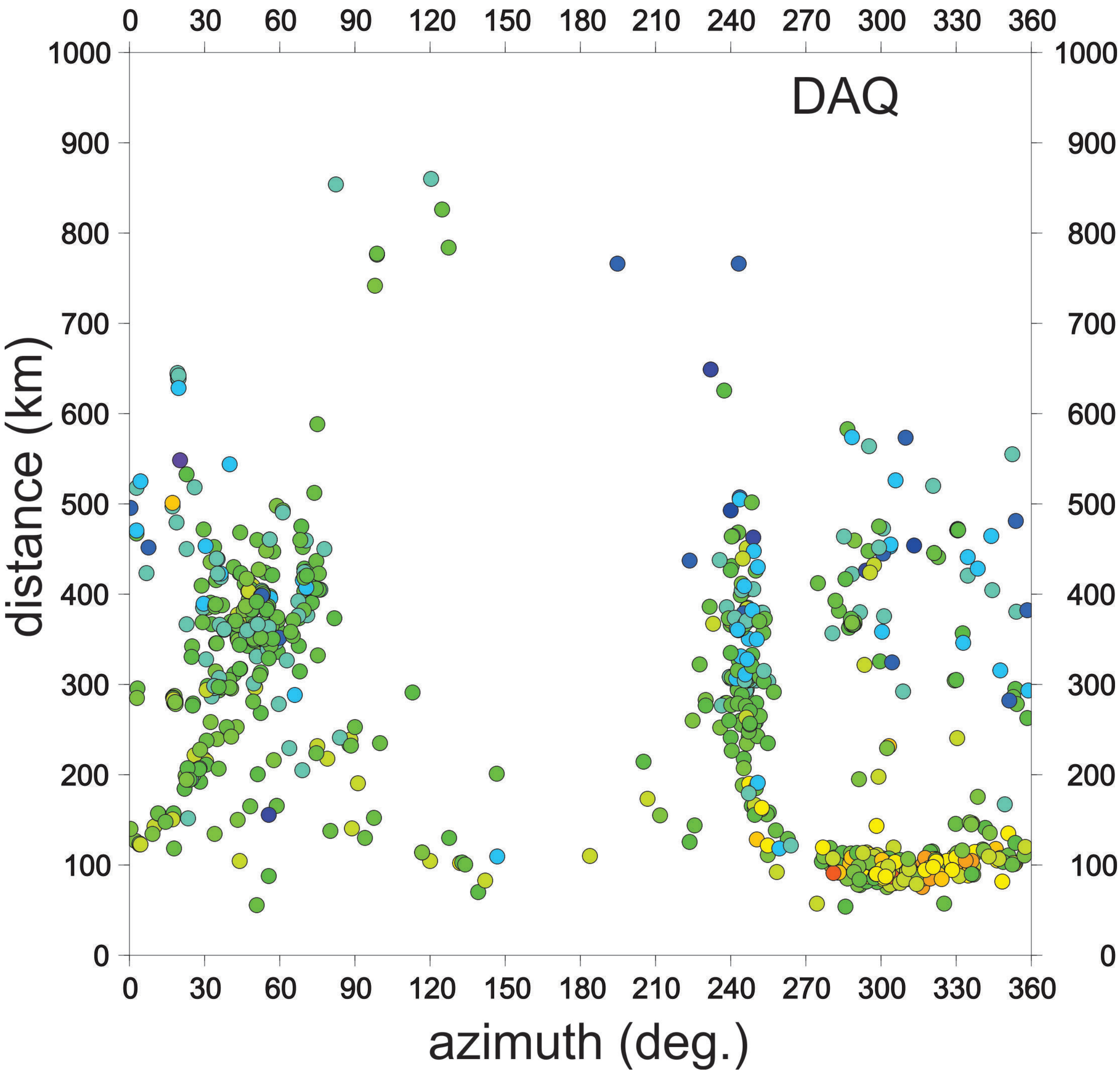


Figure 5xxiv

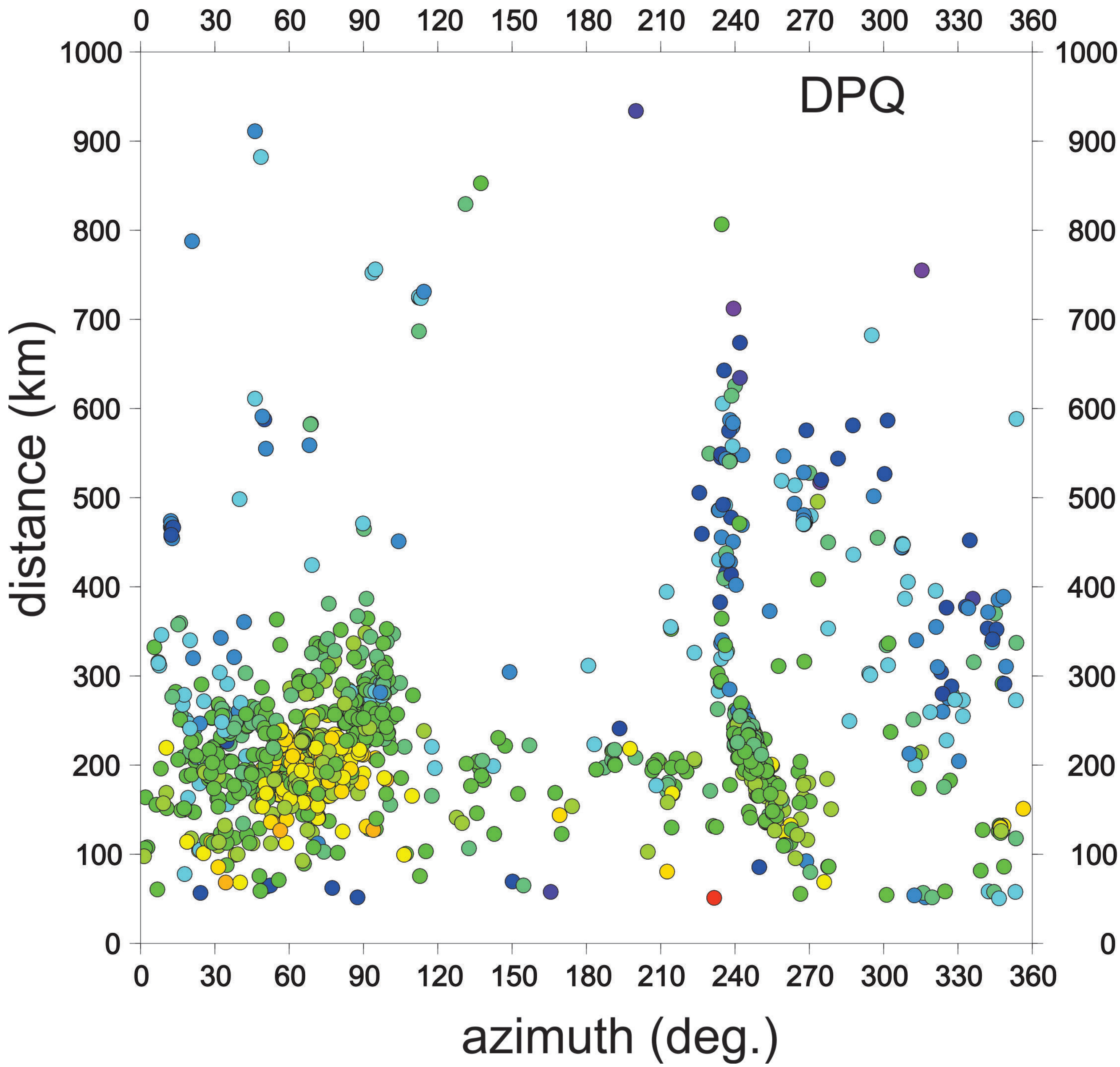

DPQ
distance (km)
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
0
100
200
300
400
500
600
700
800
900
1000

Figure 5xxv

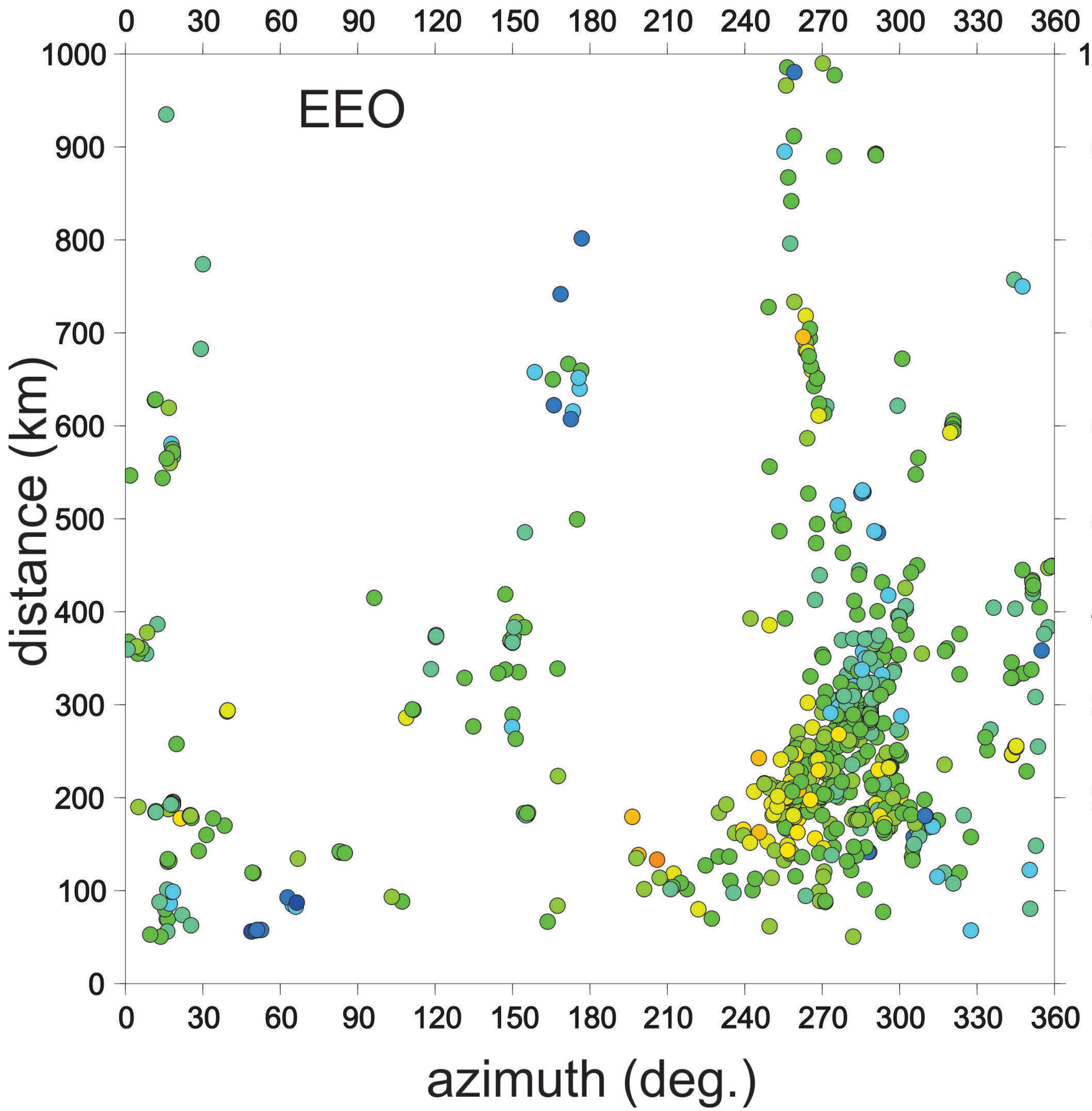


Figure 5xxvi

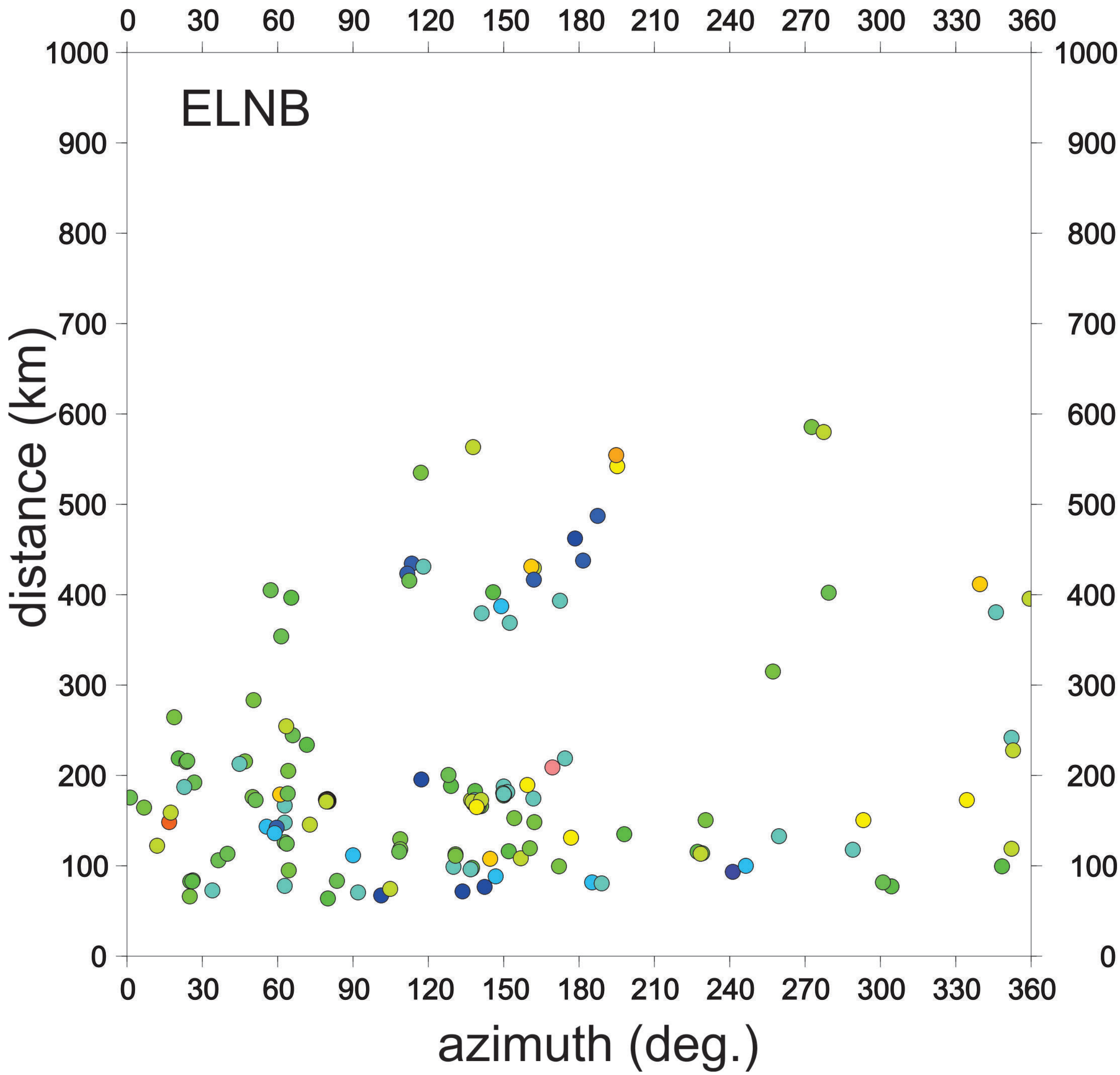


Figure 5xxvii

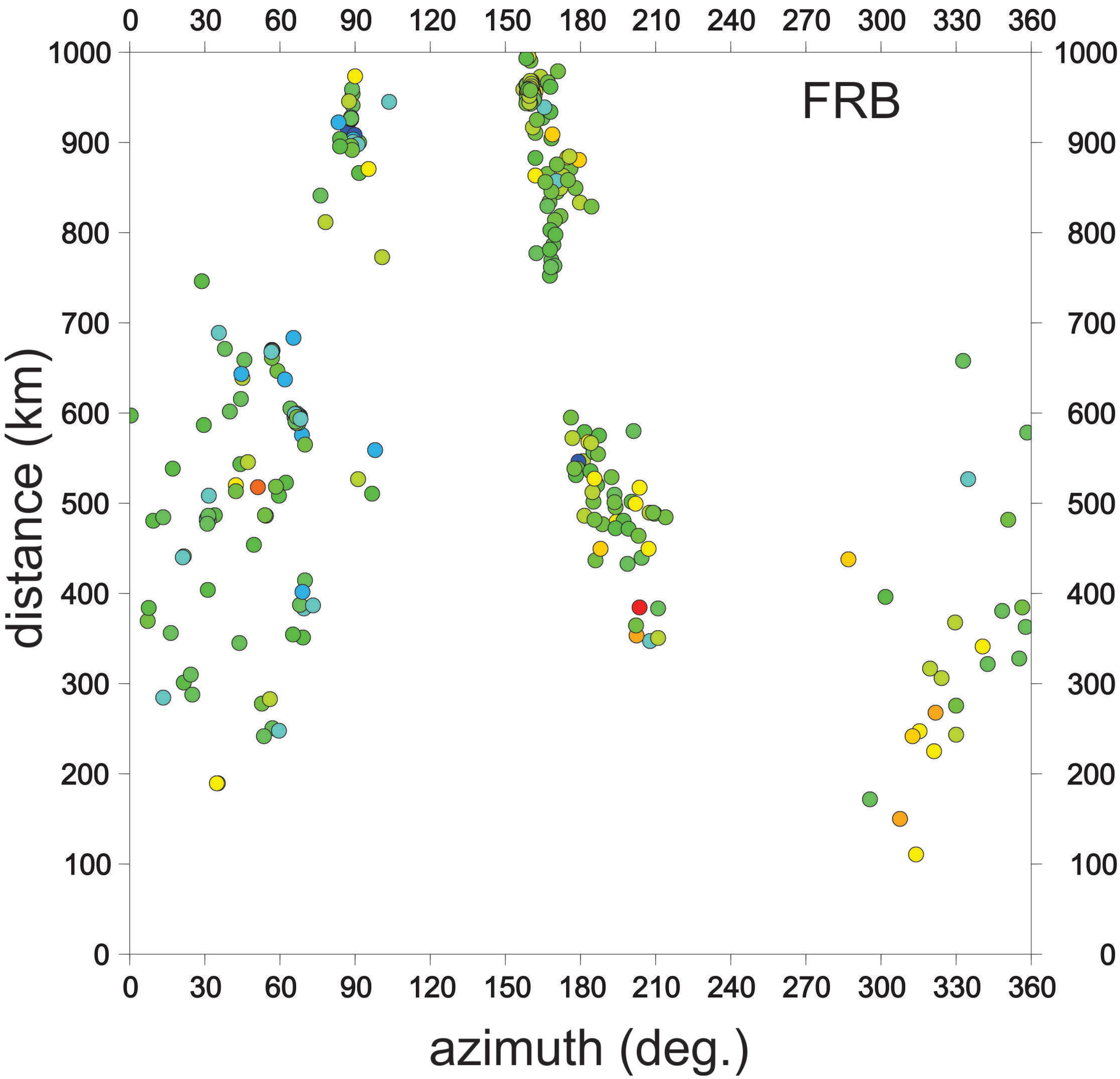


Figure 5xxviii

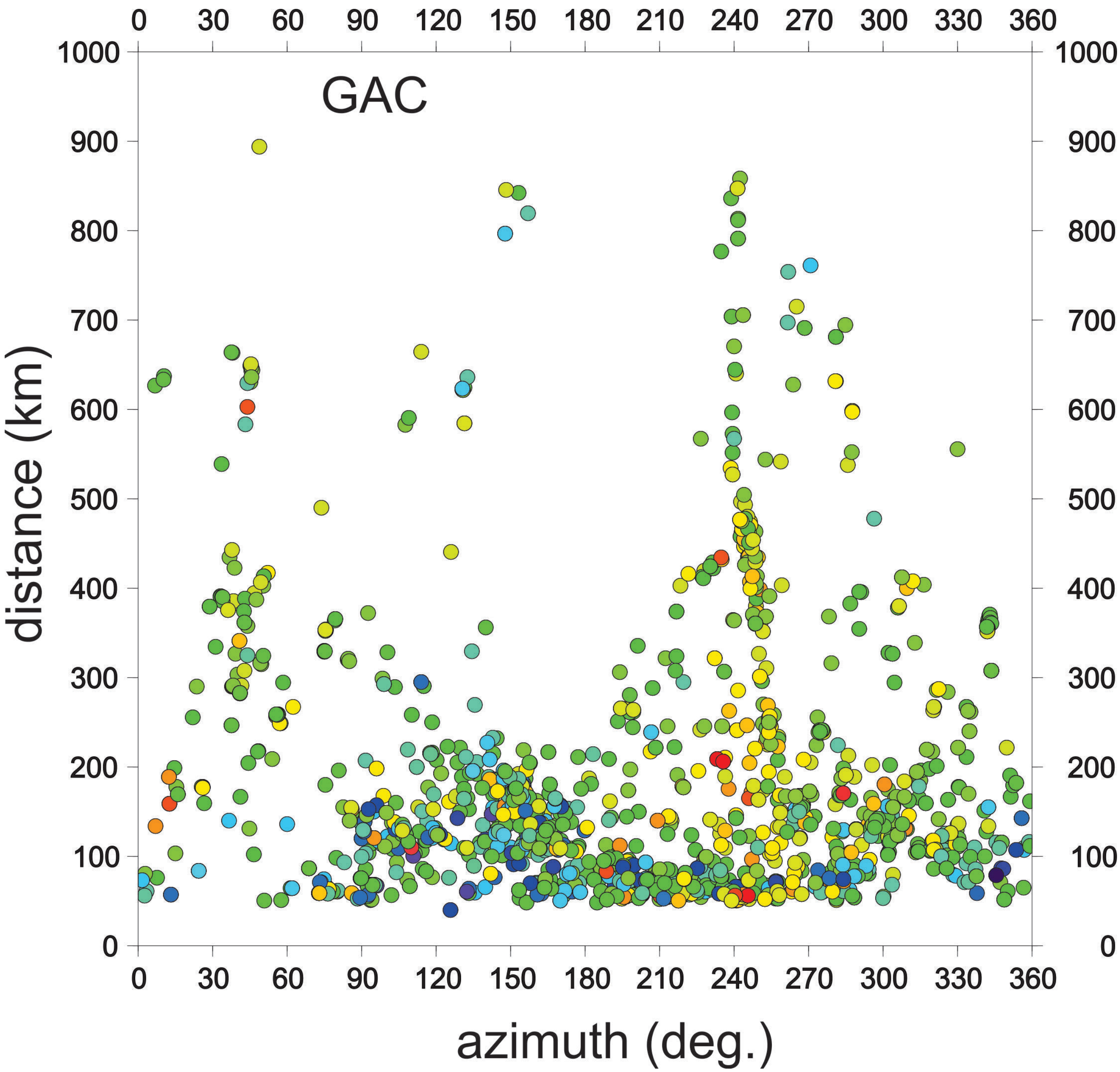


Figure 5xxix

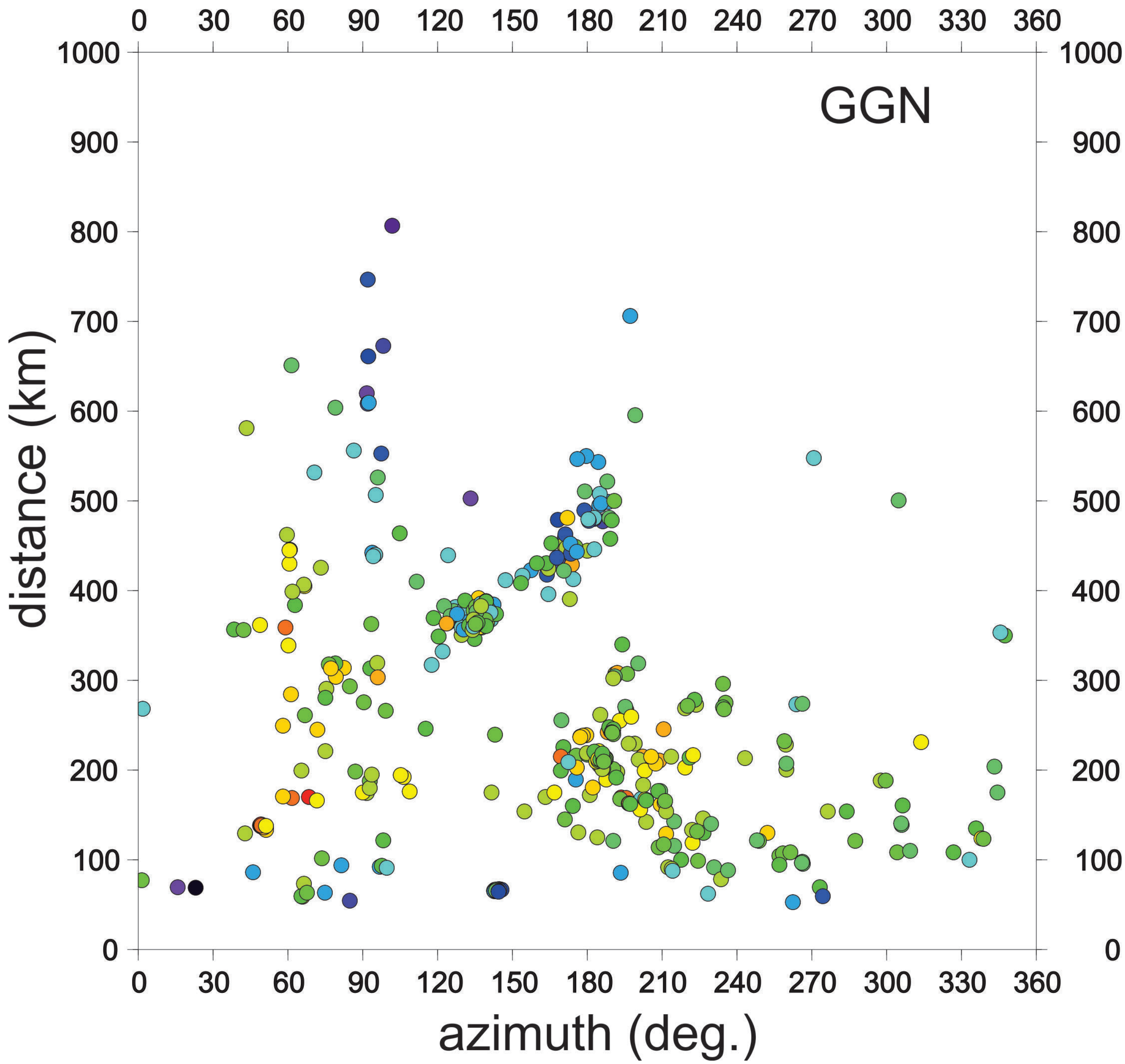

GGN
distance (km)
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
0
100
200
300
400
500
600
700
800
900
1000

Figure 5xxx

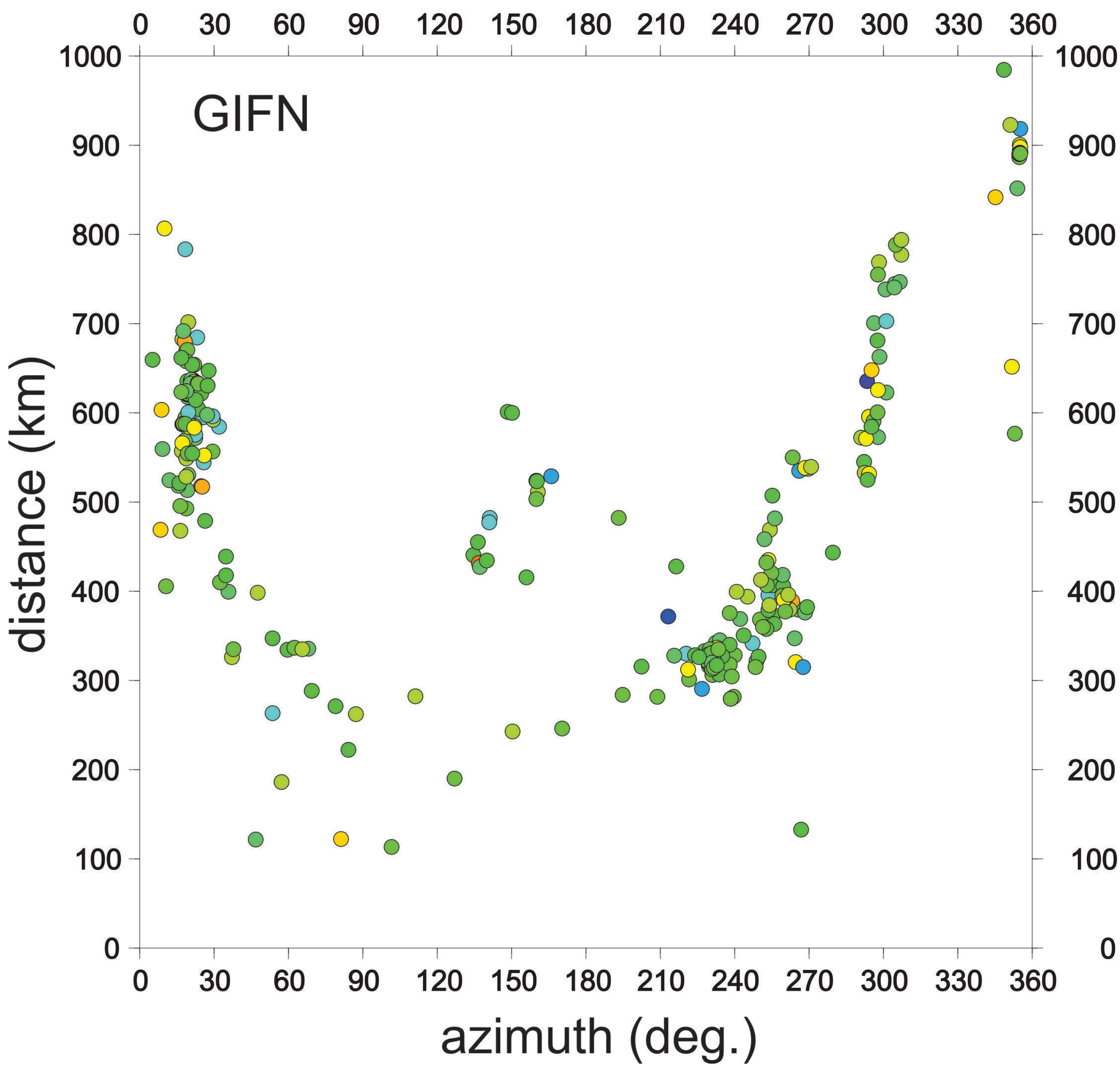


Figure 5xxxi

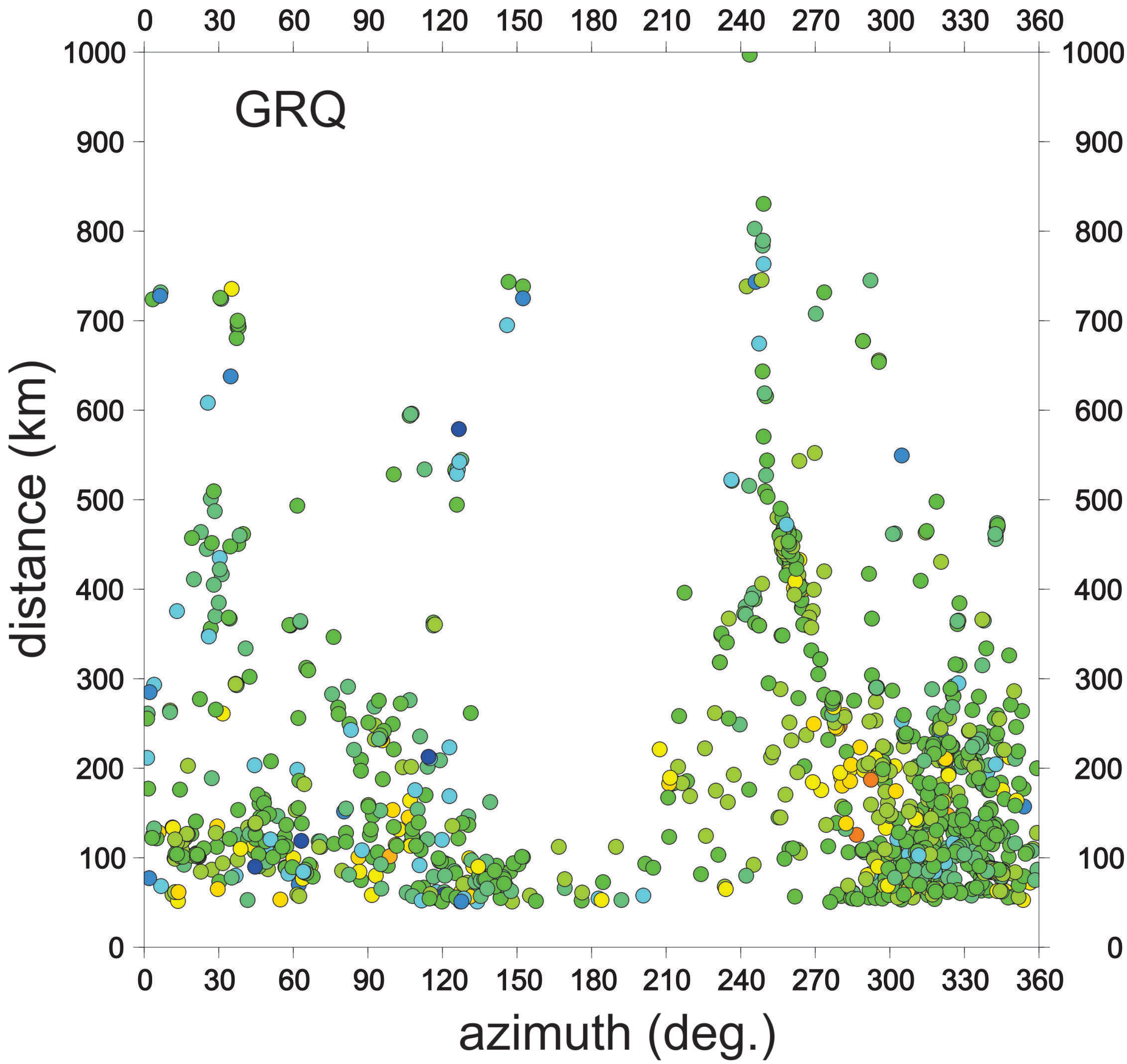


Figure 5xxxii

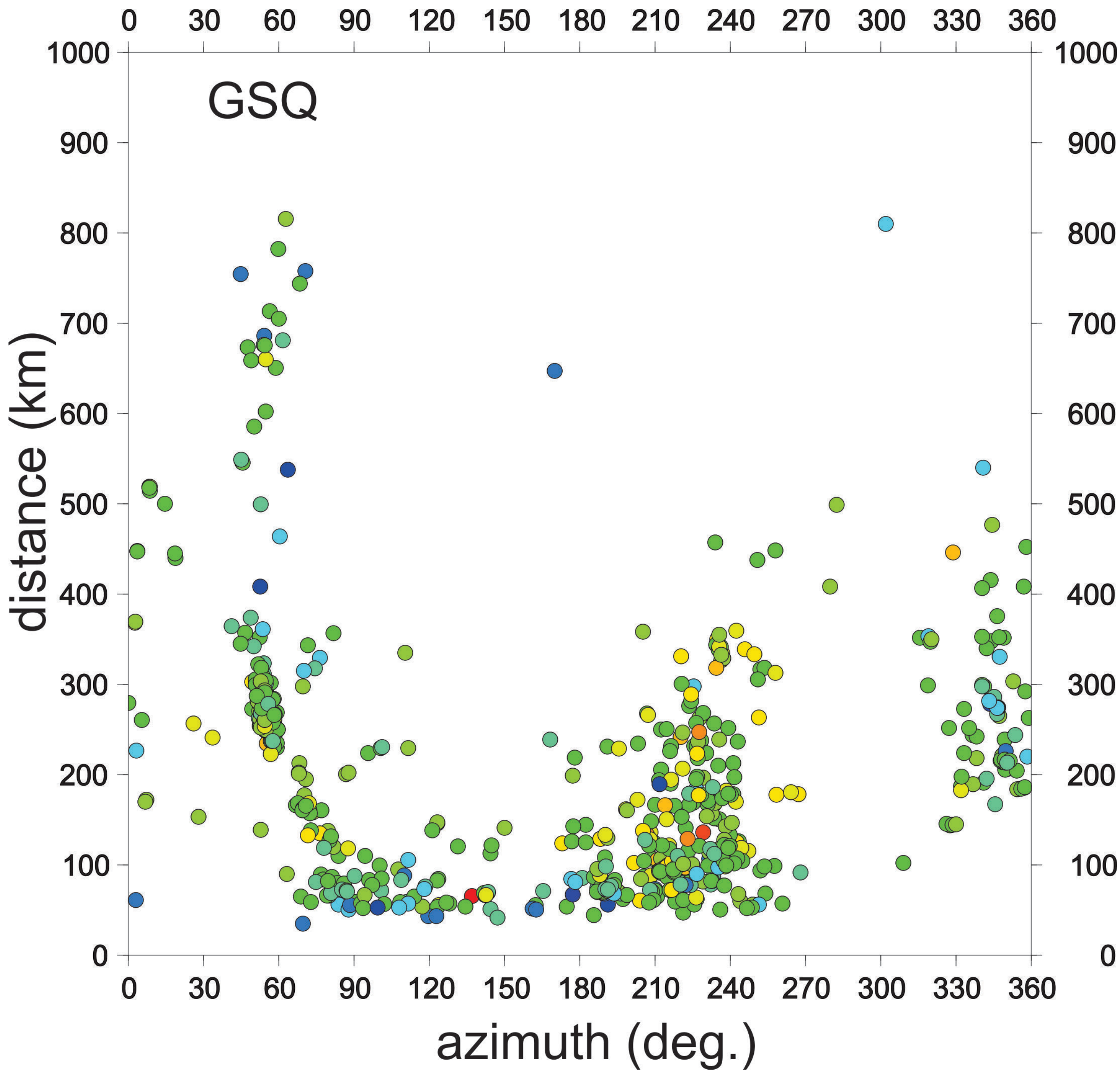


Figure 5xxxiii

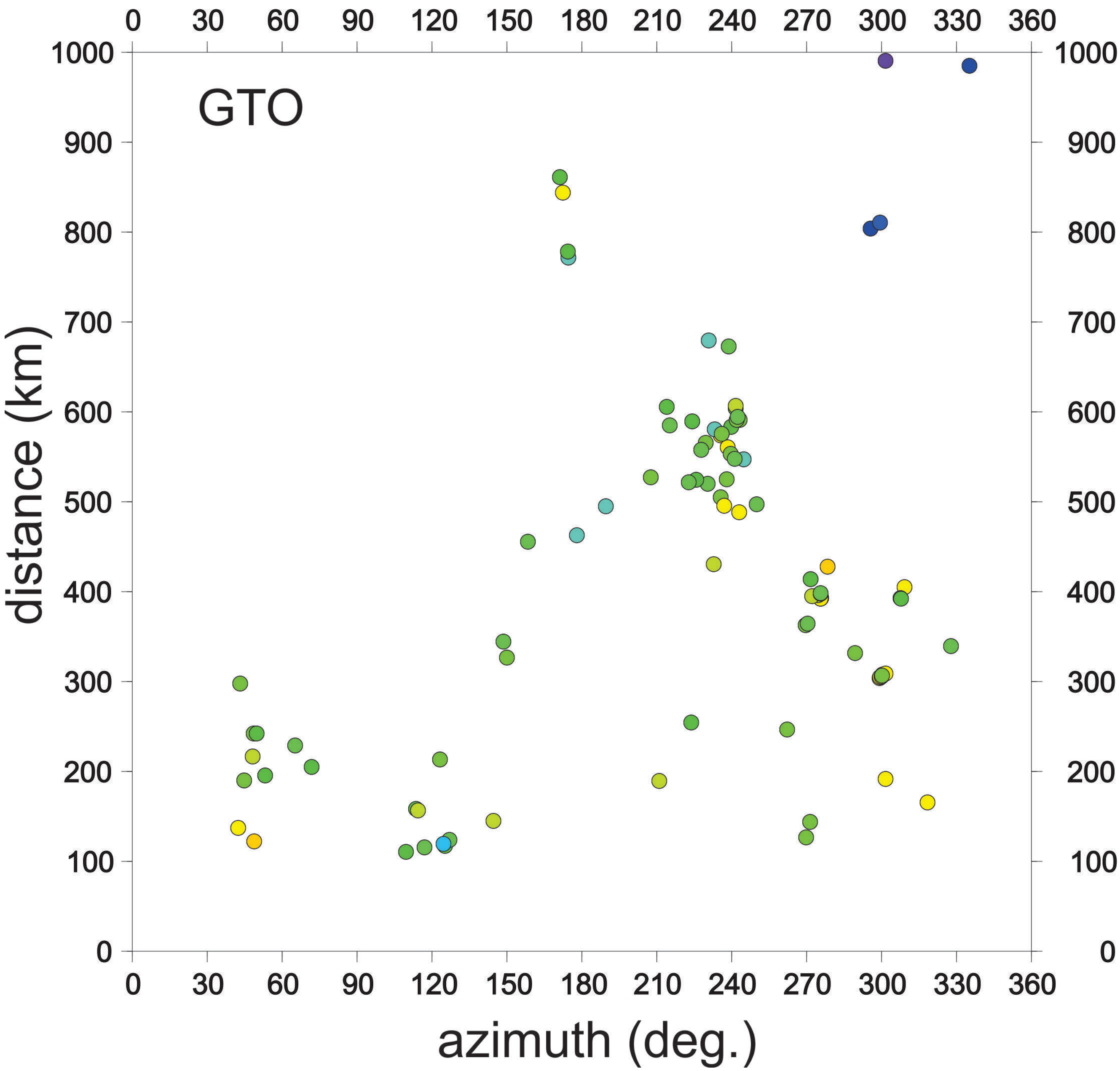


Figure 5xxxiv

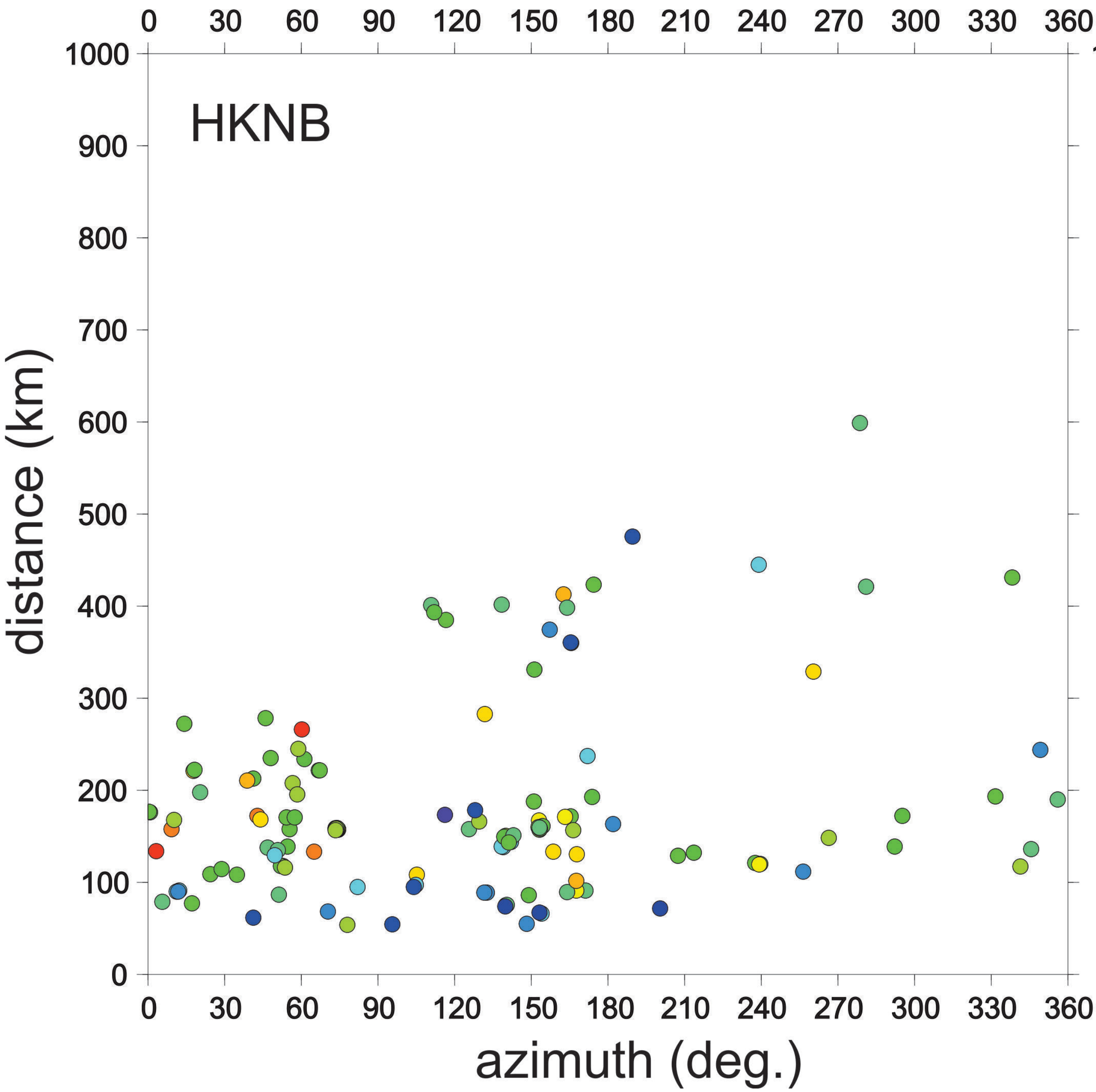


Figure 5xxxv

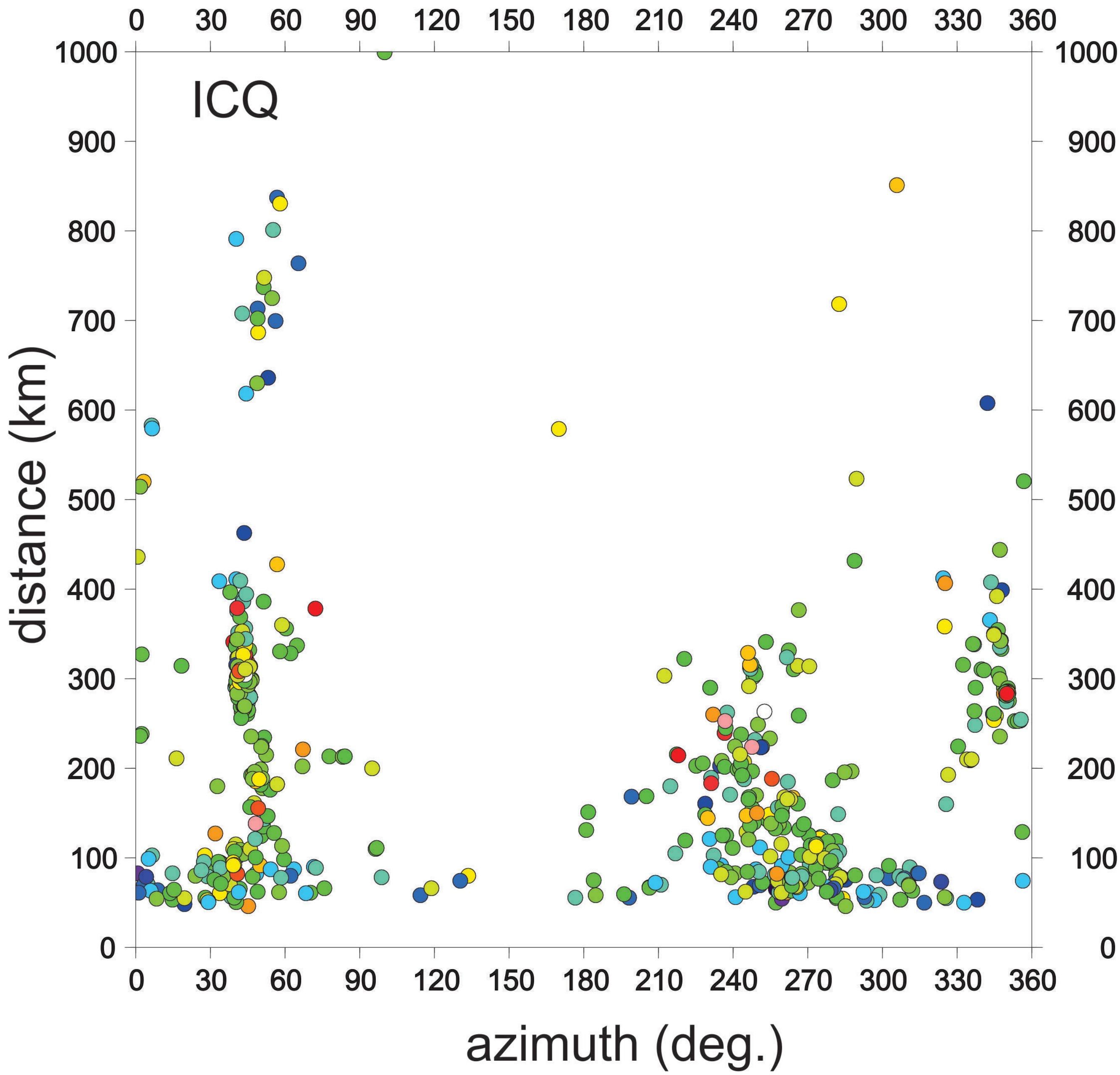


Figure 5xxxvi

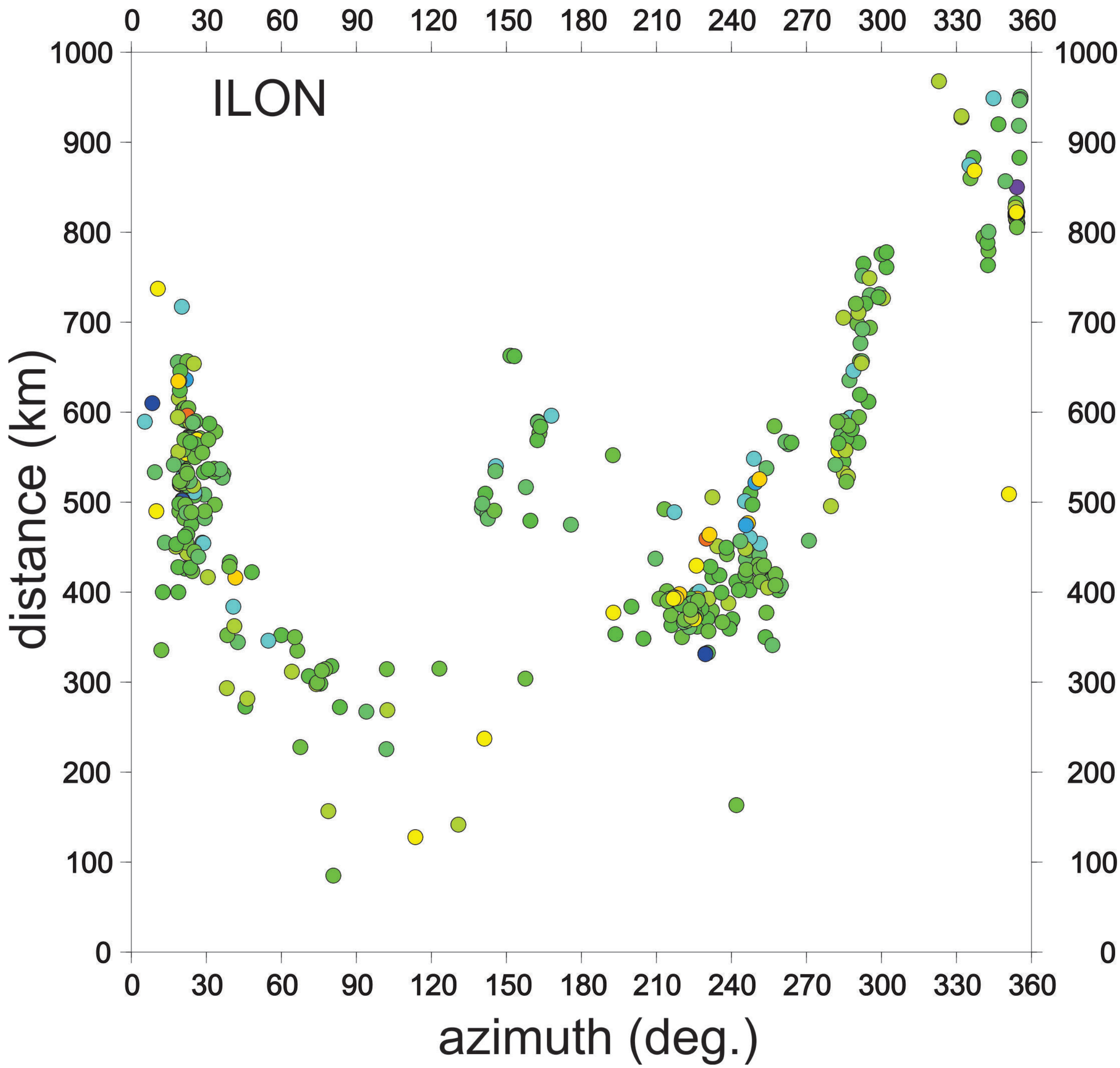


Figure 5xxxvii

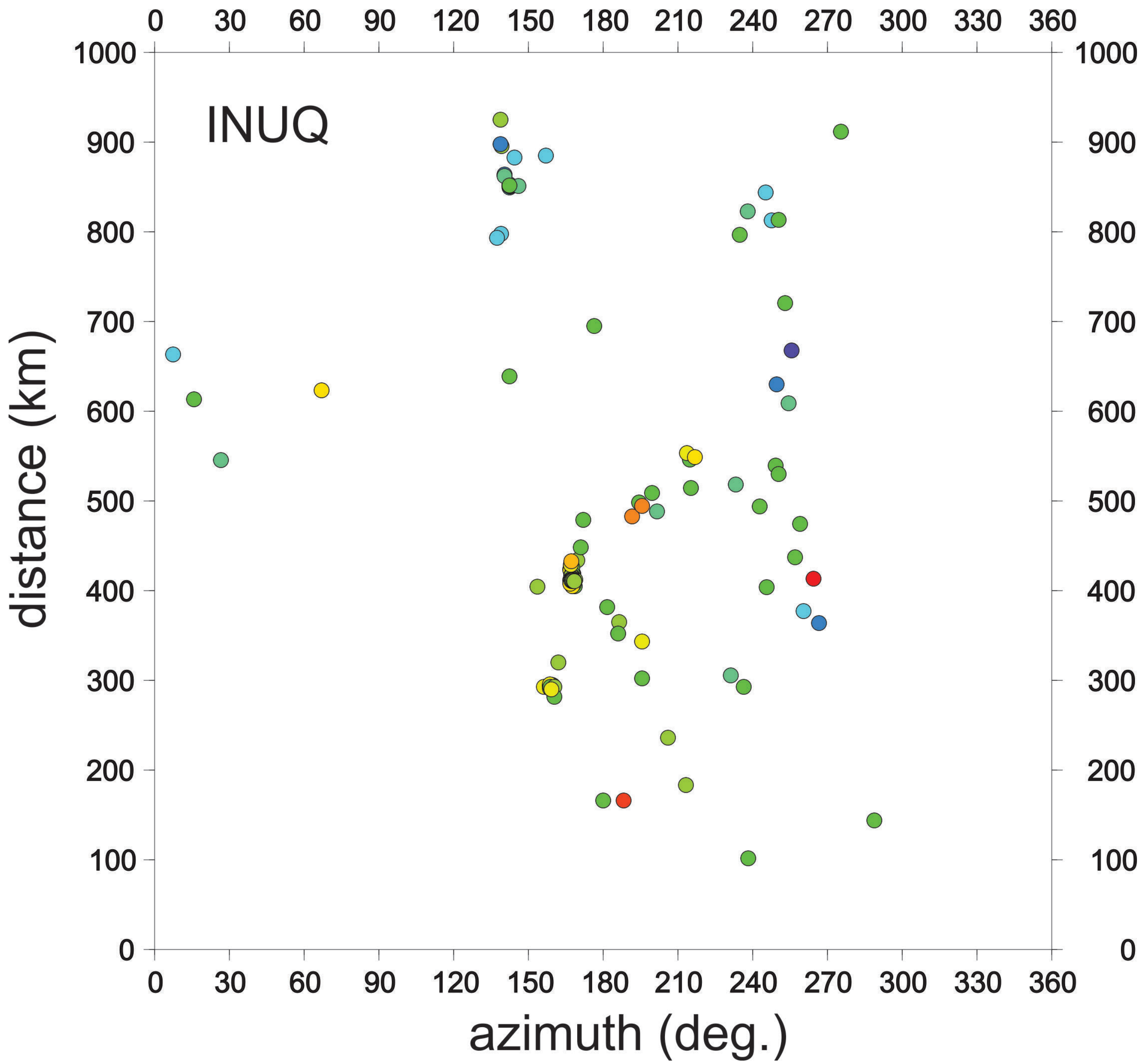


Figure 5xxxviii

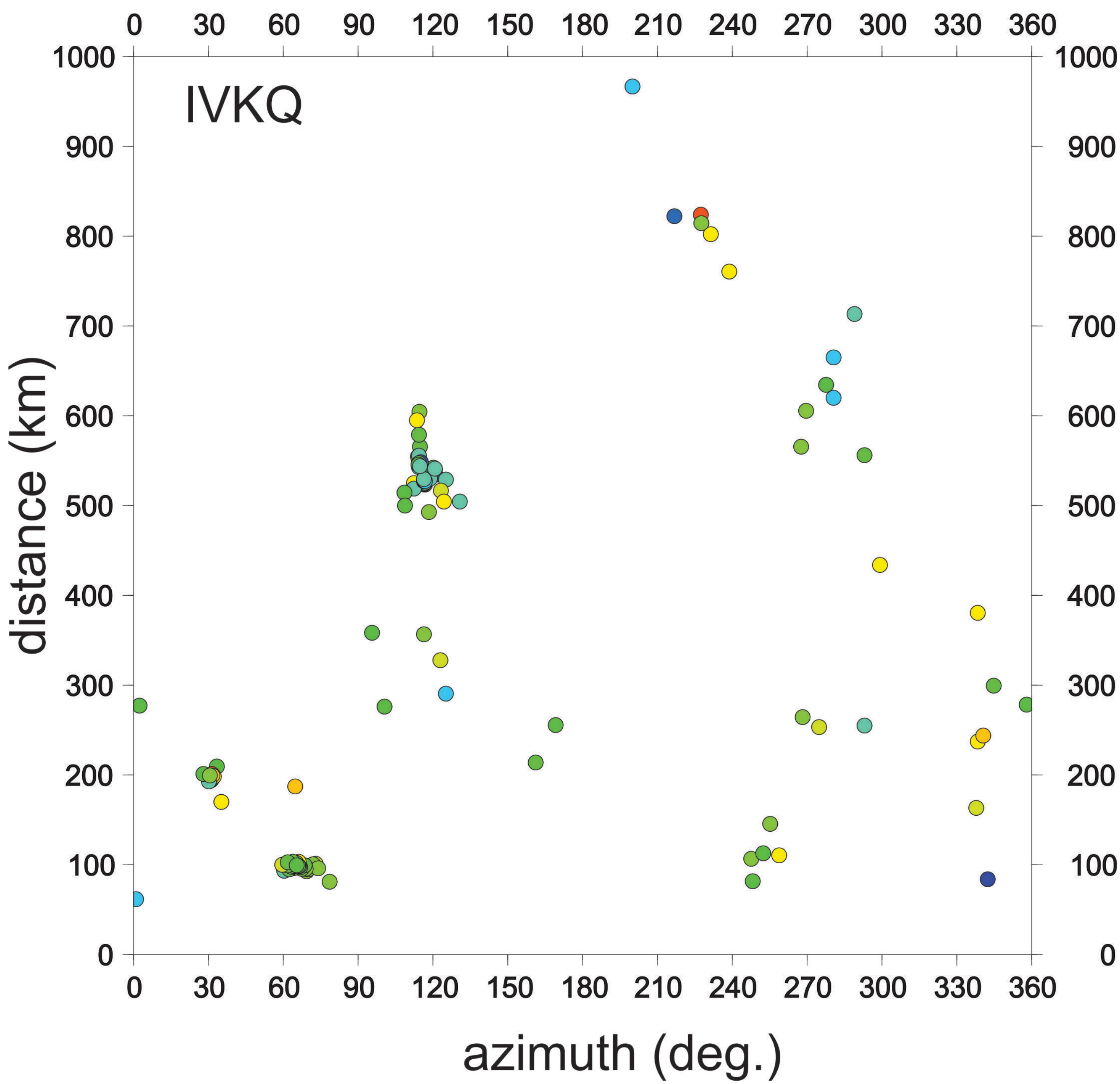
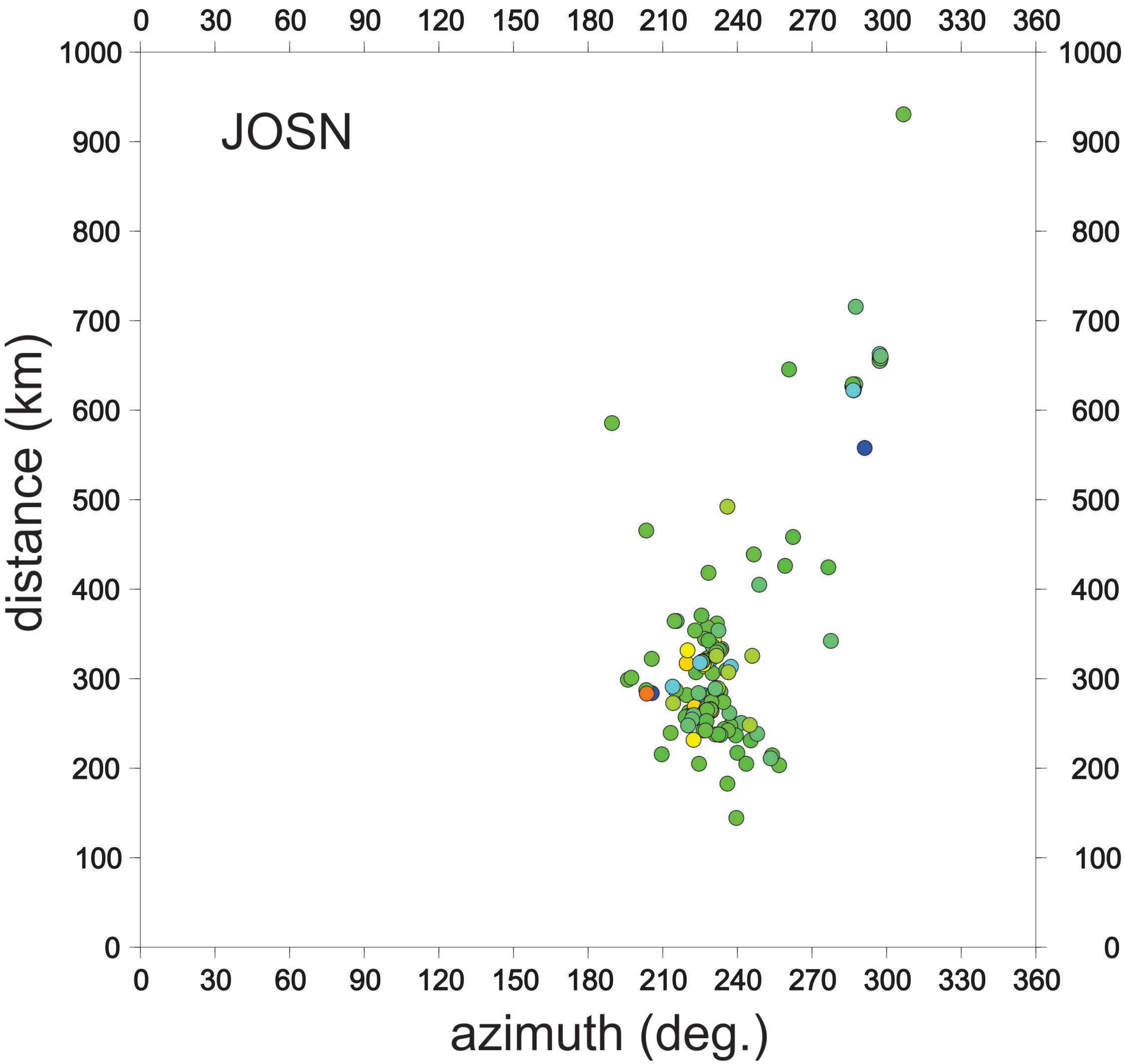


Figure 5xxxix



JOSN
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120
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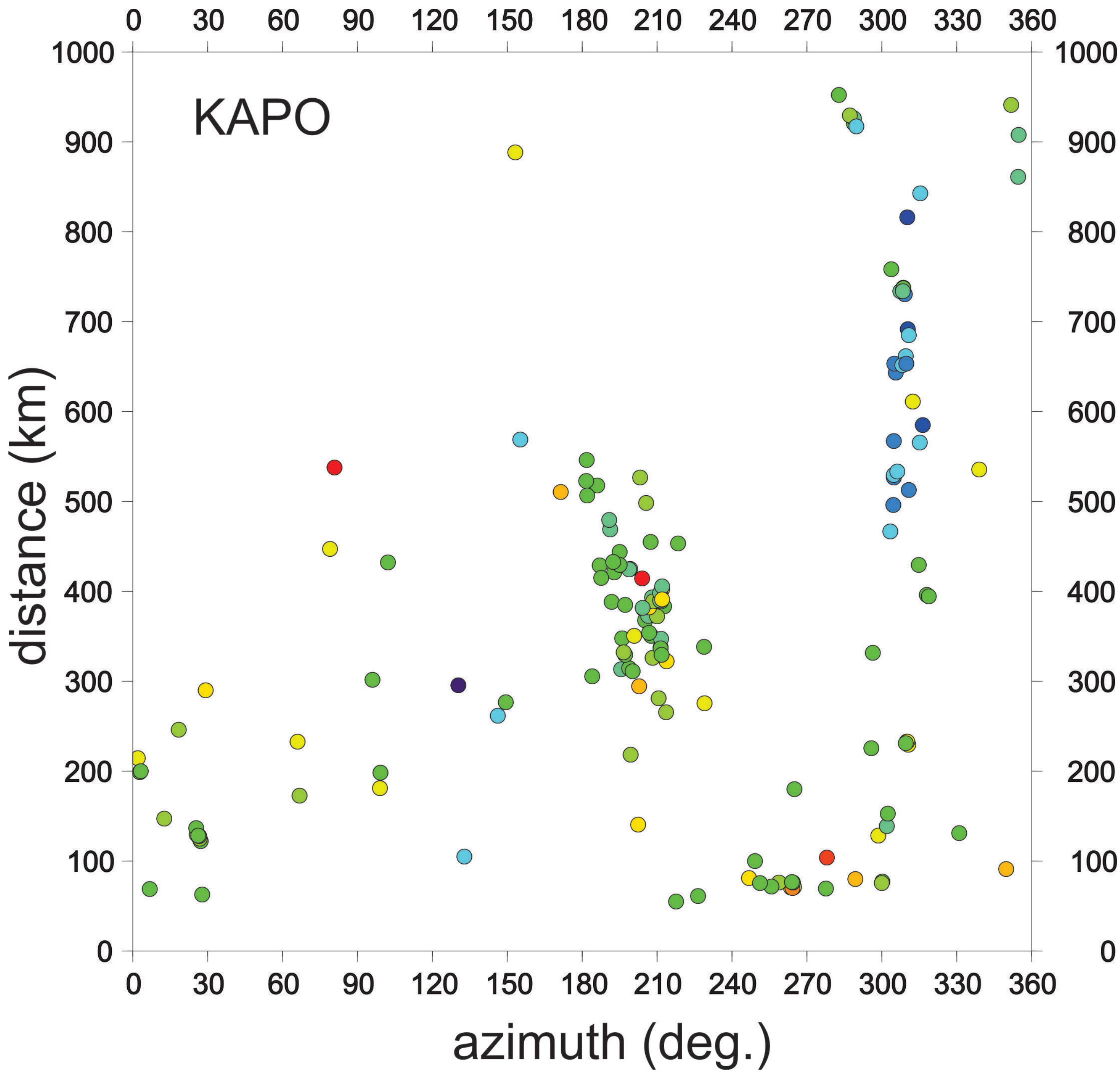
240
270
300
330
360
1000
900
800
700
600
500
400
300
200
100
0
distance (km)
azimuth (deg.)

Figure 5xl


KAPO
distance (km)
azimuth (deg.)
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100
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300
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800
900
1000
Figure 5xli

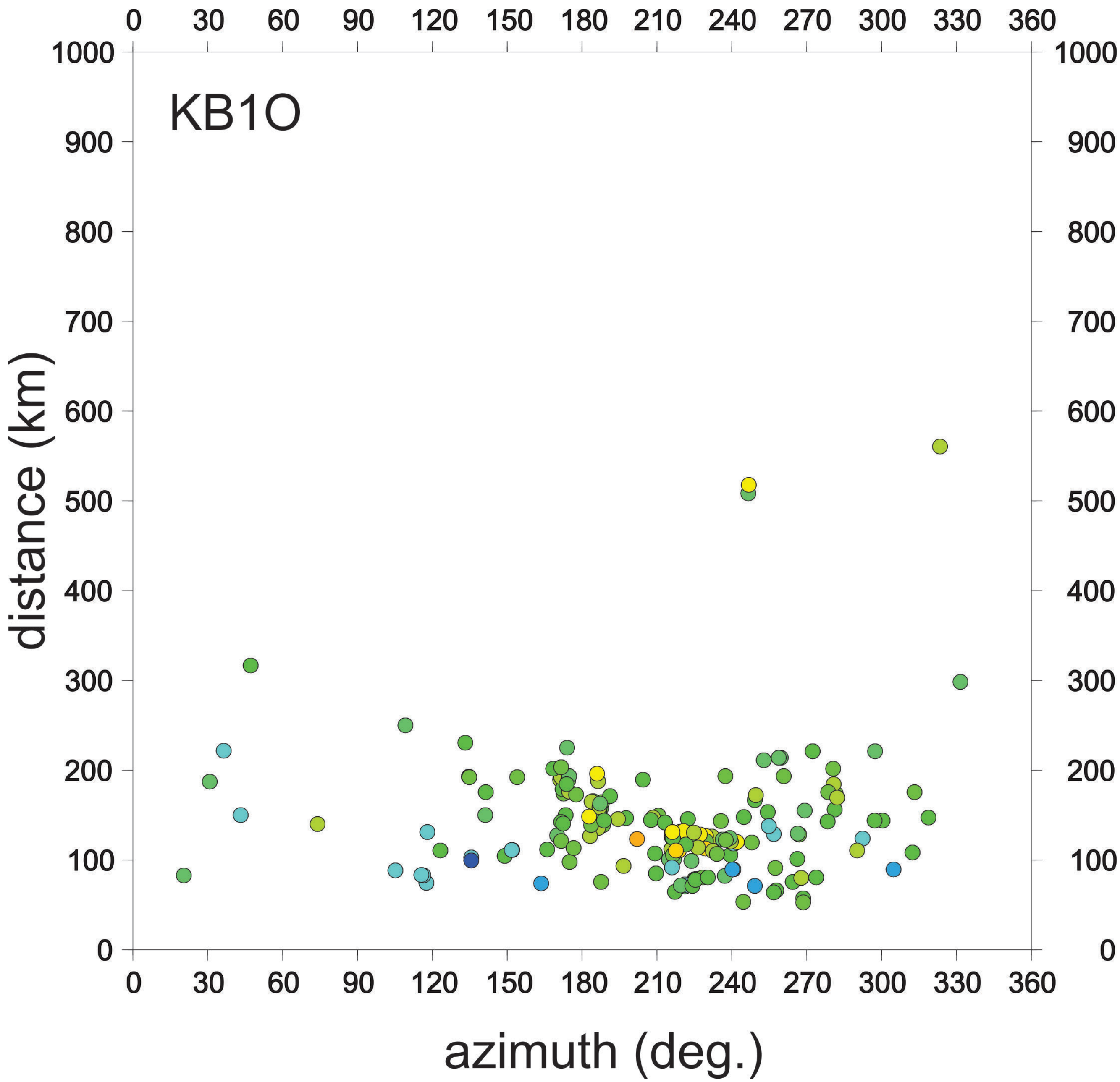


Figure 5xlii

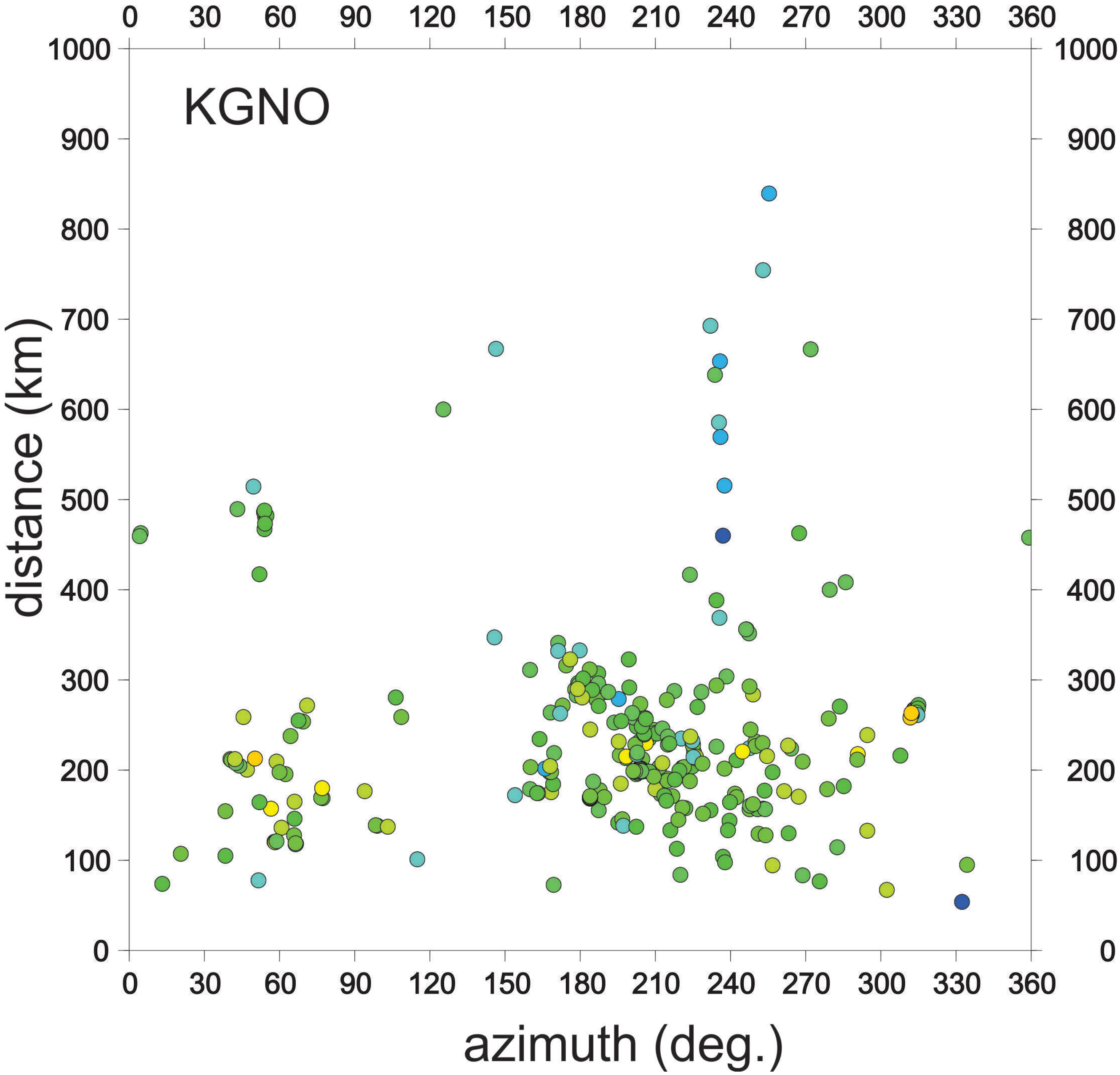


Figure 5xliii

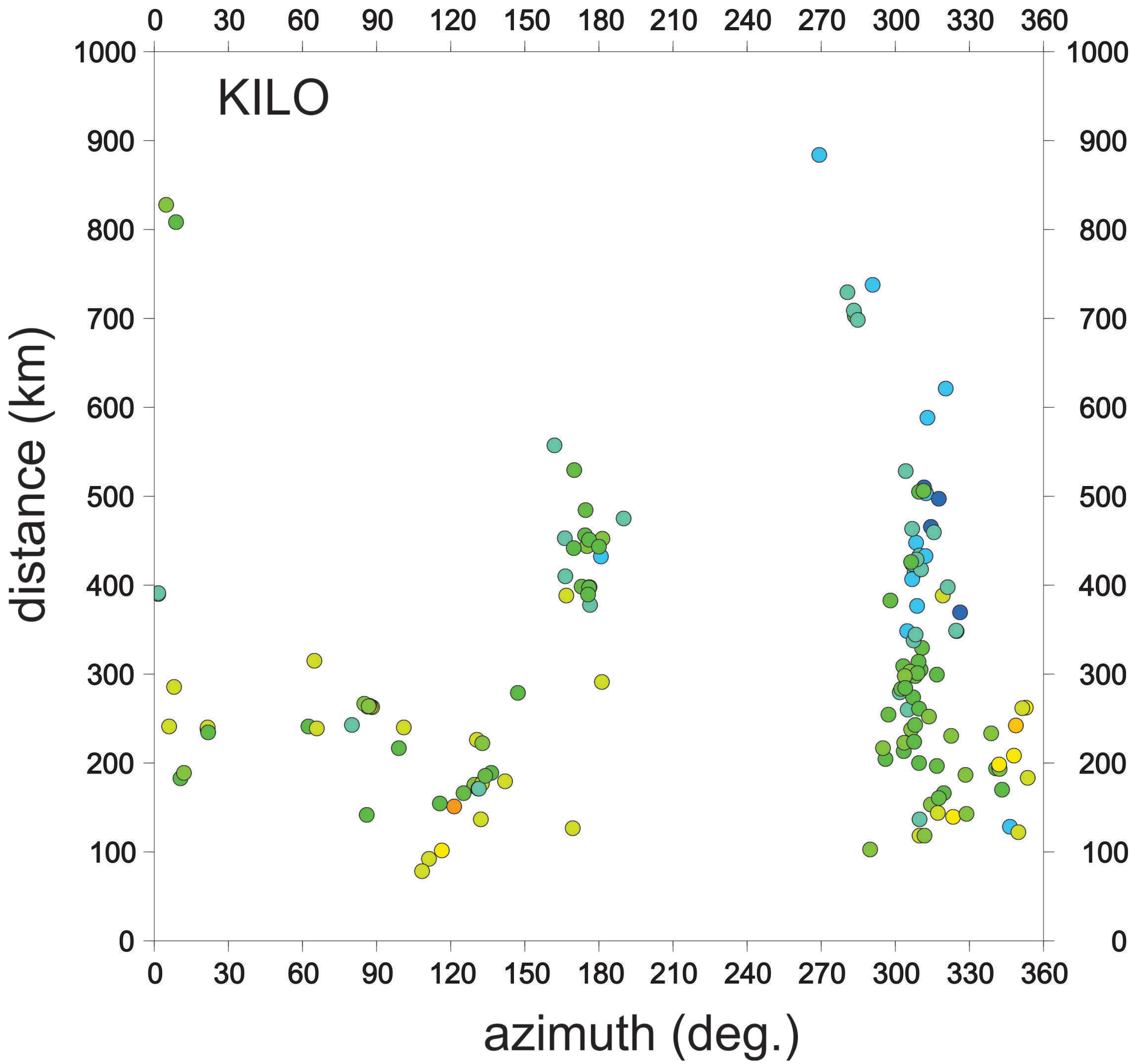
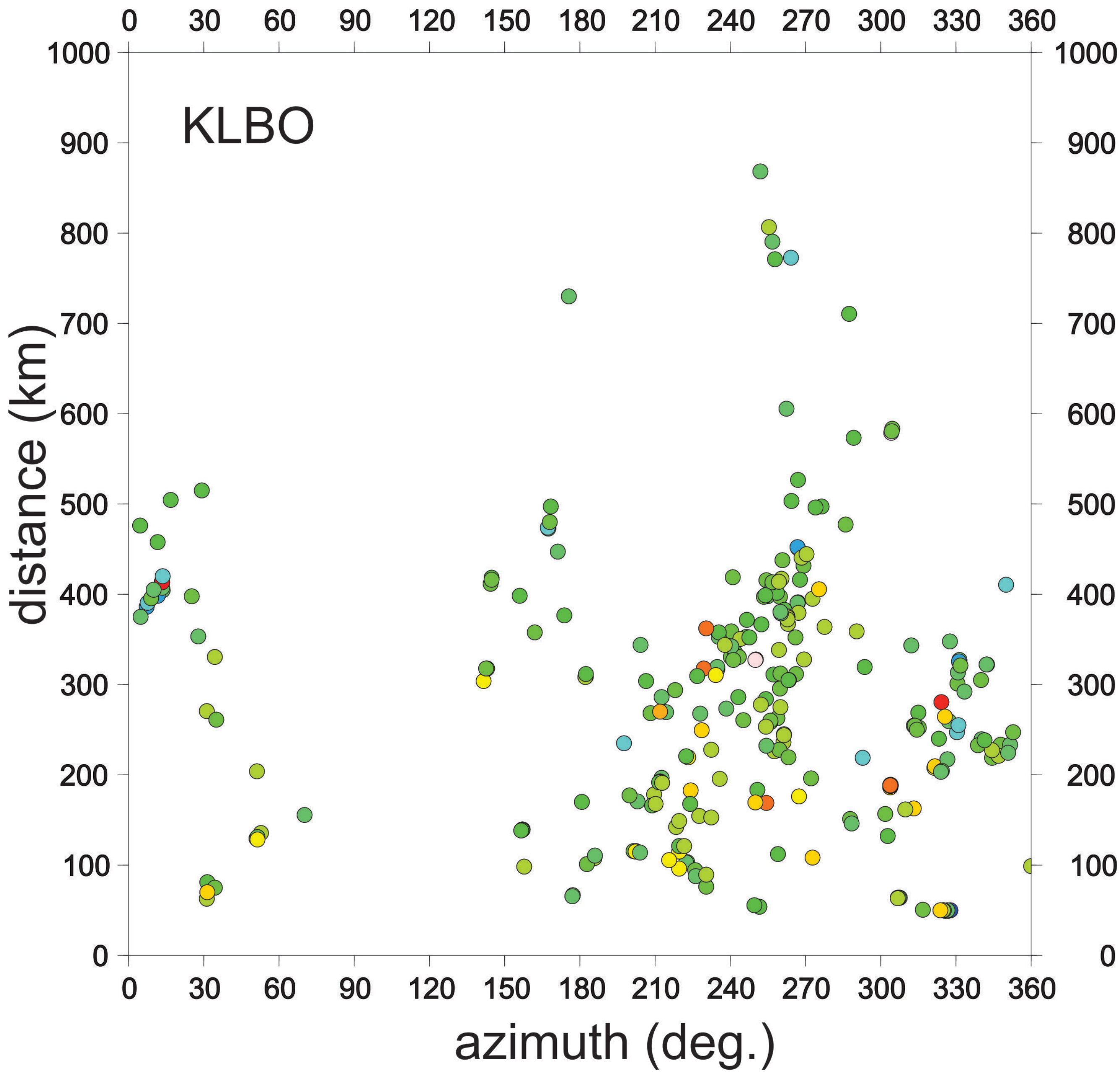


Figure 5xliv



KLBO
distance (km)
azimuth (deg.)
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60
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120
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500
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800
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Figure 5xlv

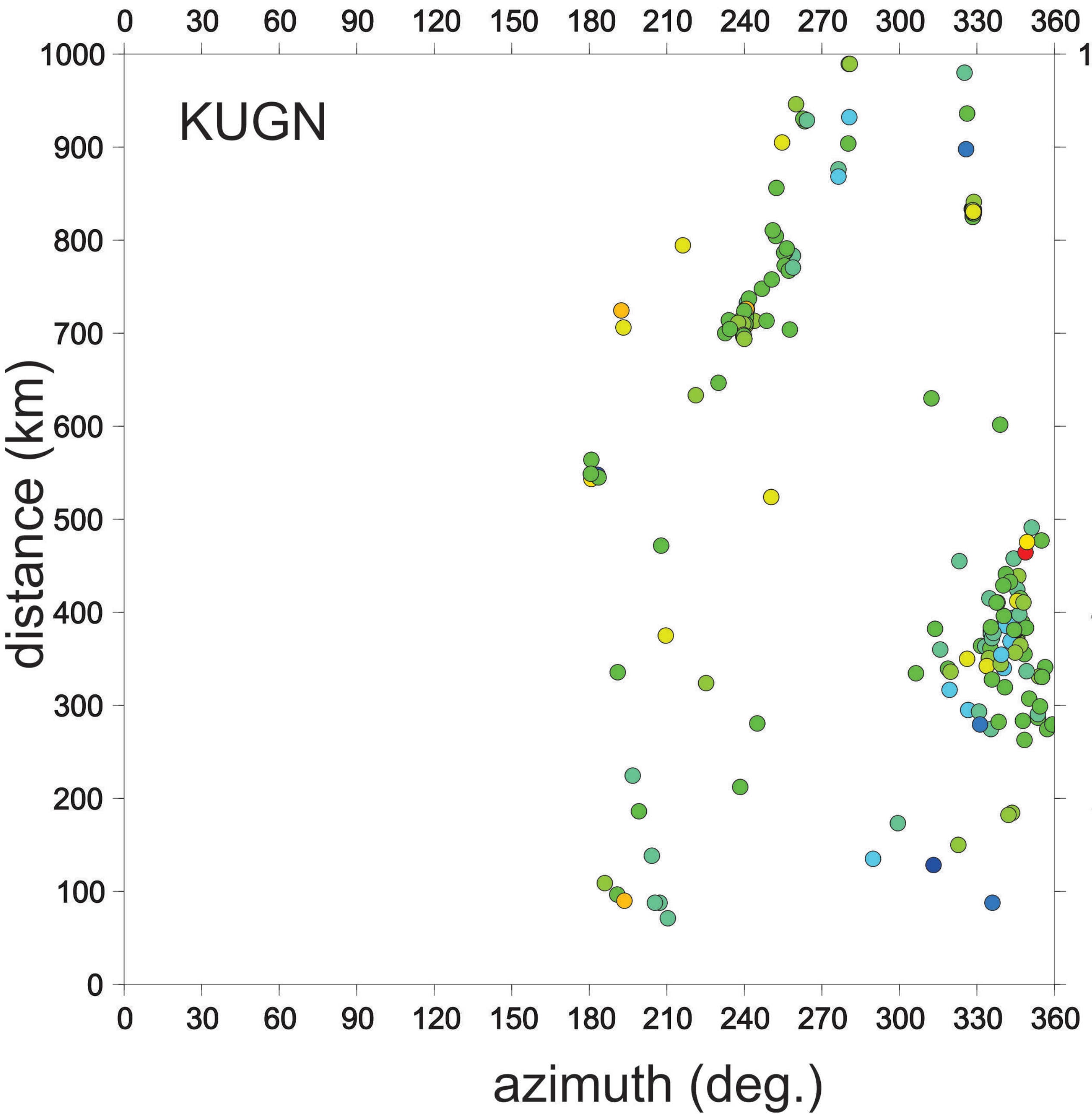


Figure 5xlvi

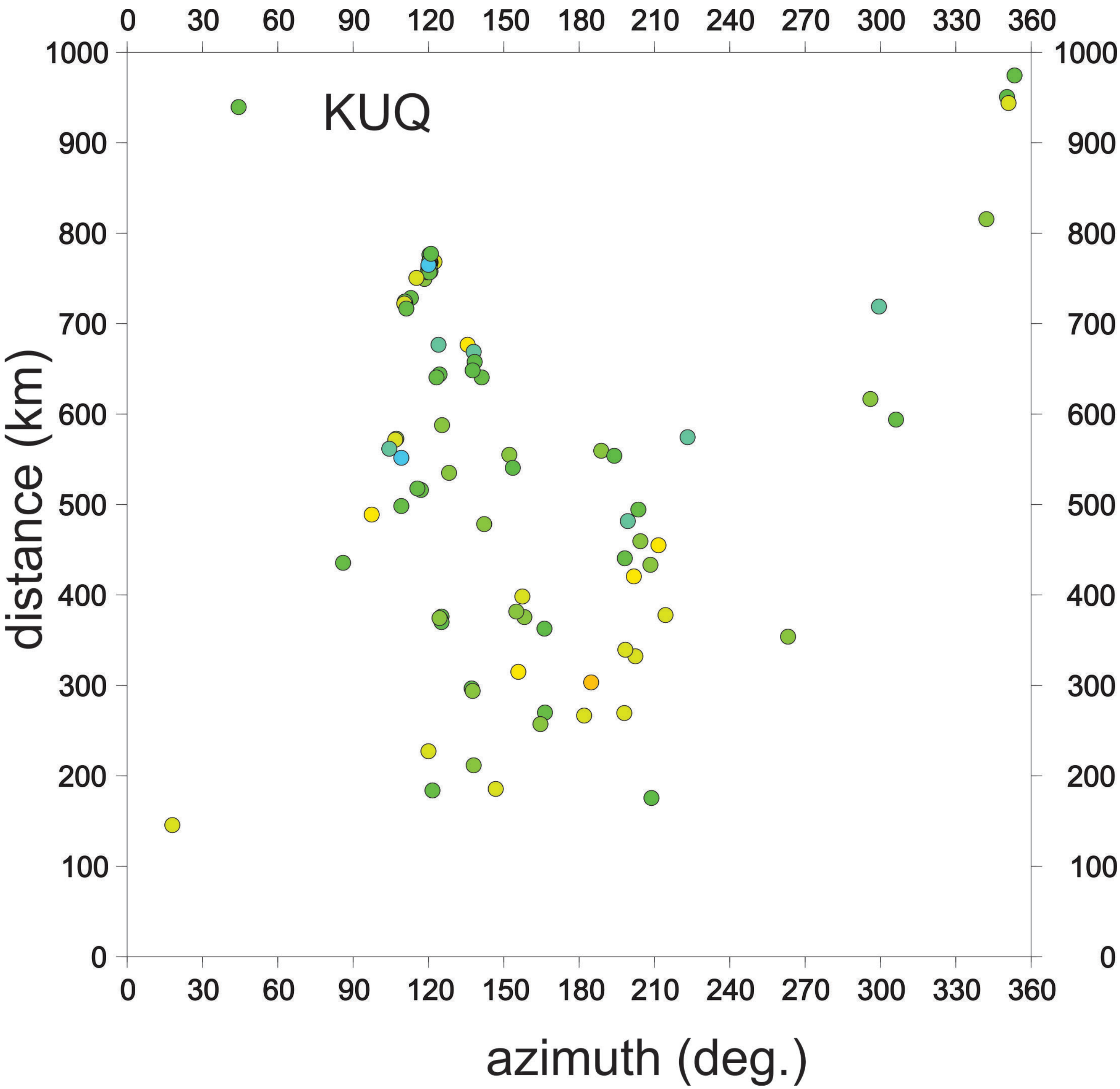


Figure 5xlvii

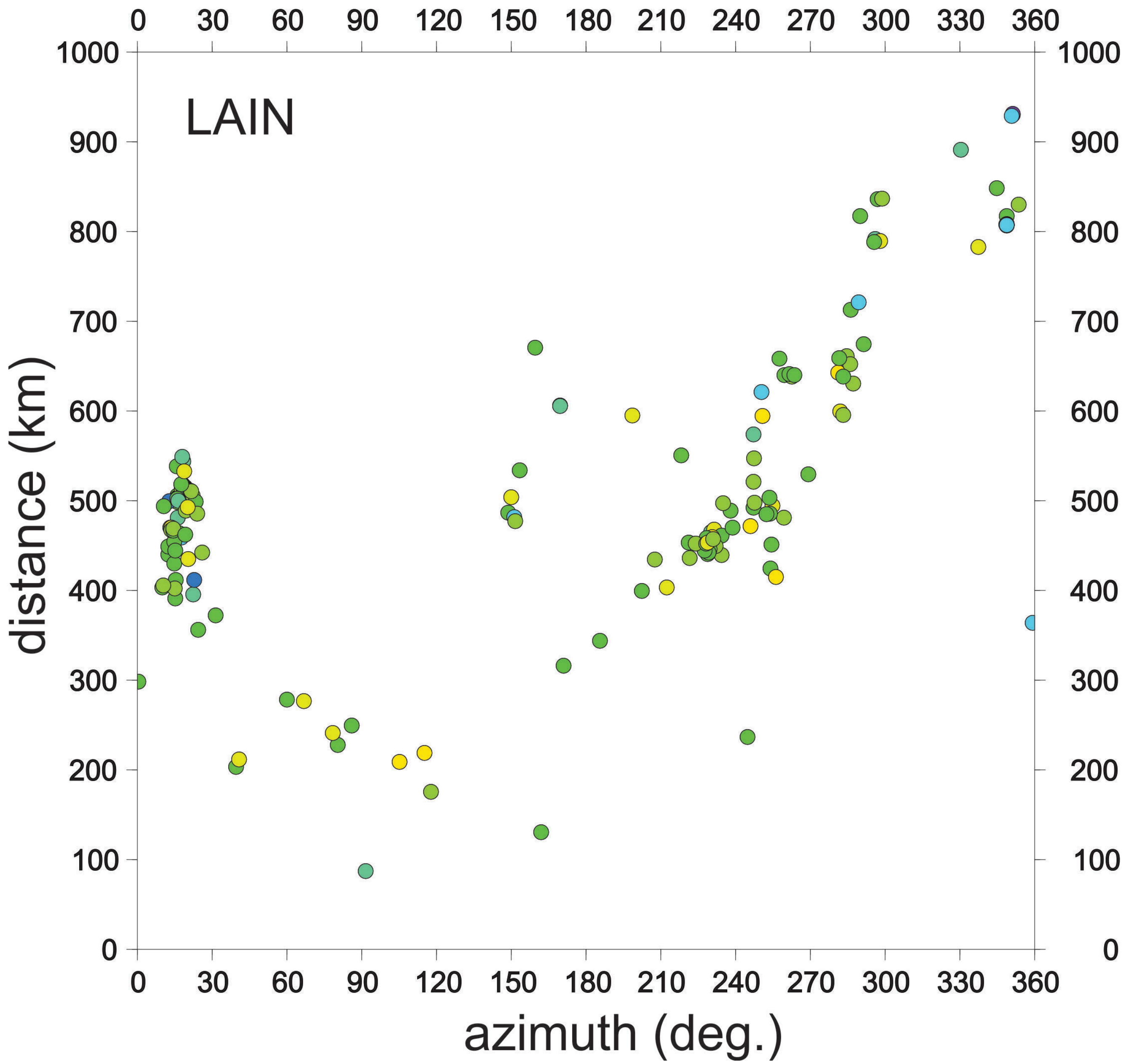


Figure 5xlviii

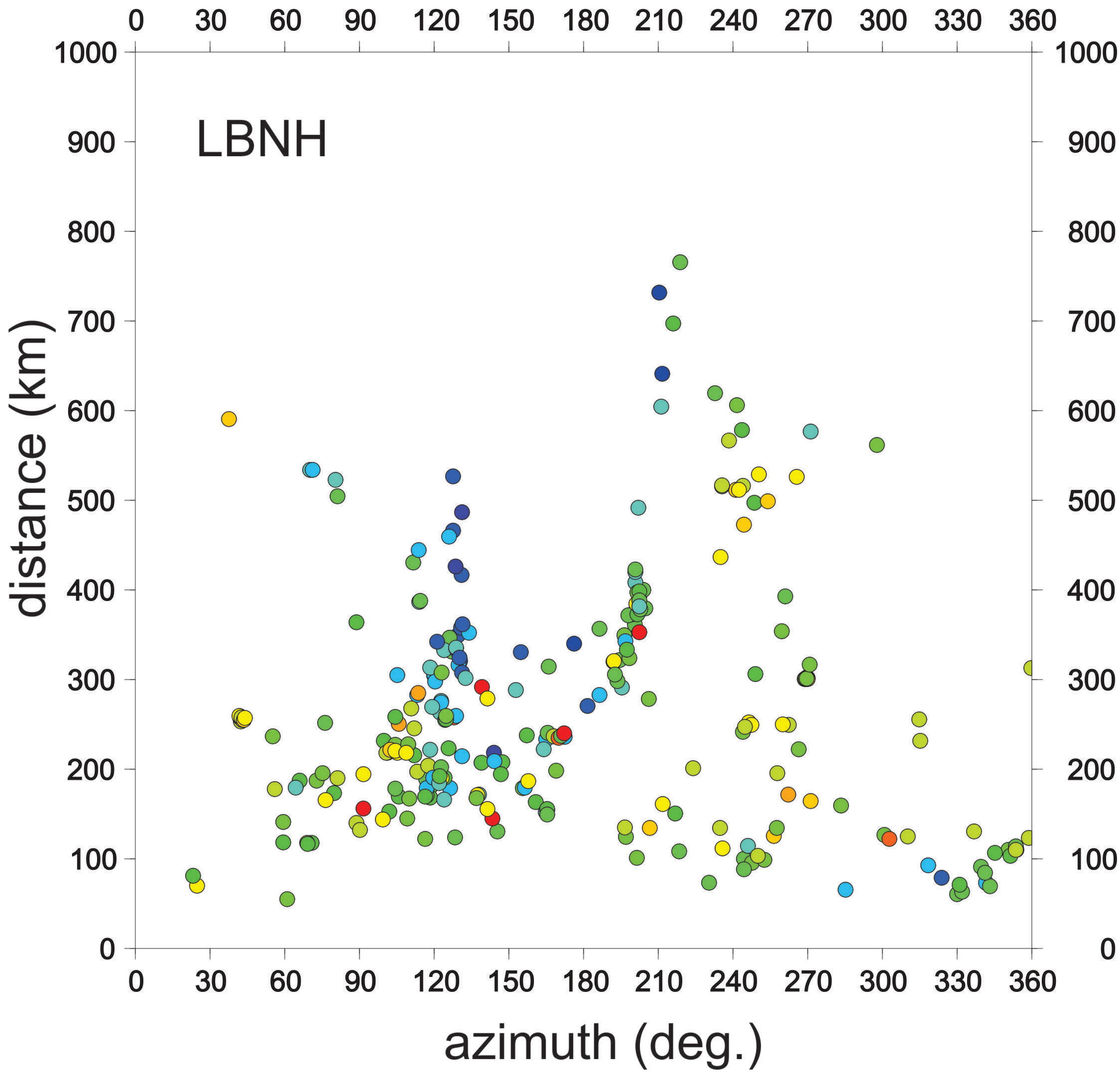
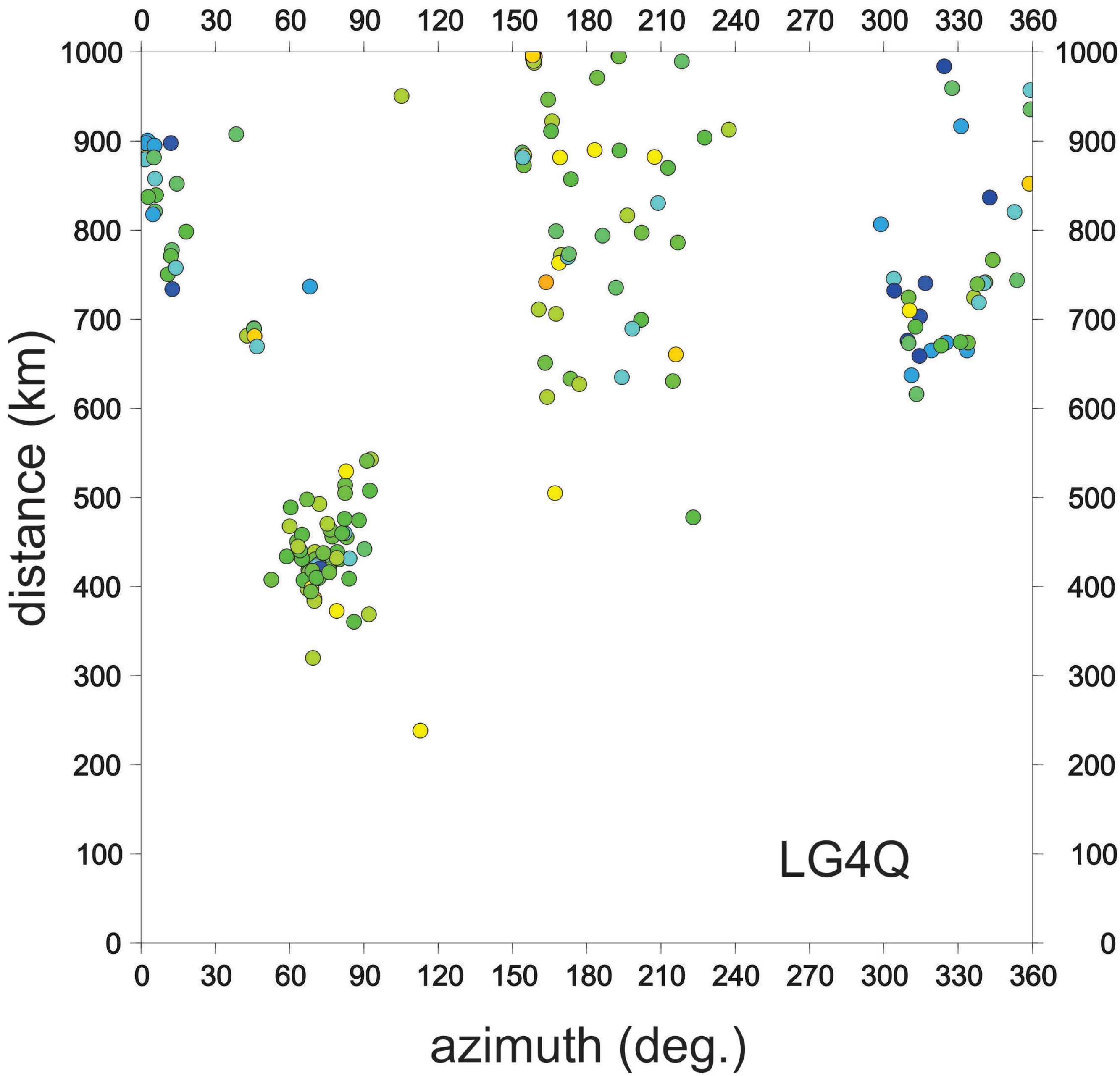


Figure 5xlix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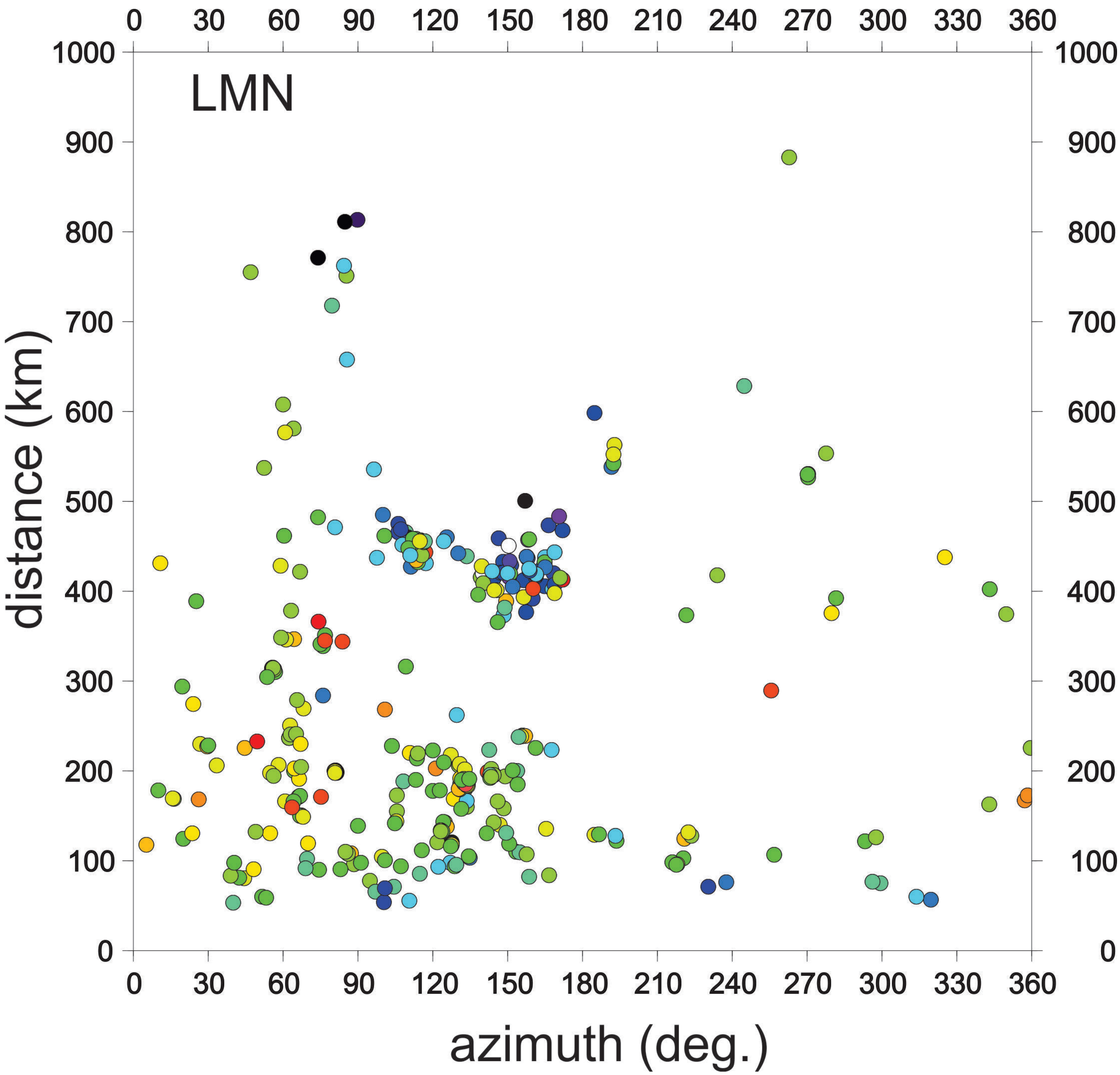
300
200
100
0
distance (km)
LG4Q
azimuth (deg.)

Figure 5I


LMN
distance (km)
azimuth (deg.)
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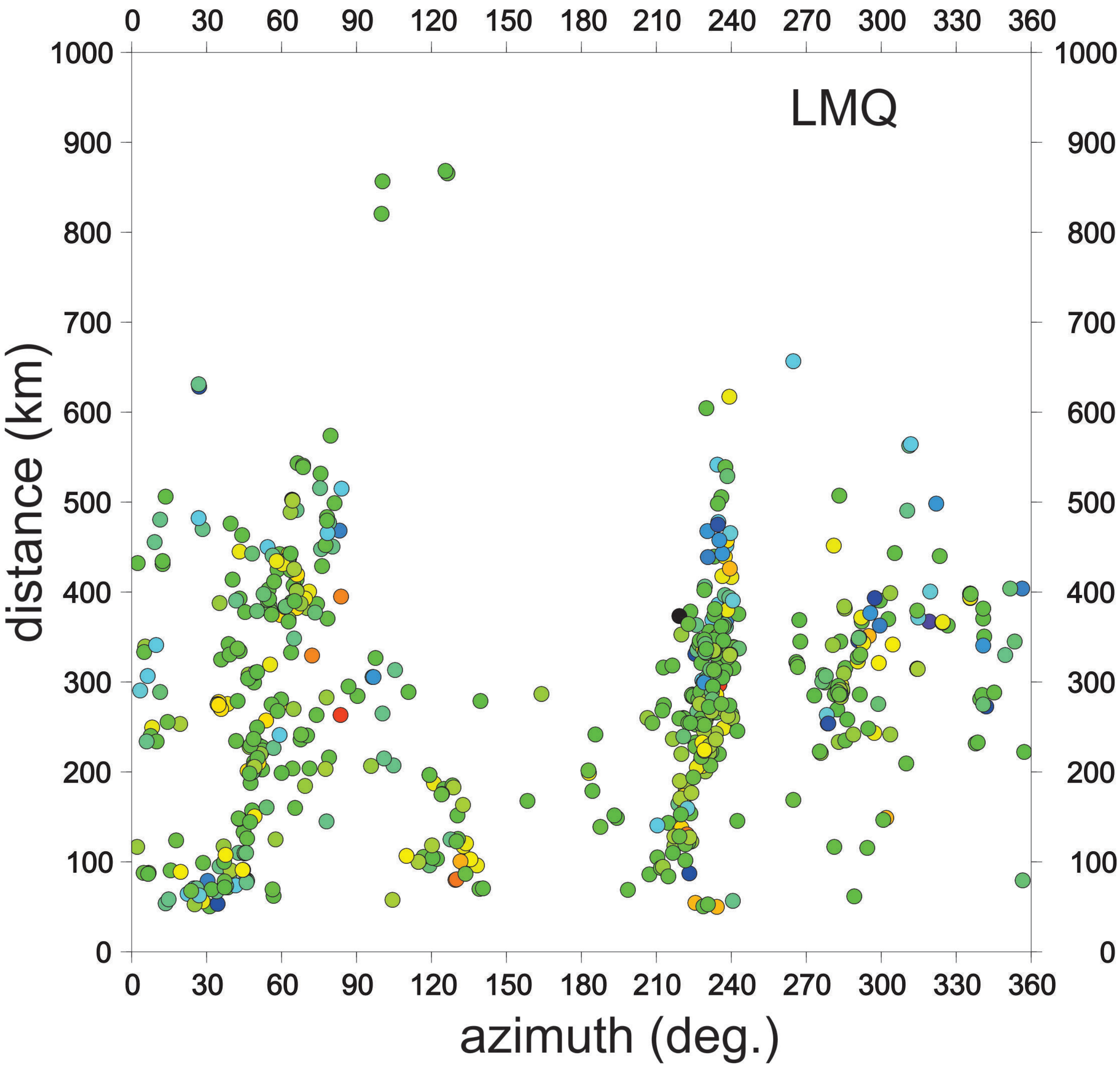
400
500
600
700
800
900
1000

Figure 5li



LMQ
distance (km)
azimuth (deg.)
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100
200
300
400
500
600
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900
1000
0
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90
120
150
180
210
240
270
300
330
360

Figure 5lii

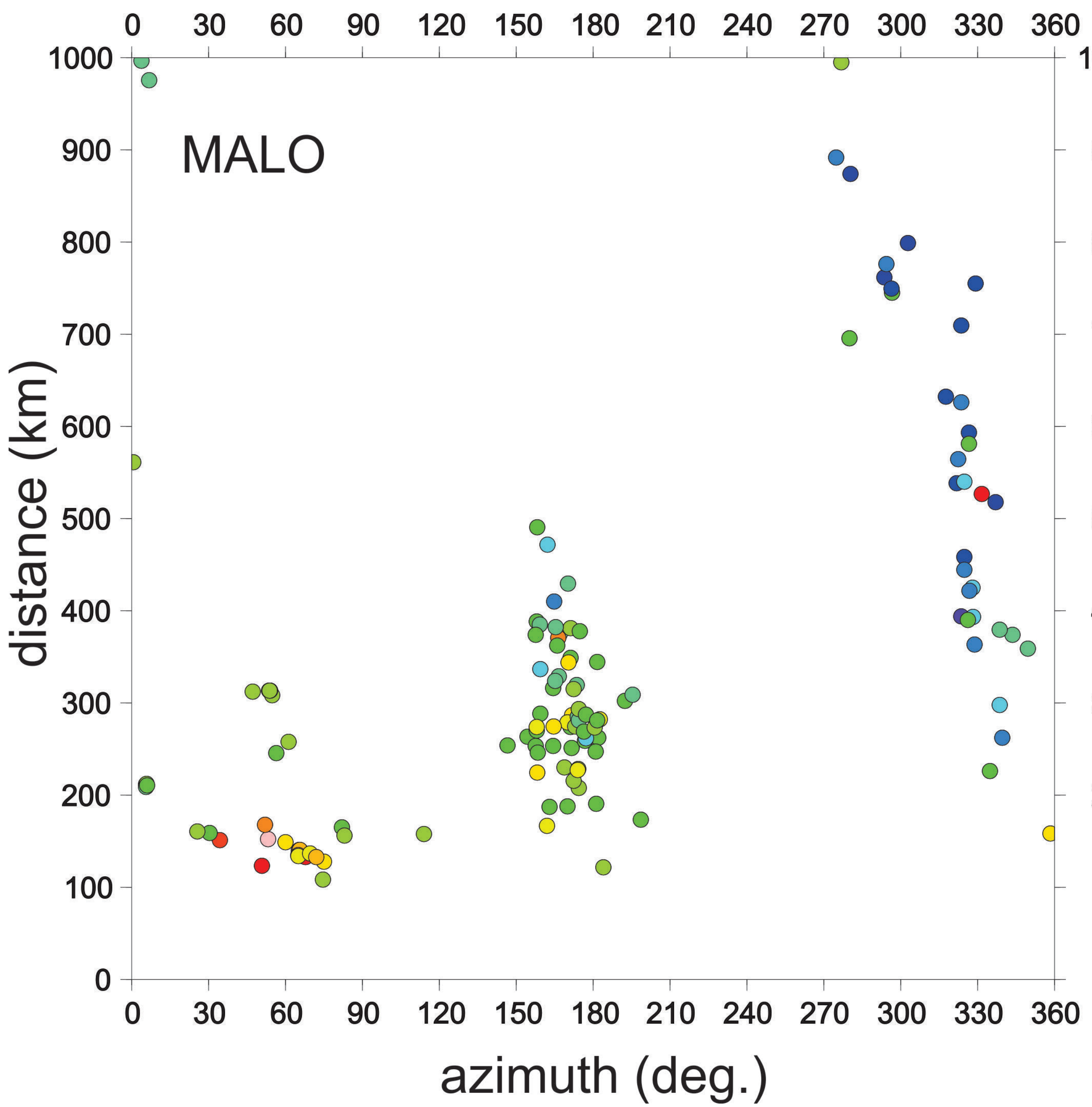
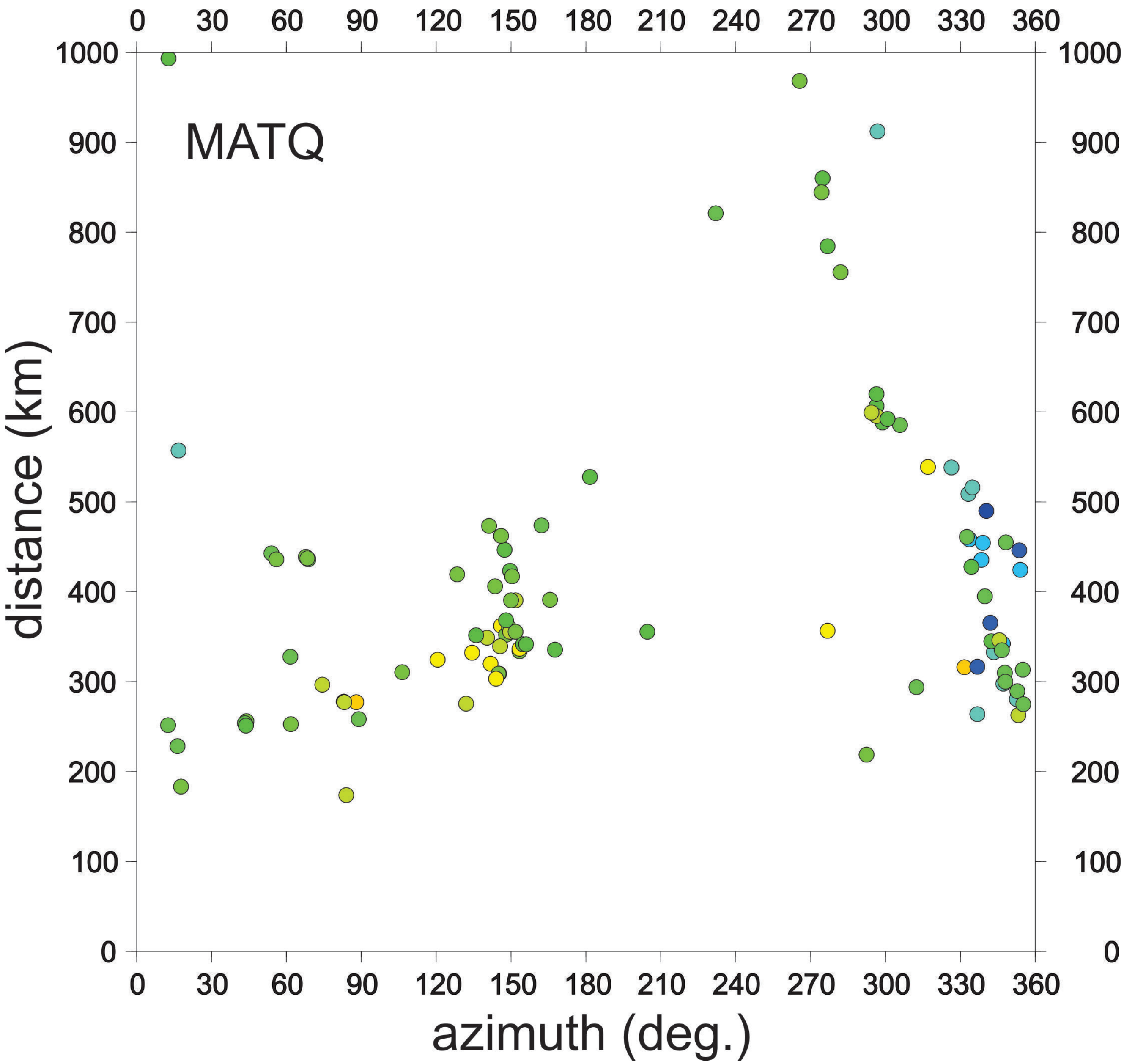


Figure 5liii


MATQ
distance (km)
azimuth (deg.)
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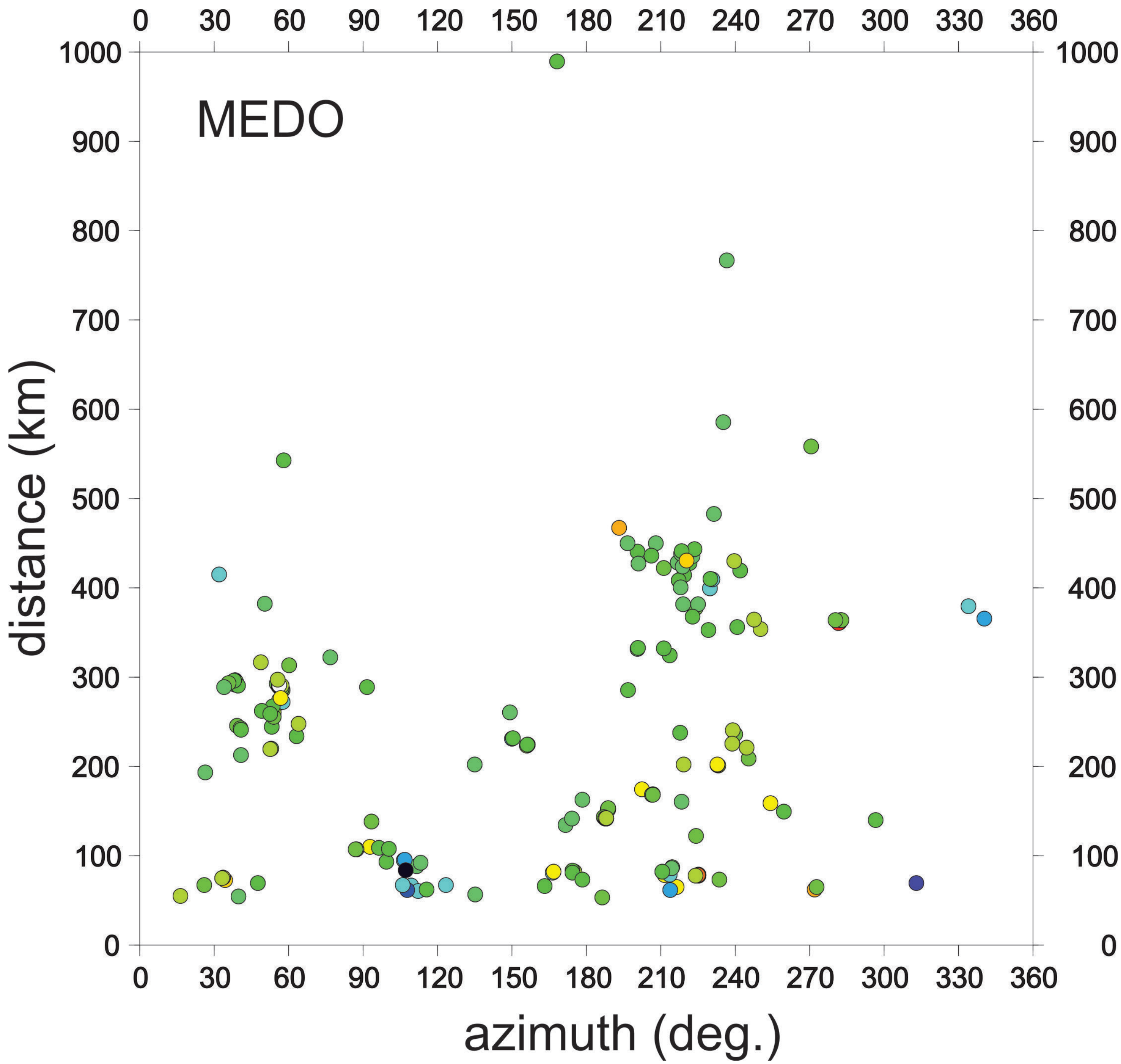
0 100 200 300 400 500 600 700 800 900 1000

Figure 5liv


MEDO
distance (km)
azimuth (deg.)
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90
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0
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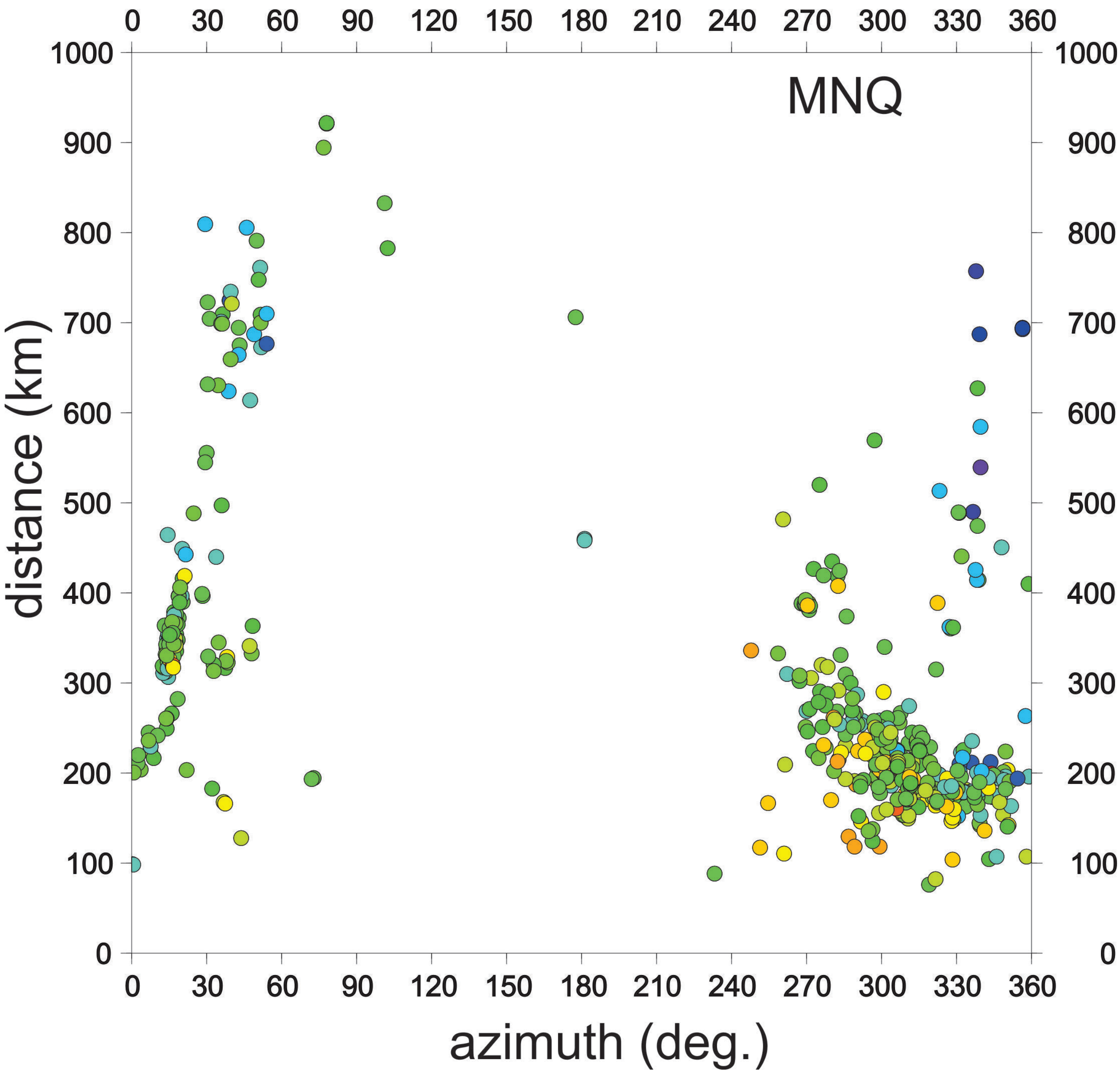
Figure 5lv



MNQ
distance (km)
azimuth (deg.)
0
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60
90
120
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900
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500
400
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100
0

Figure 5lvi

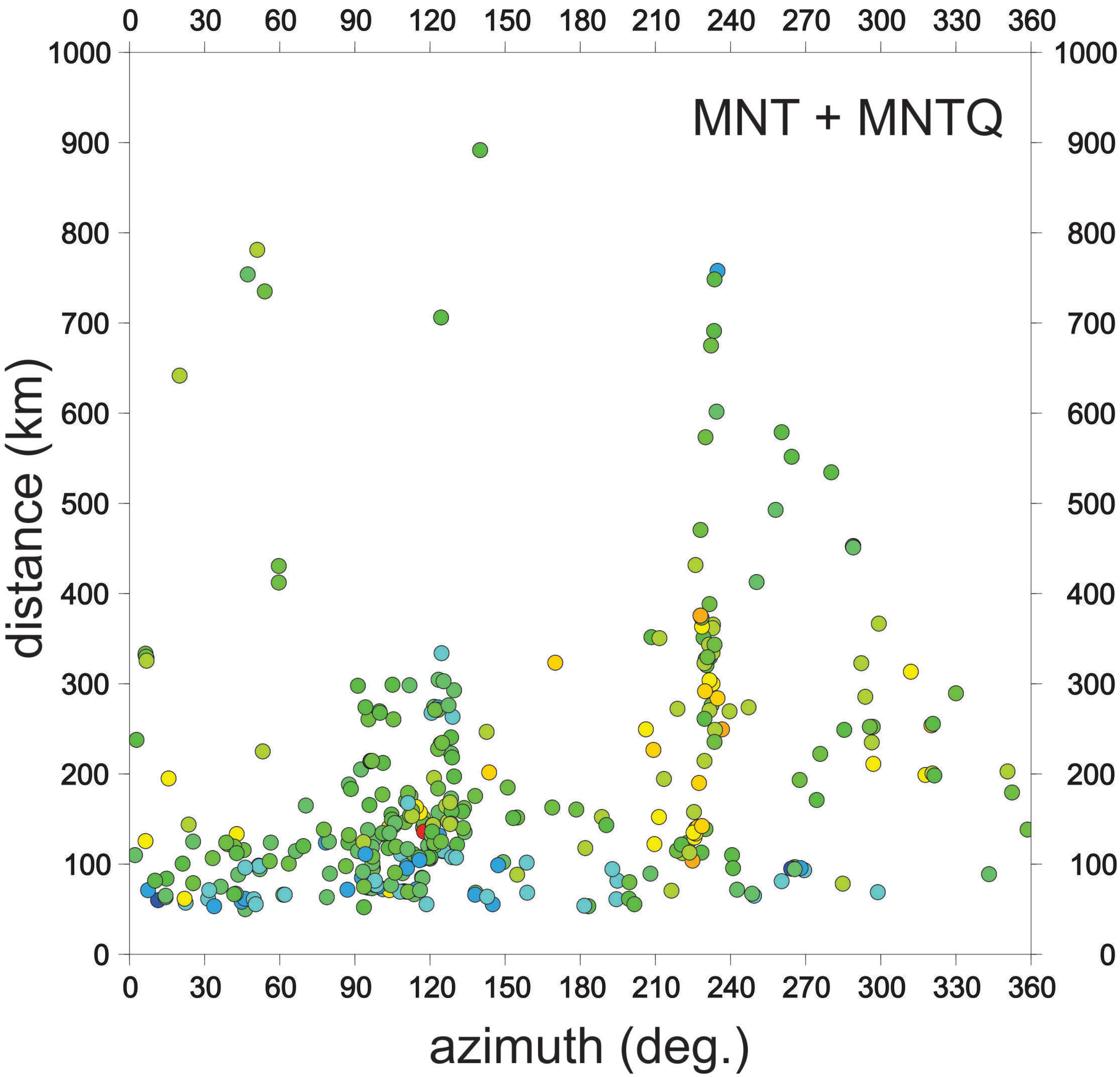


Figure 5lvii

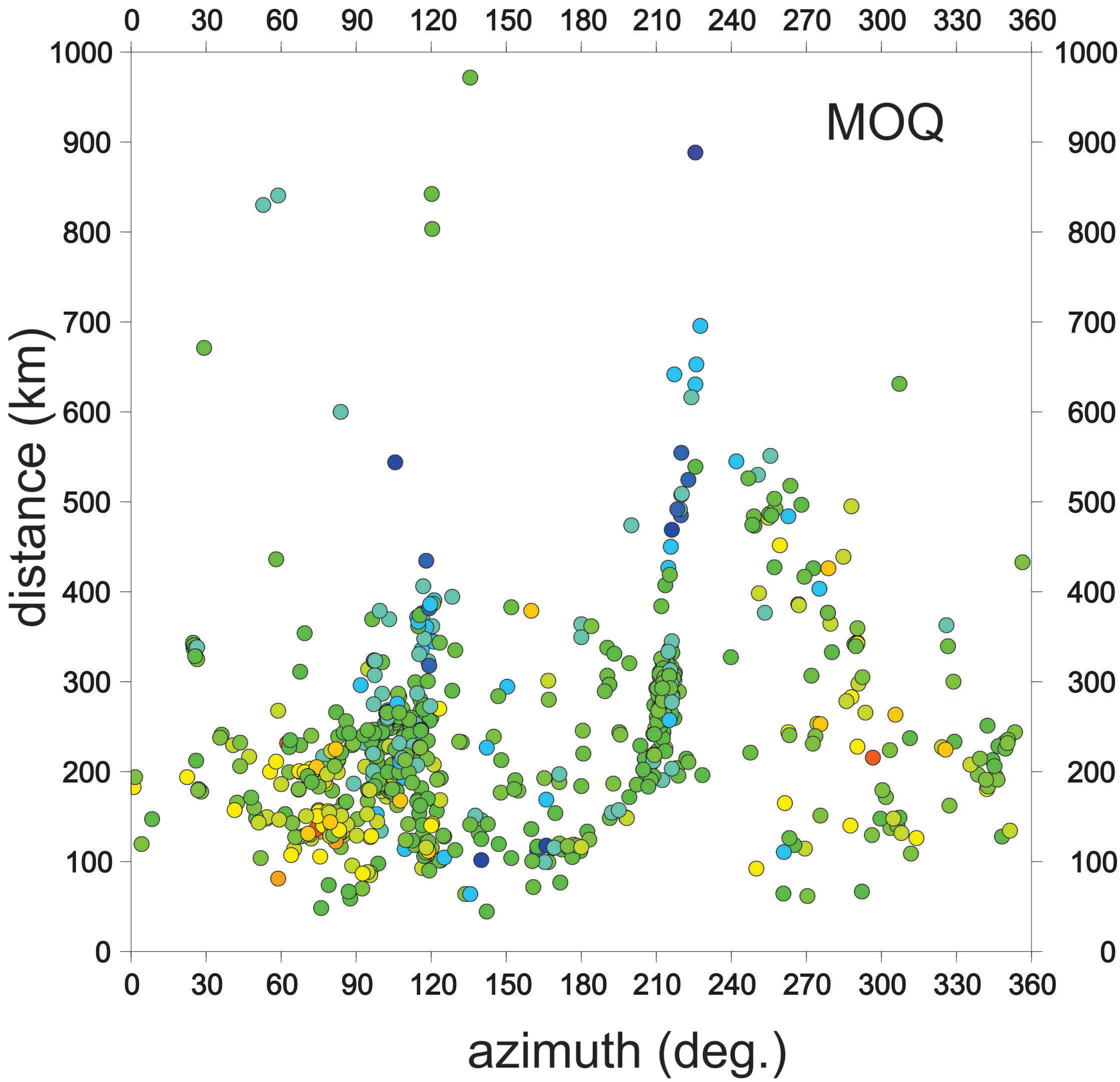
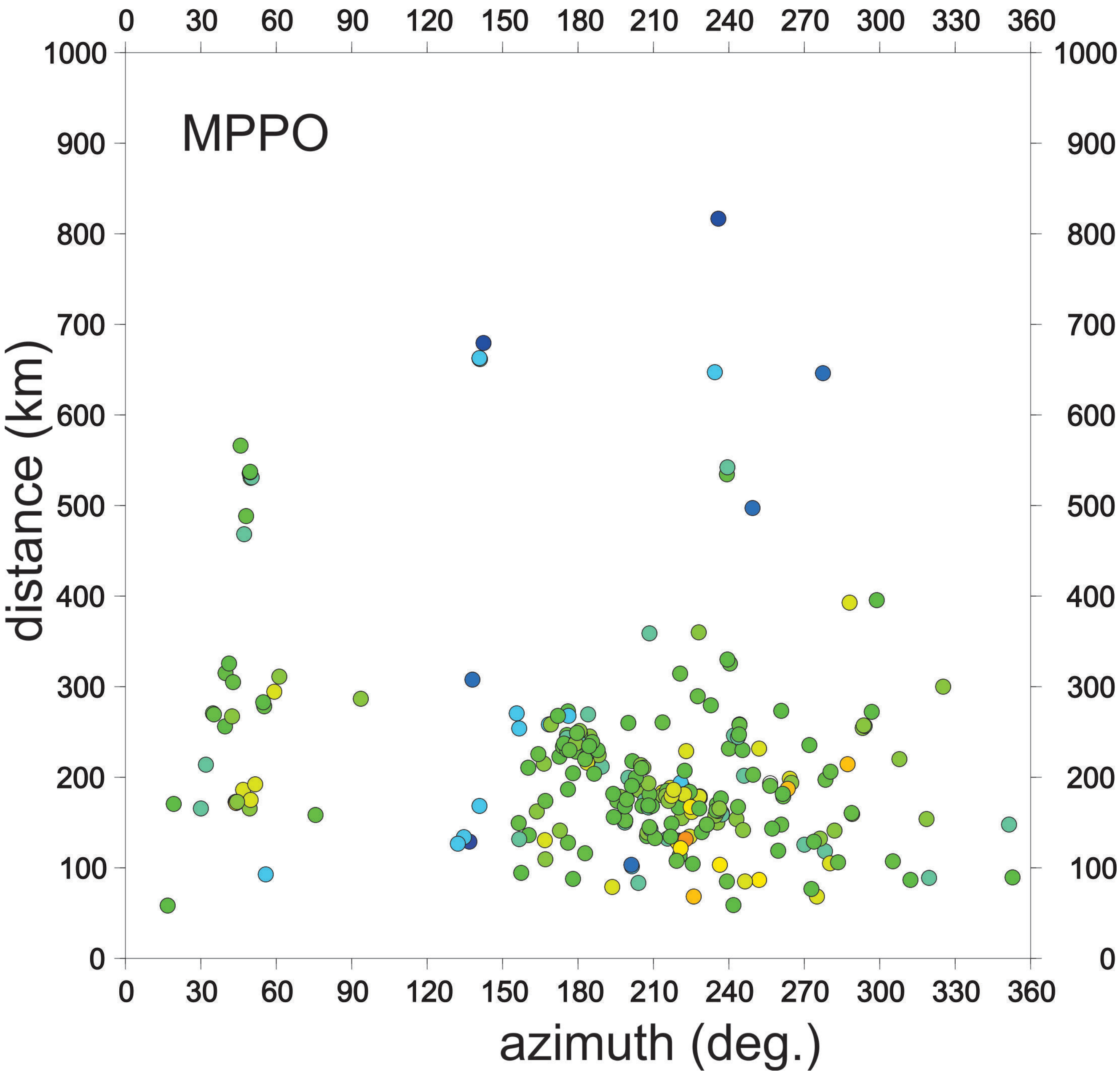


Figure 5lviii


MPPO
distance (km)
azimuth (deg.)
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120
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500
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700
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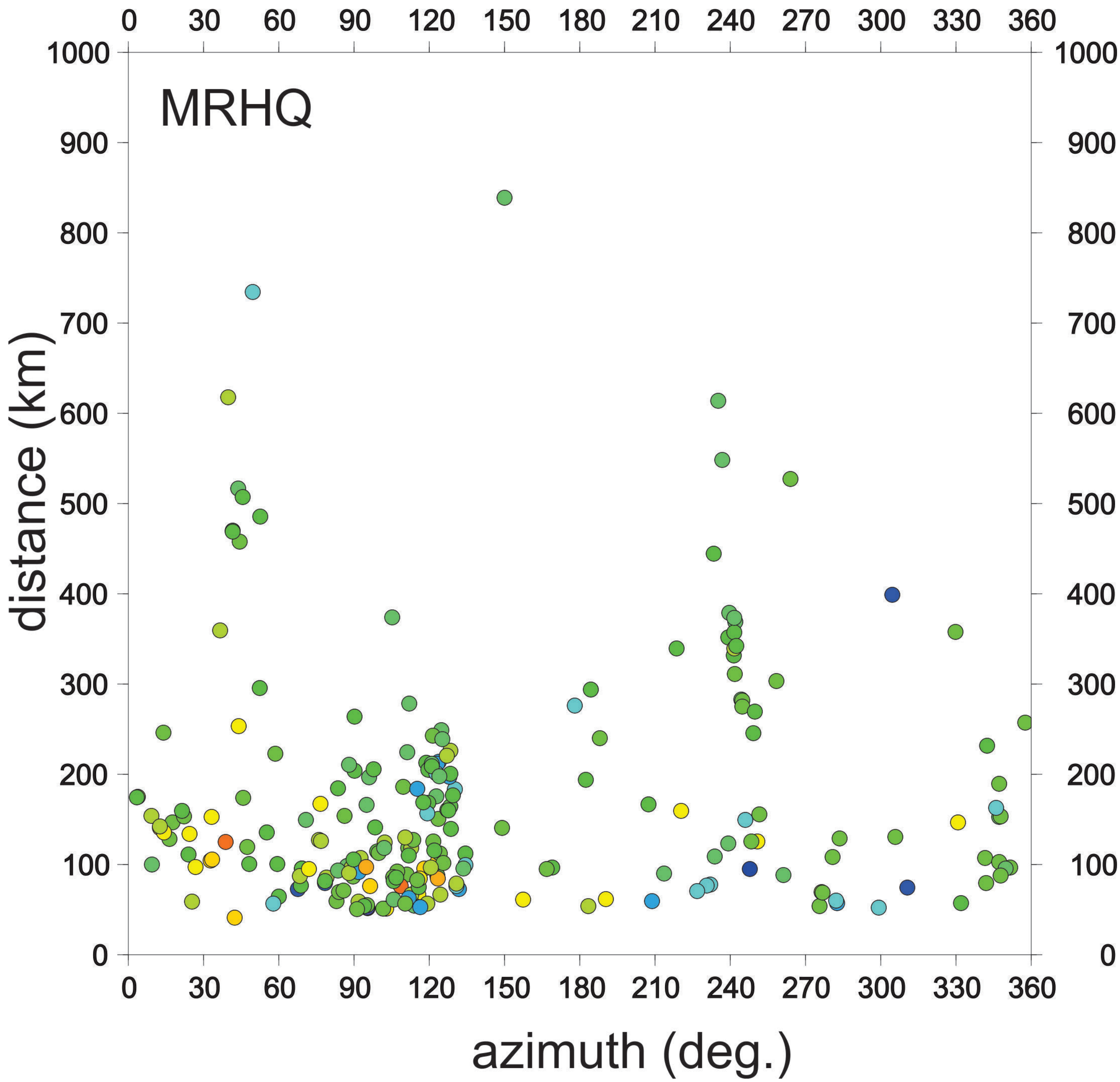
900
1000

Figure 5lix


MRHQ
distance (km)
azimuth (deg.)
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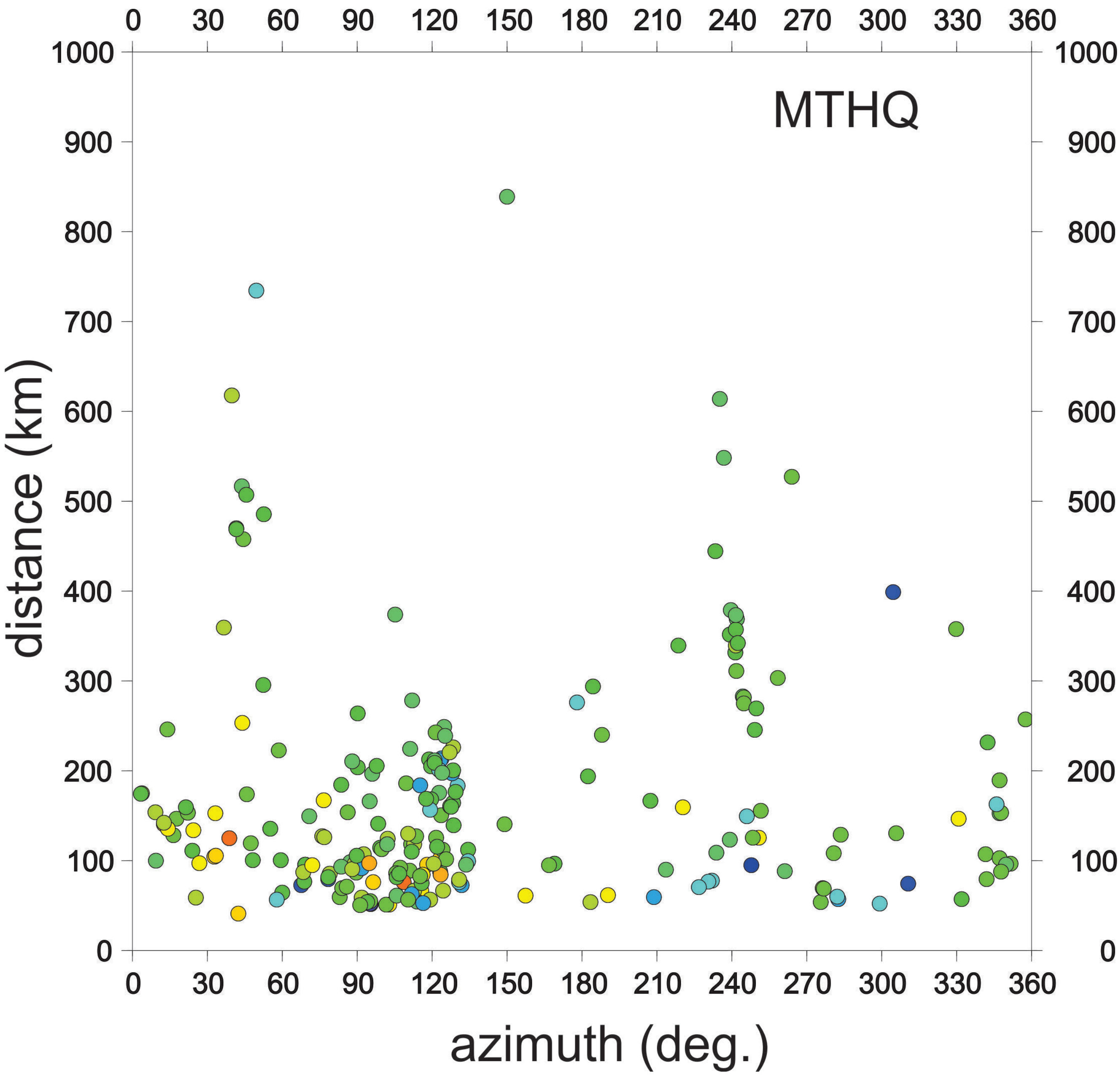
0 100 200 300 400 500 600 700 800 900 1000

Figure 5lx


MTHQ
distance (km)
azimuth (deg.)
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0 100 200 300 400 500 600 700 800 900 1000

Figure 5lxi

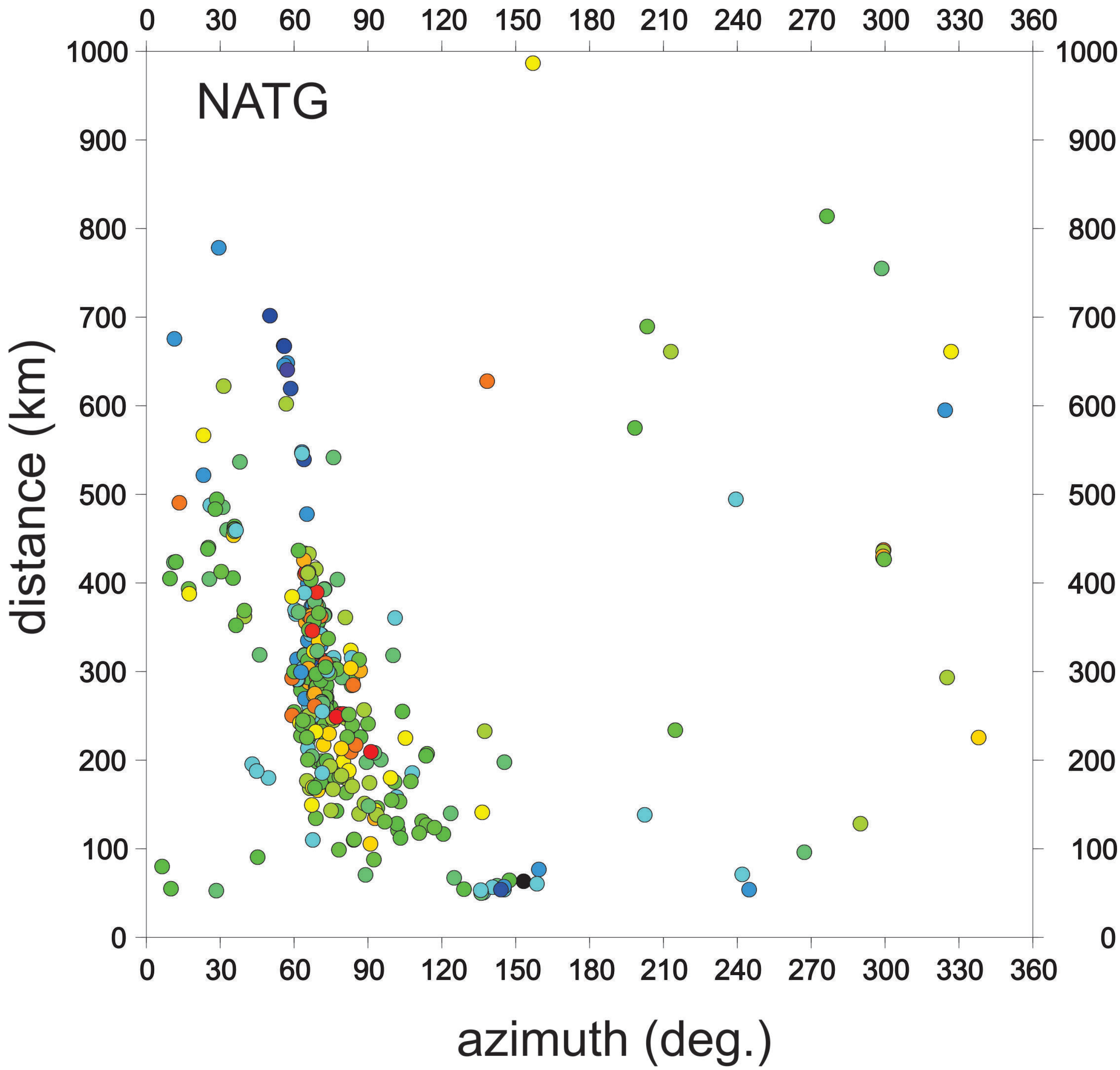

Figure 5lxii

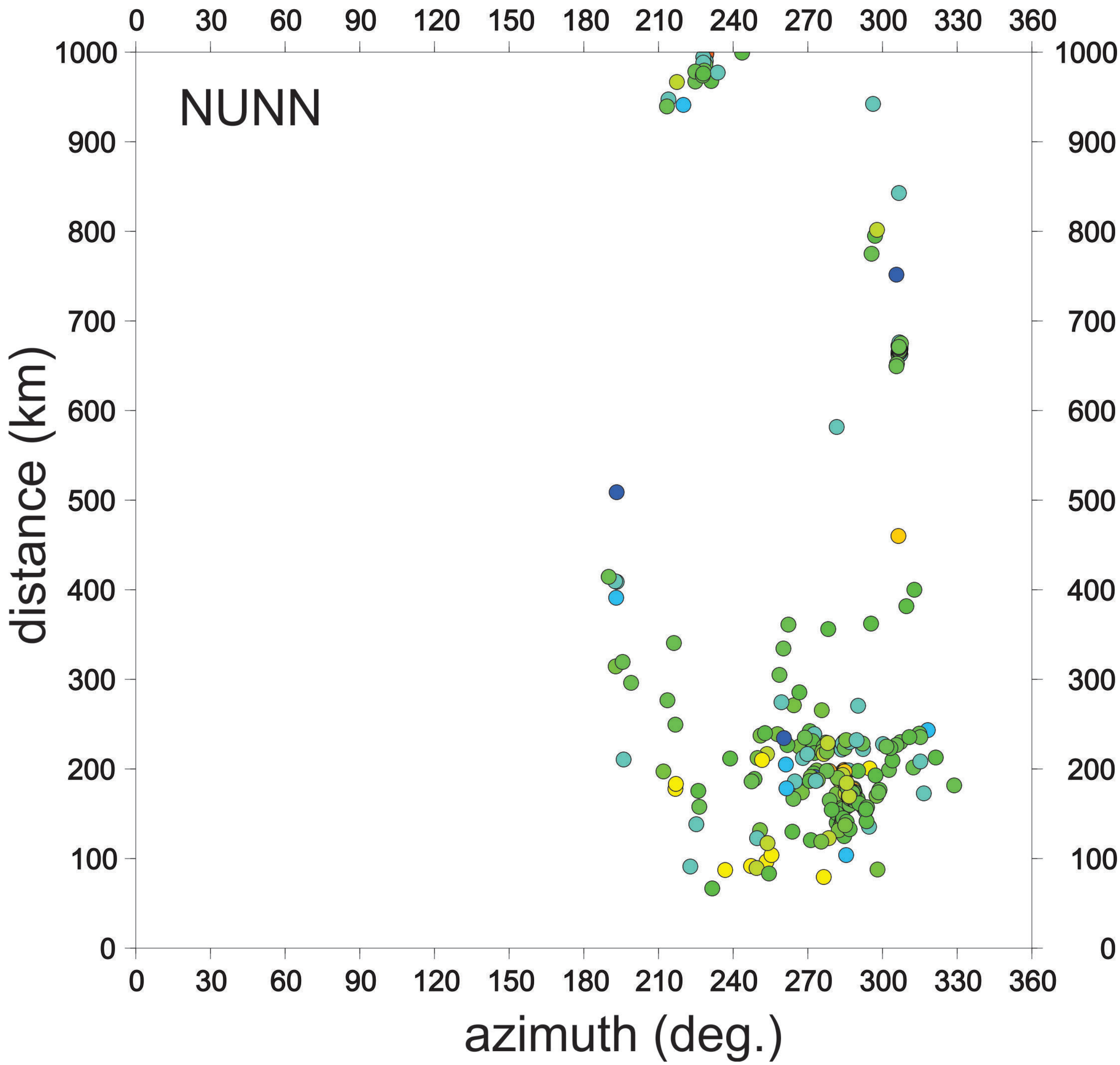

Figure 5lxiii

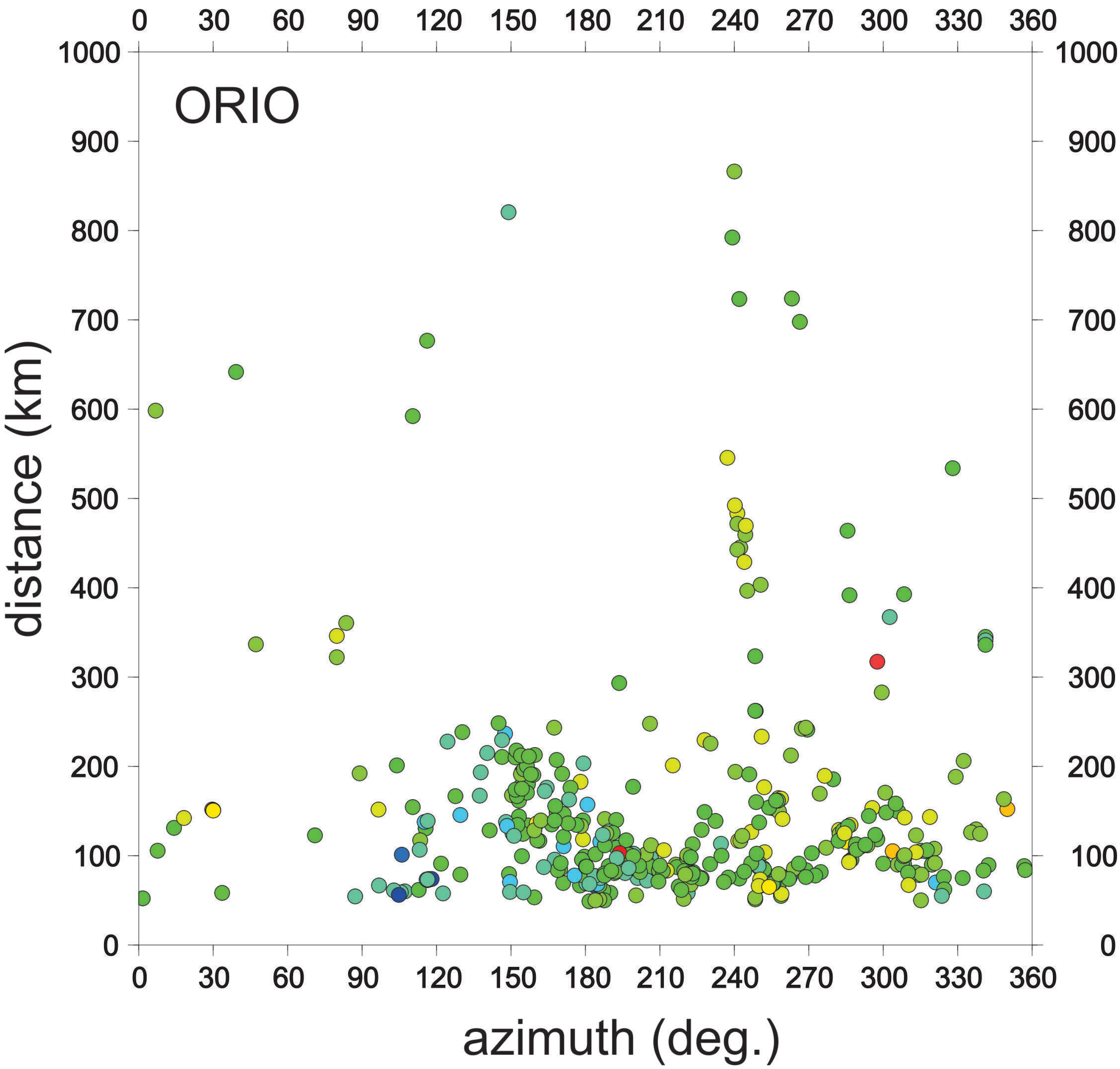

Figure 5lxiv

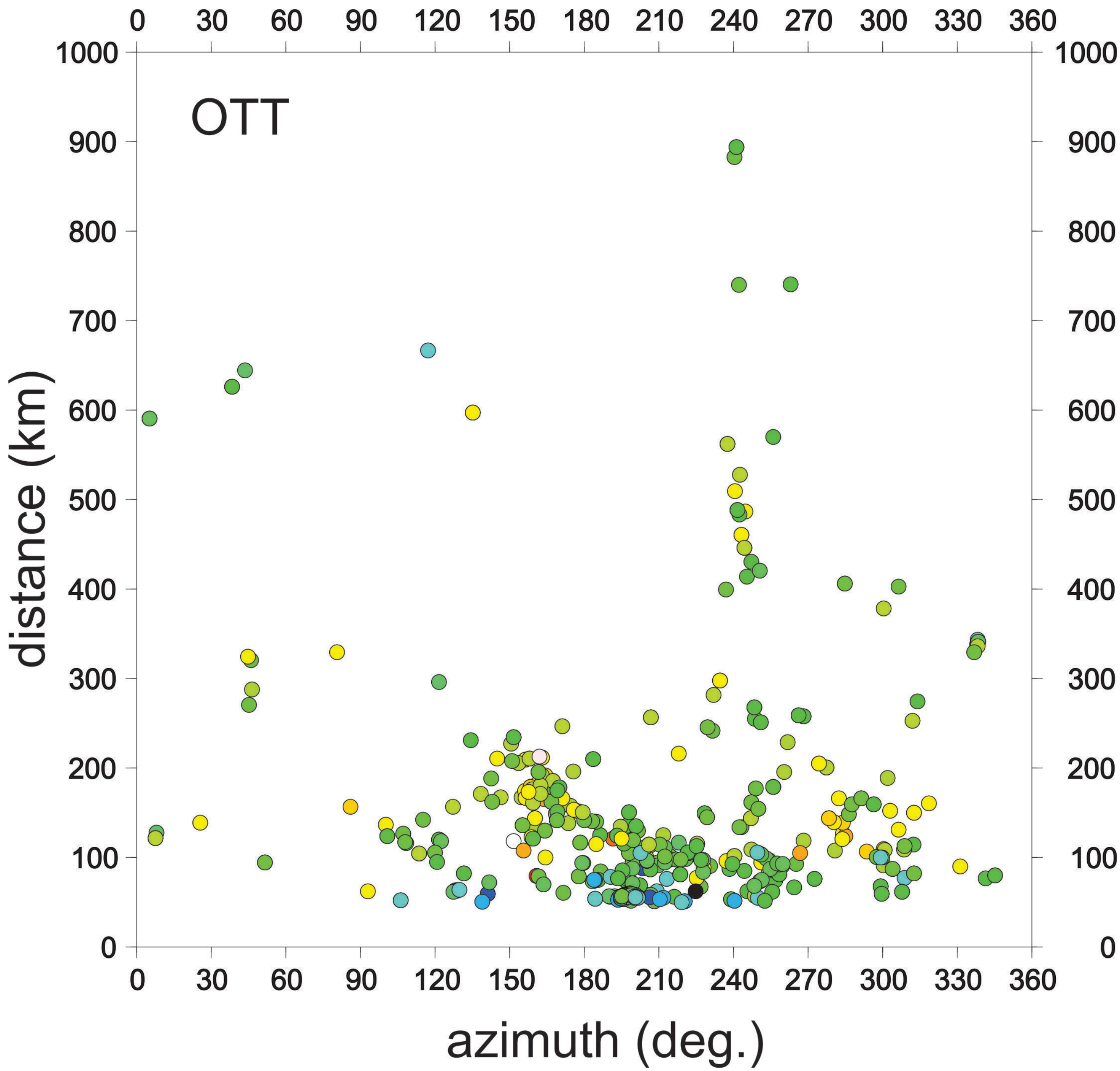
OTT
distance (km)
azimuth (deg.)
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Figure 5lxv

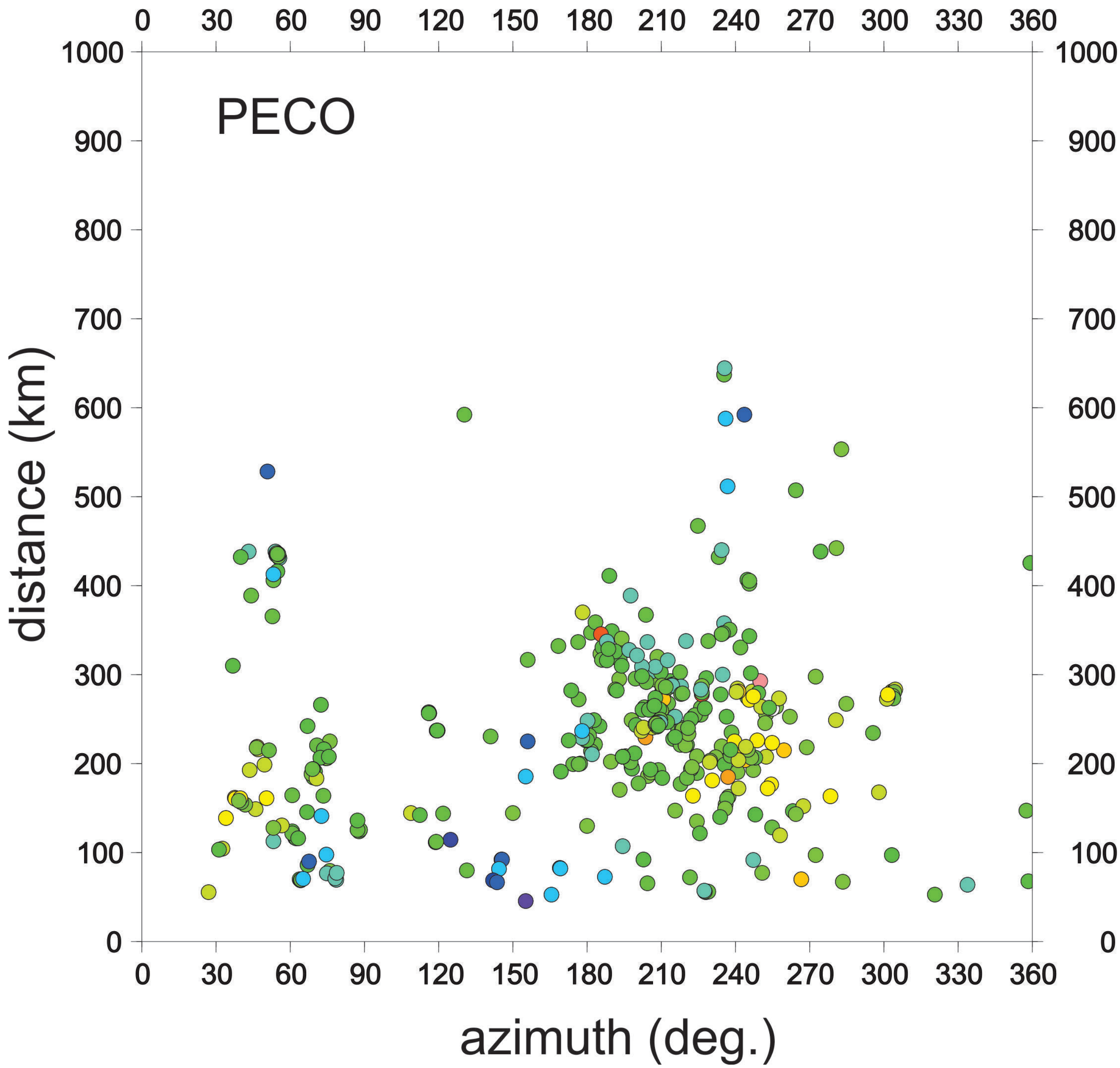

Figure 5lxvi

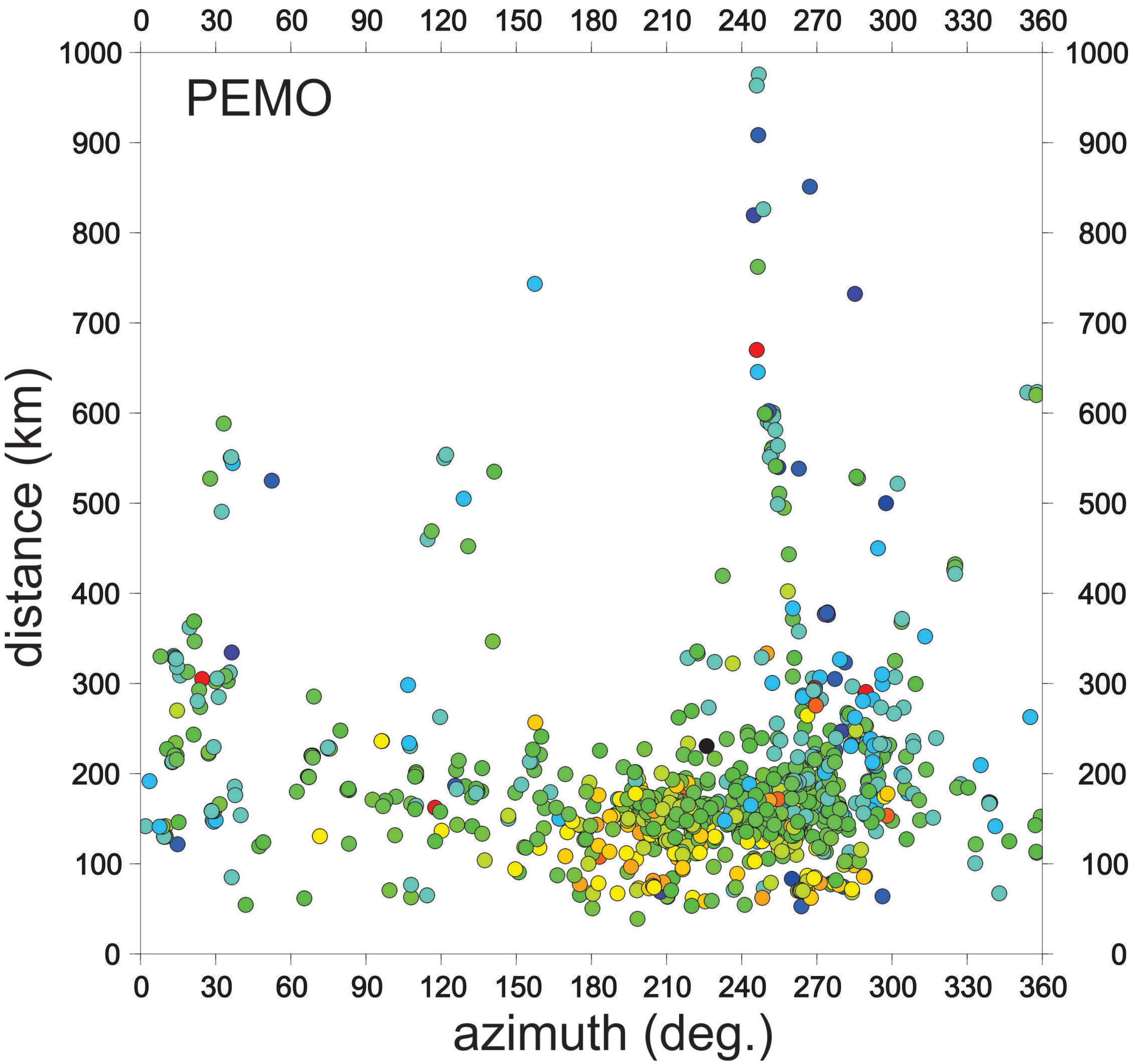

Figure 5lxvii

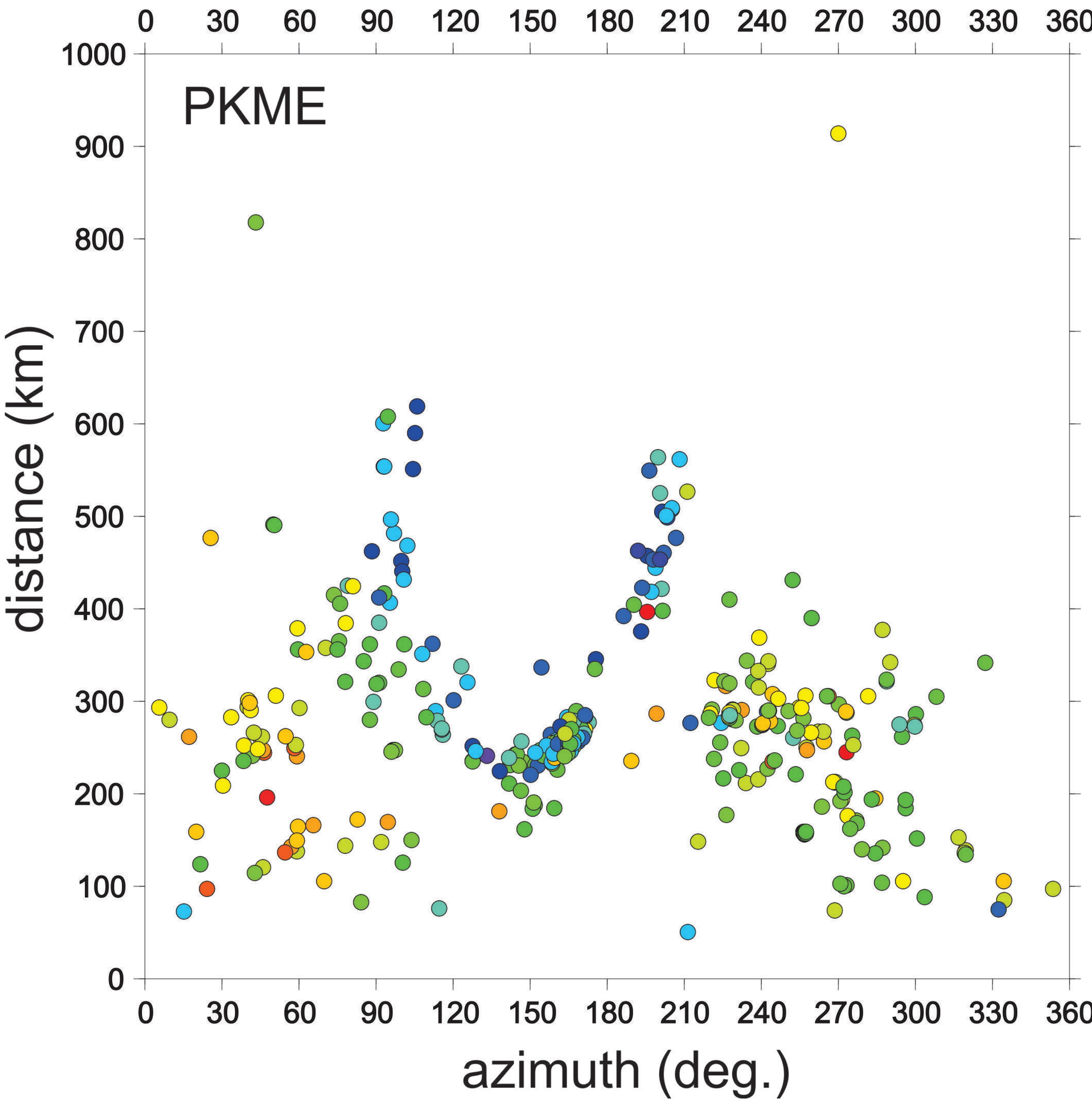

Figure 5lxviii

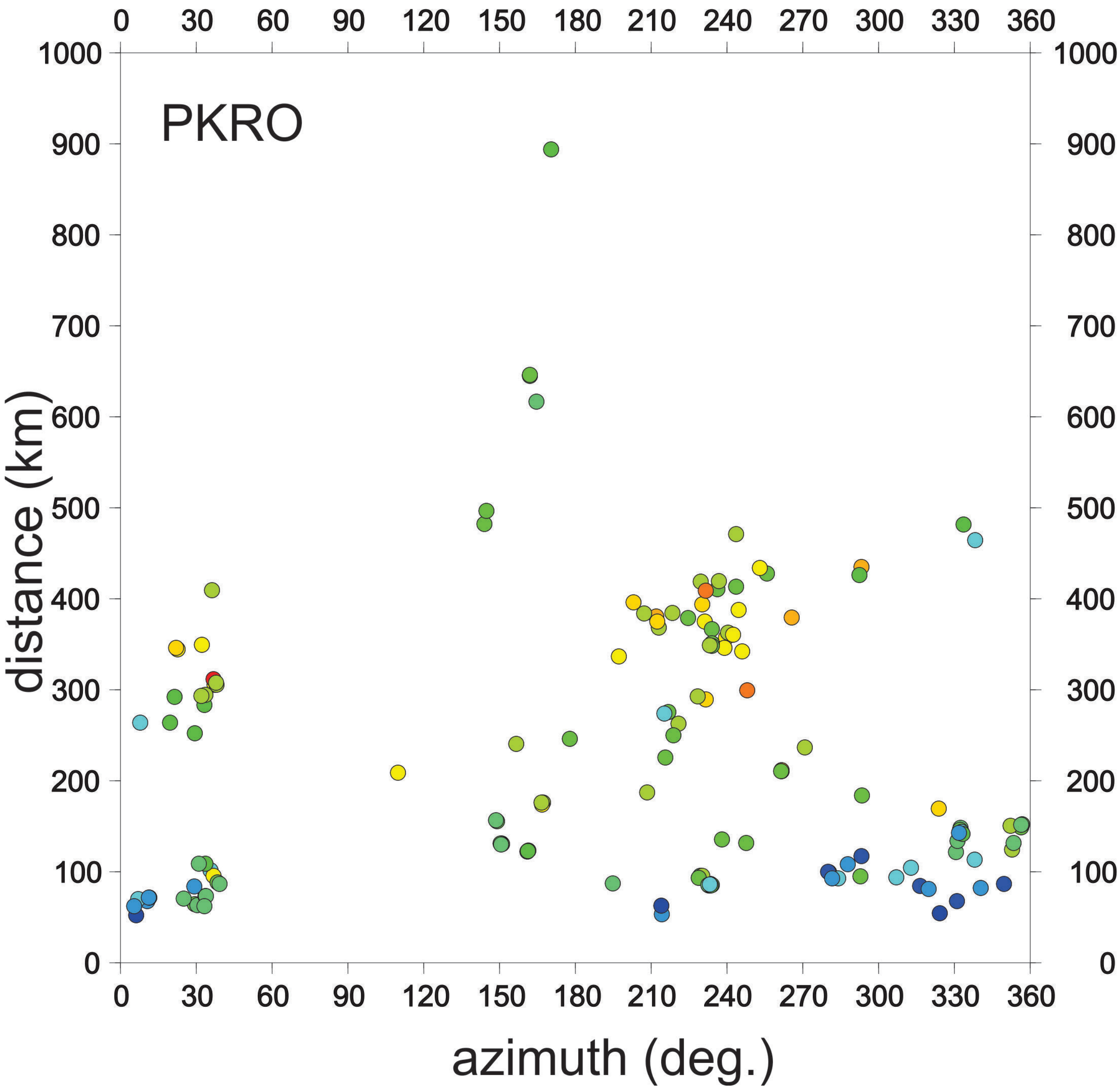

Figure 5lxix

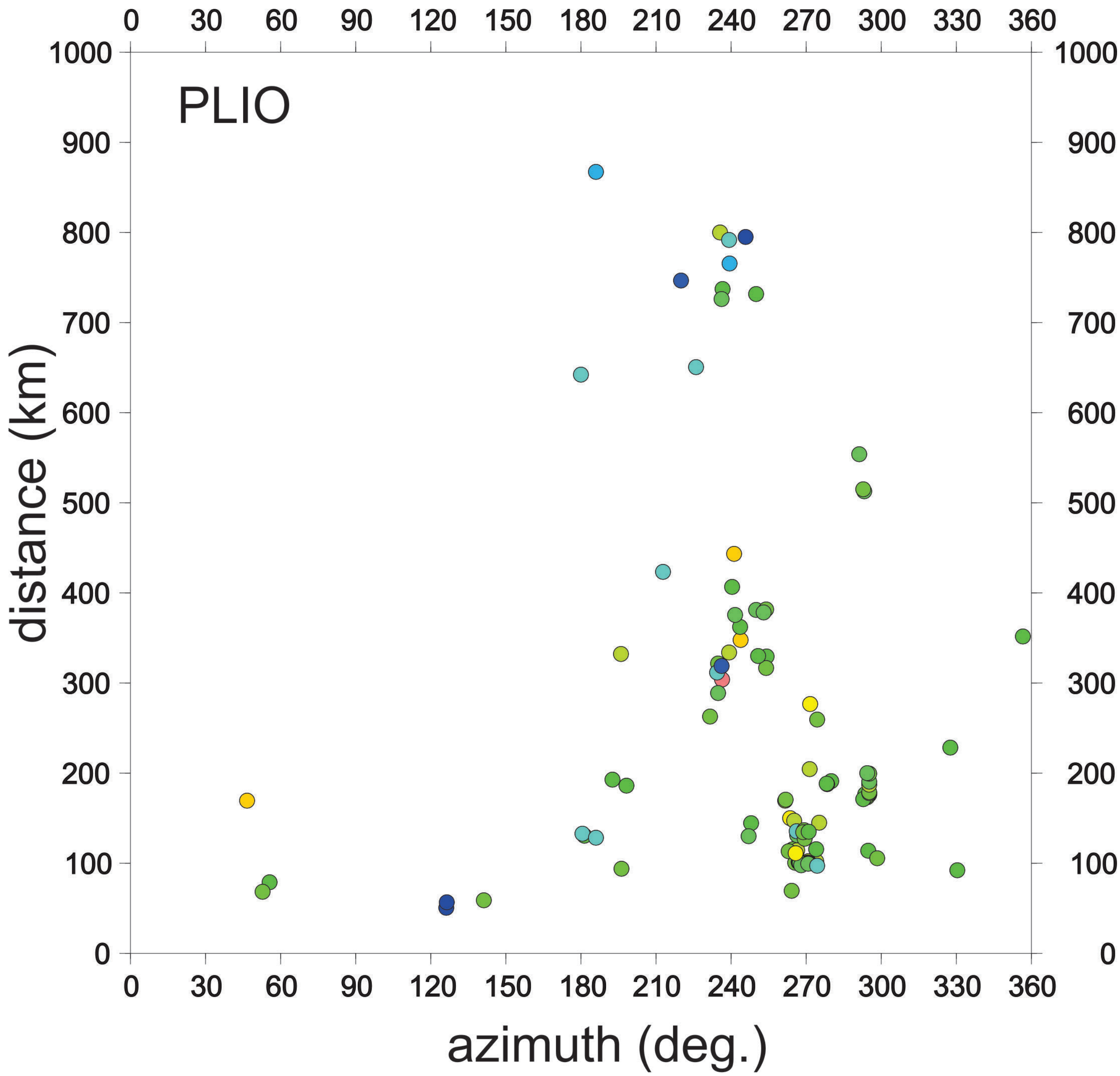
PLIO
distance (km)
azimuth (deg.)
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Figure 5lxx

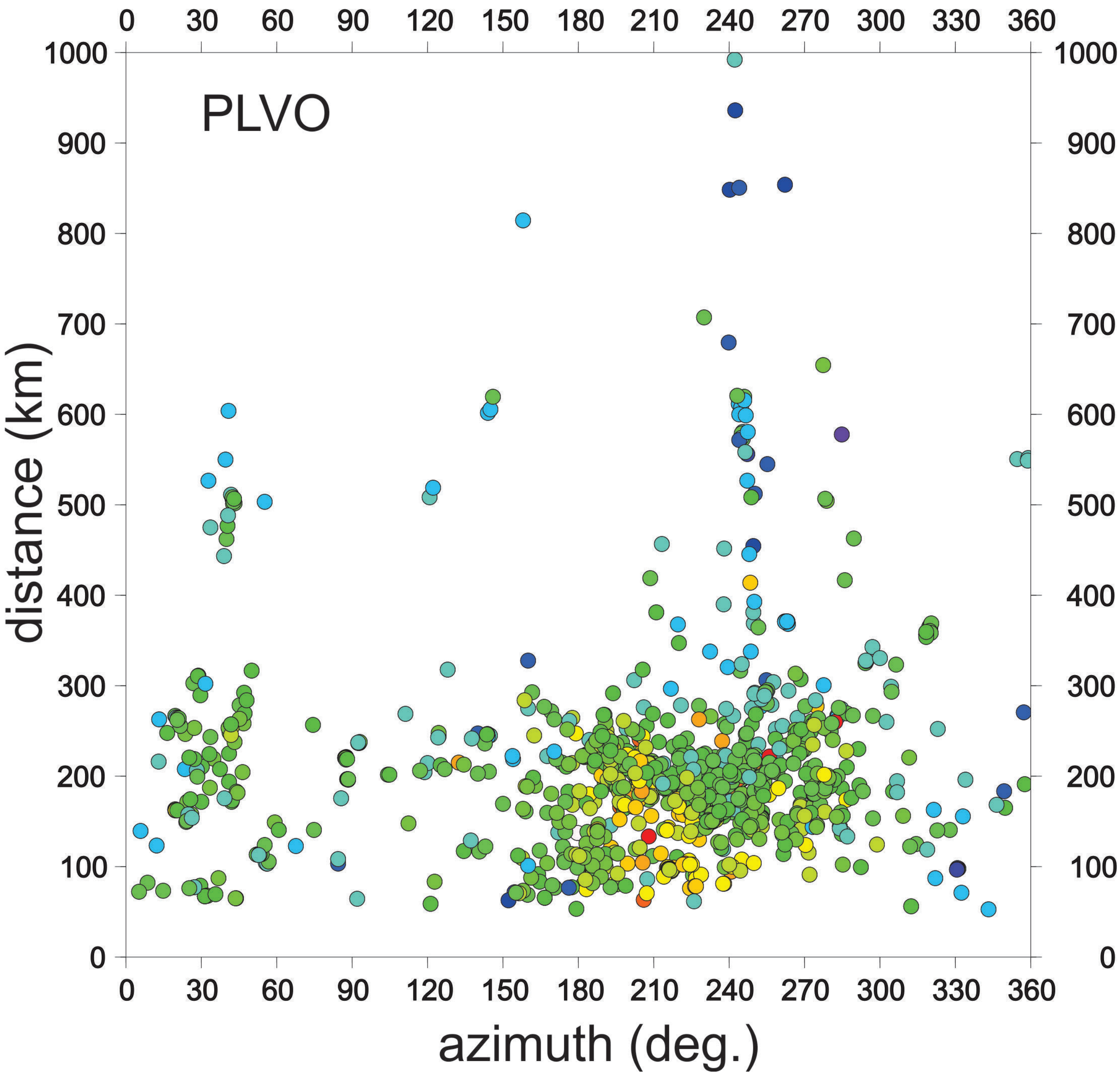


Figure 5lxxi

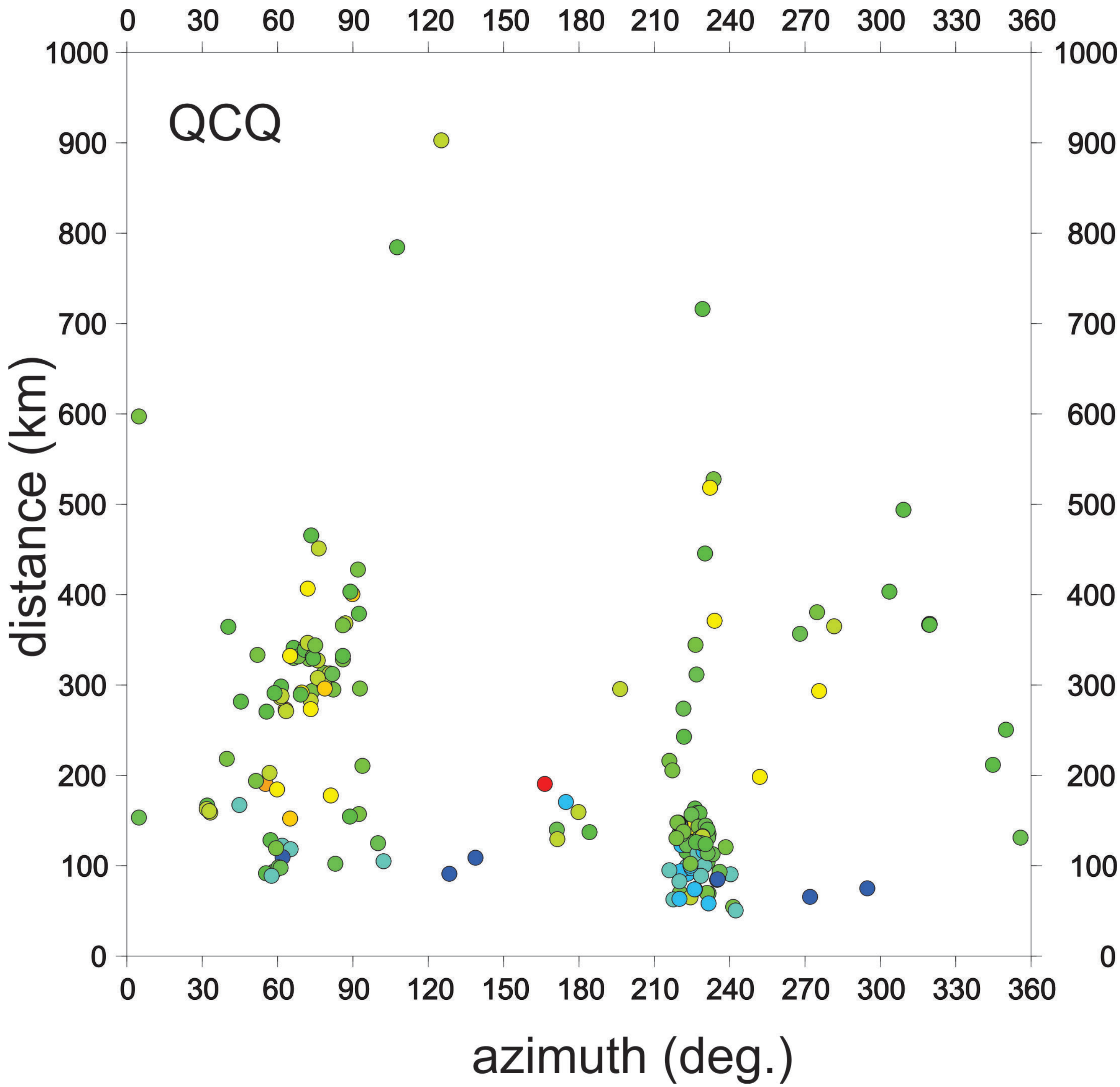


Figure 5lxxii

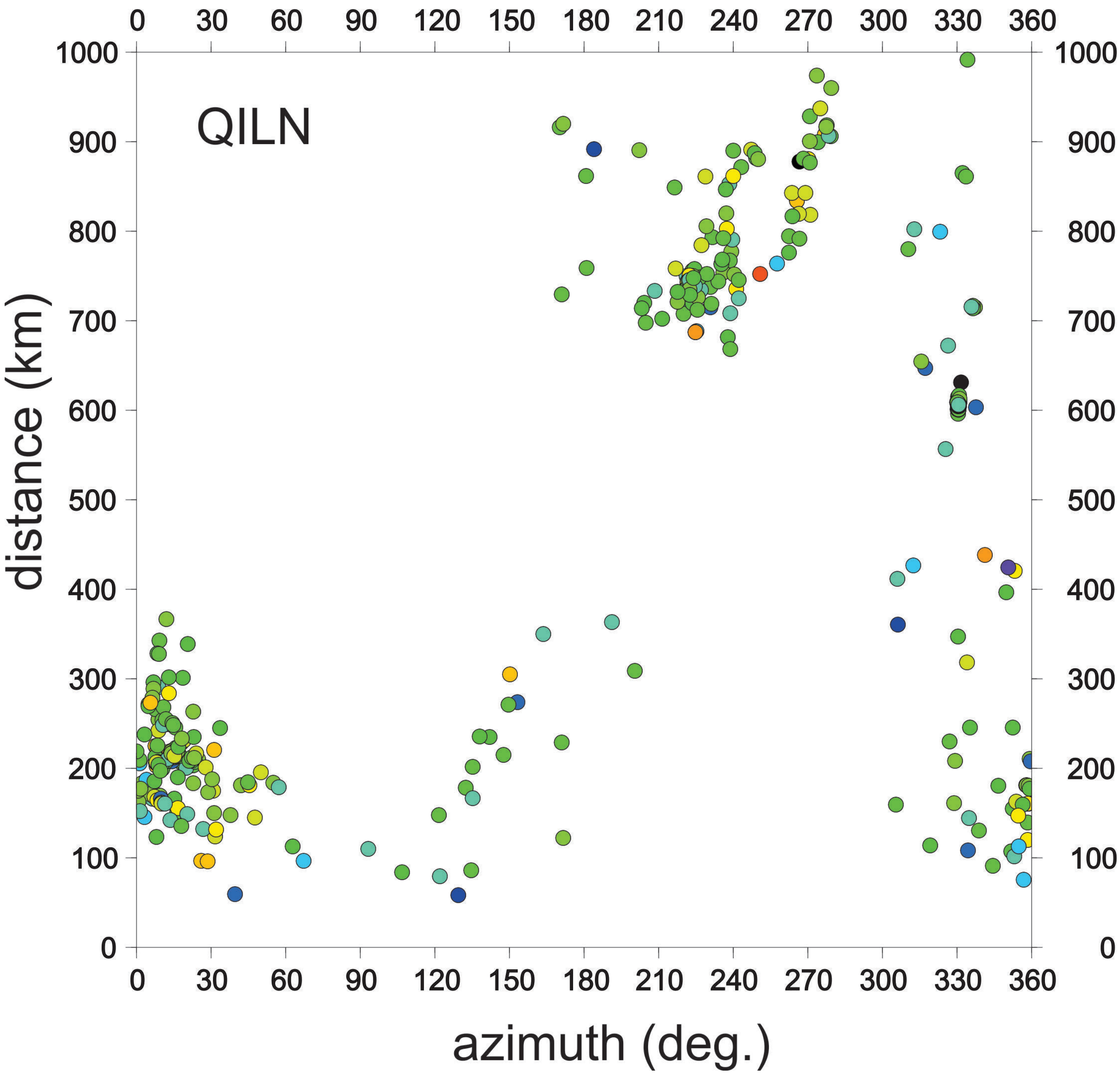


Figure 5lxxiii

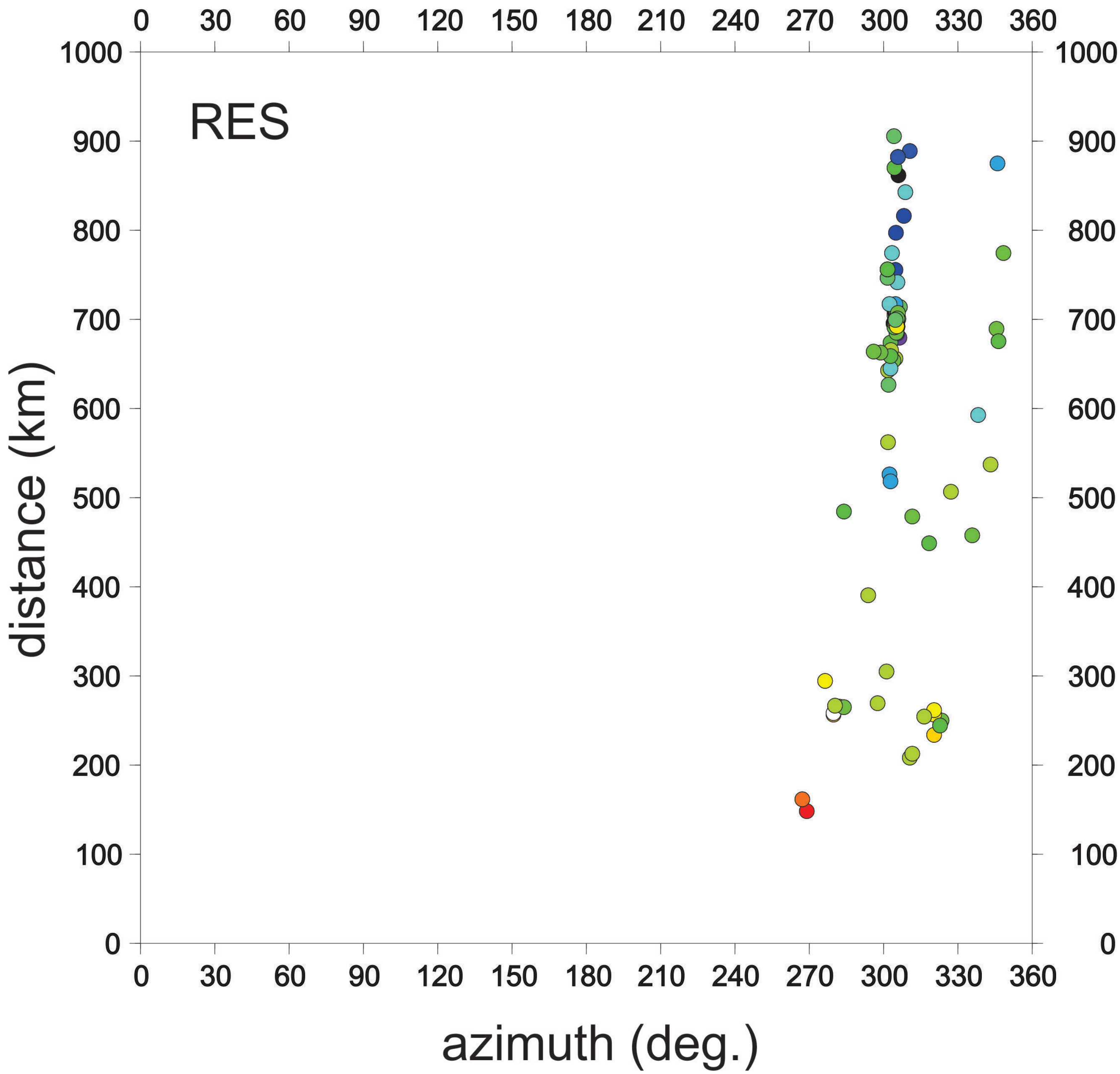


Figure 5lxxiv

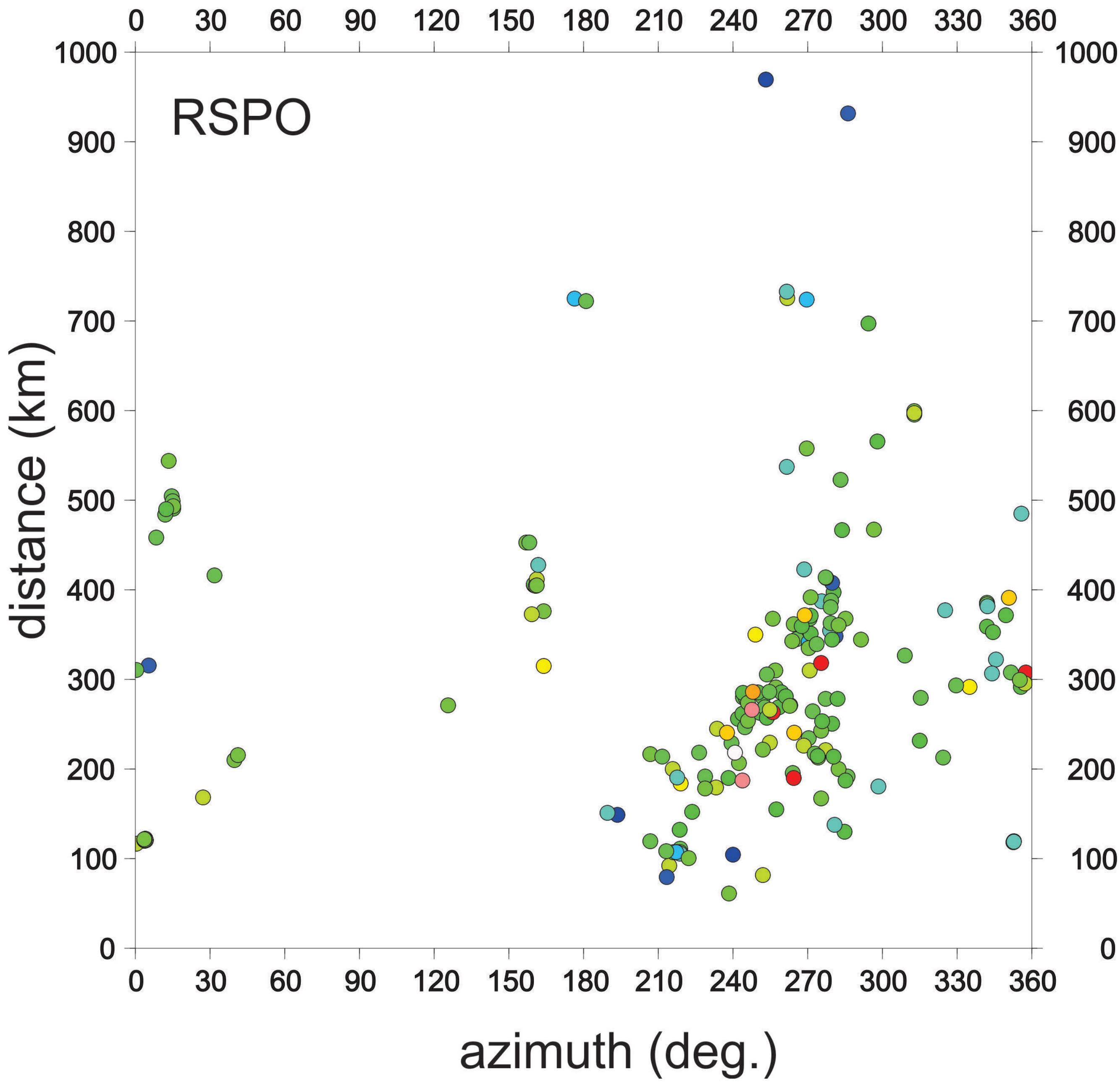


Figure 5lxxv

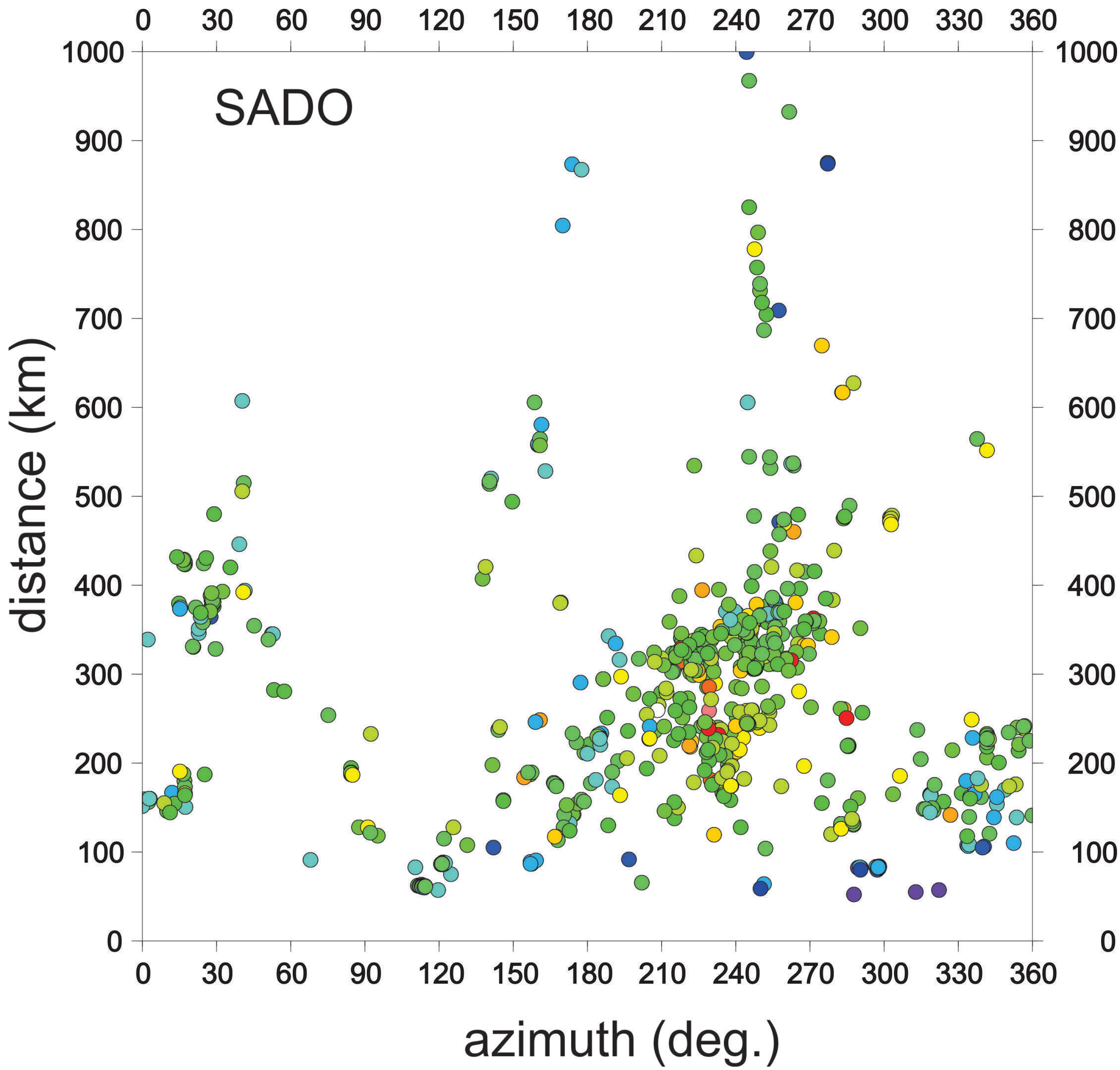


Figure 5lxxvi

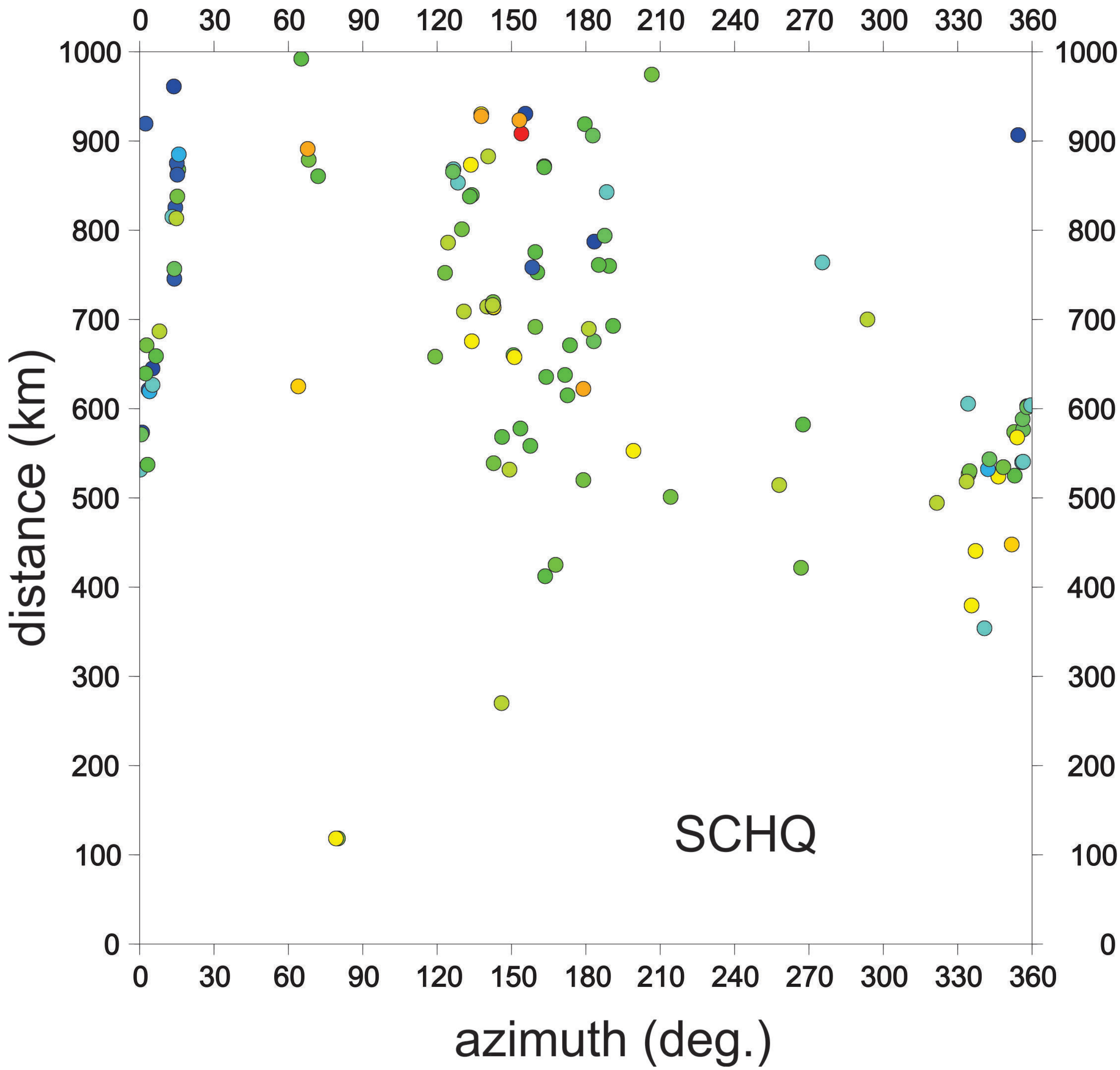


Figure 5lxxvii

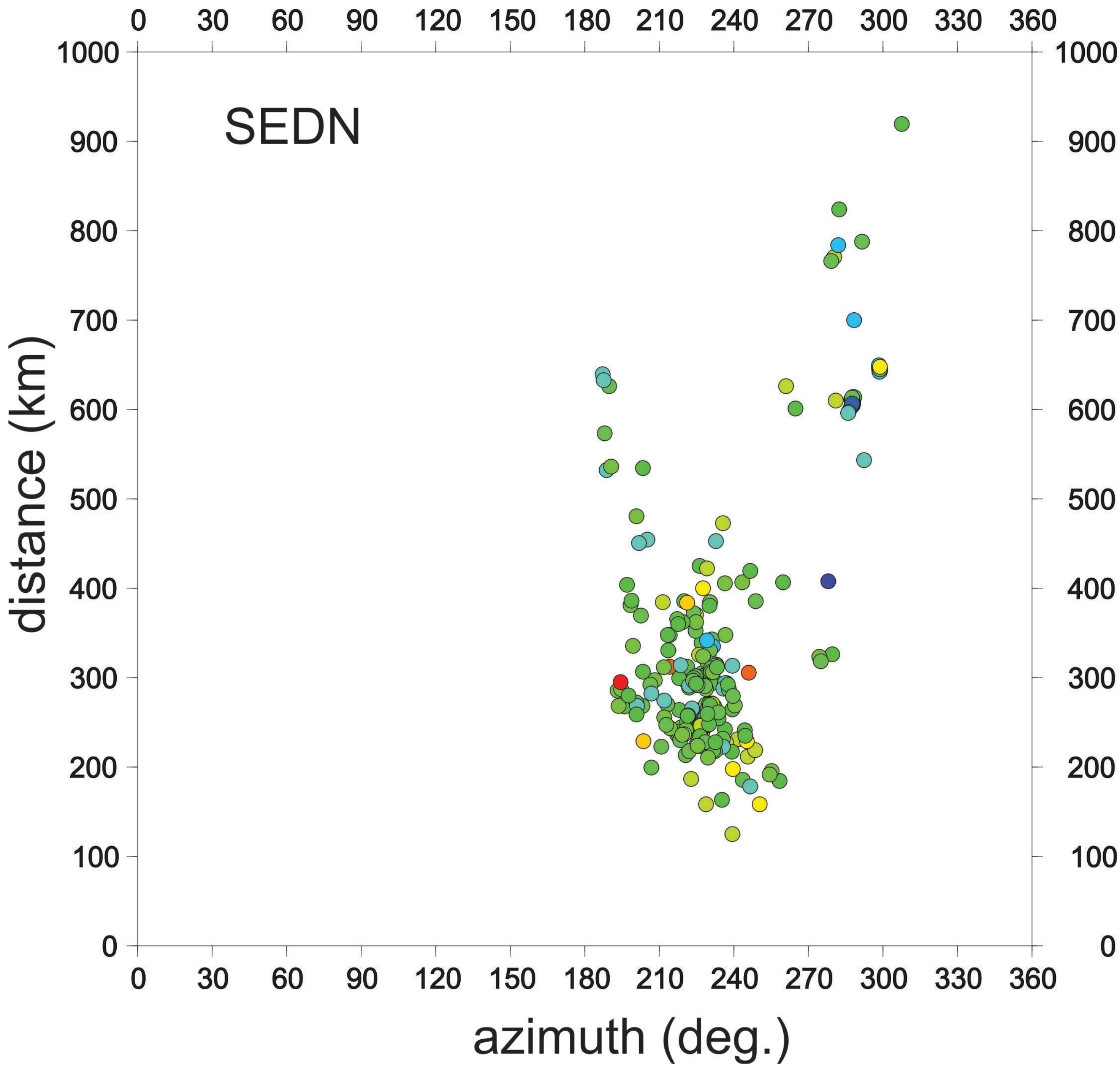


Figure 5lxxviii

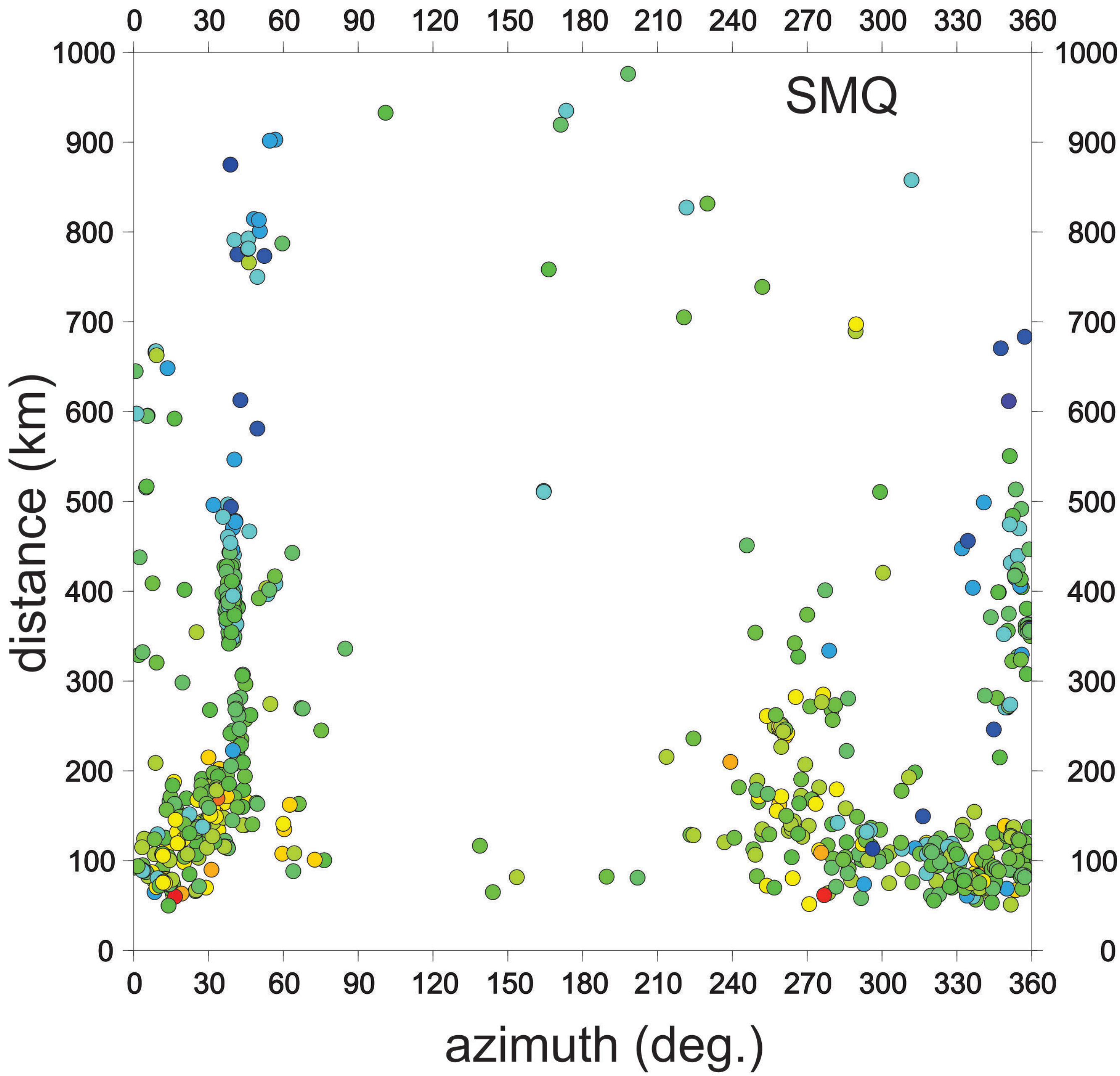


Figure 5lxxix

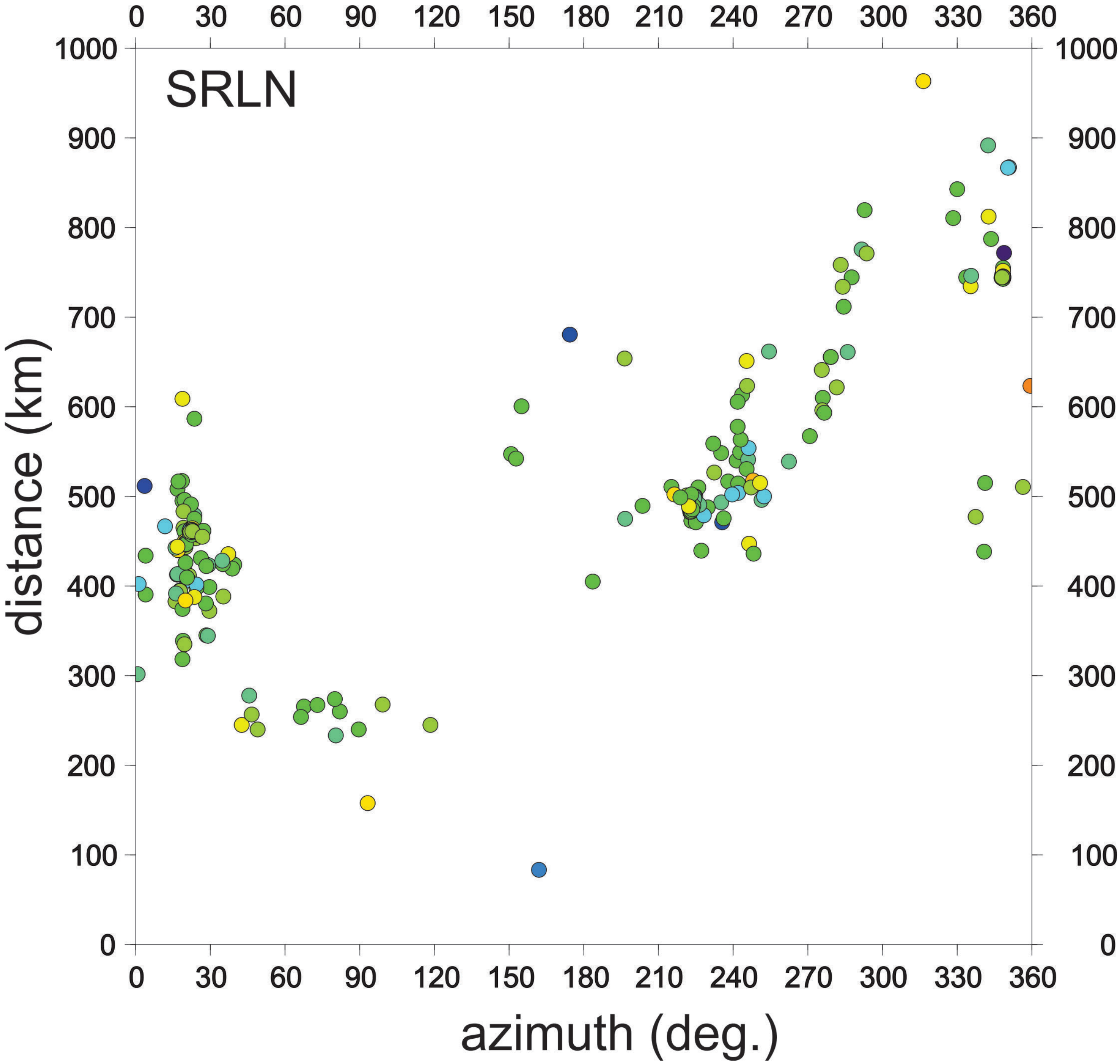


Figure 5lxxx

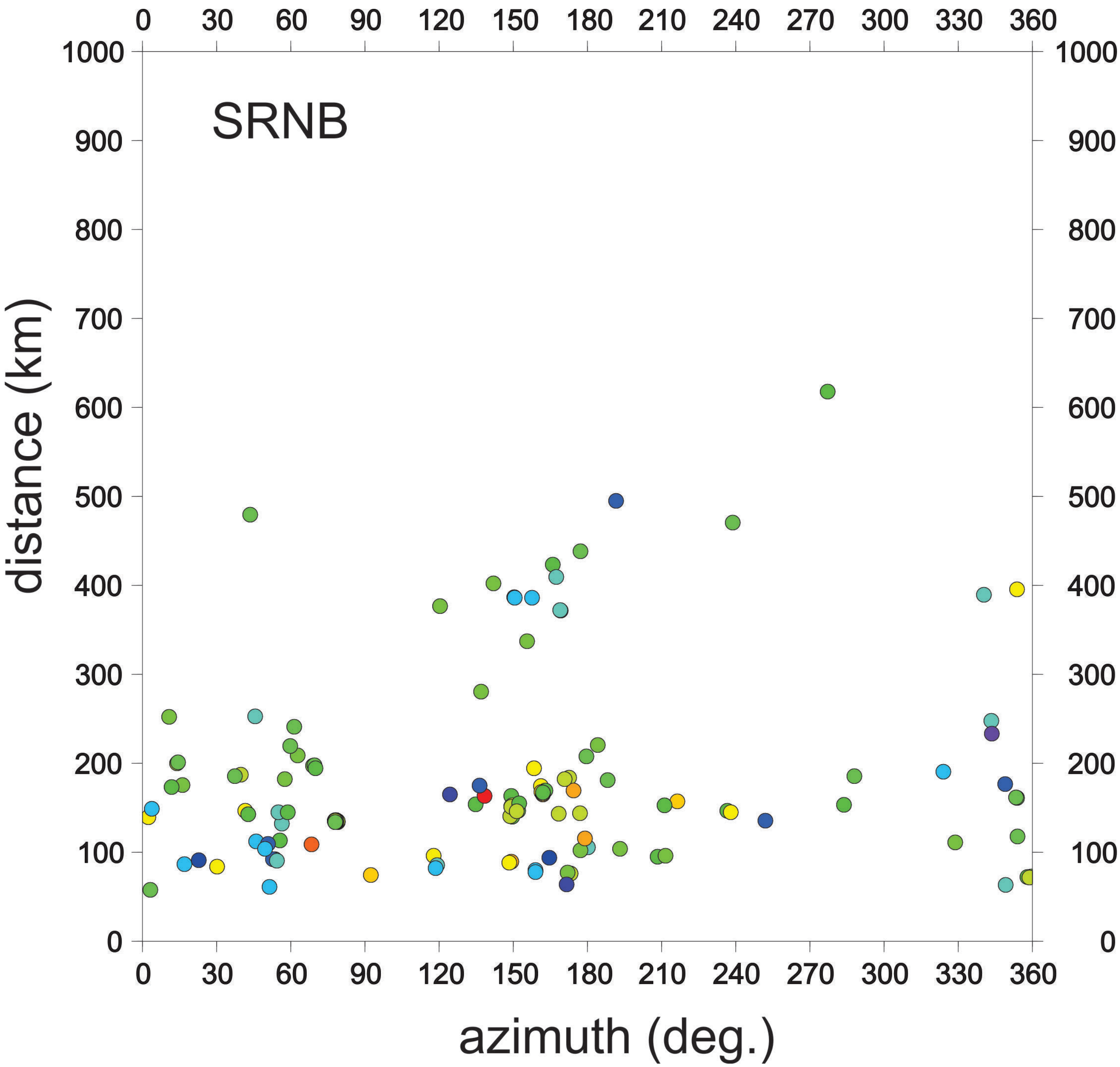


Figure 5lxxxi

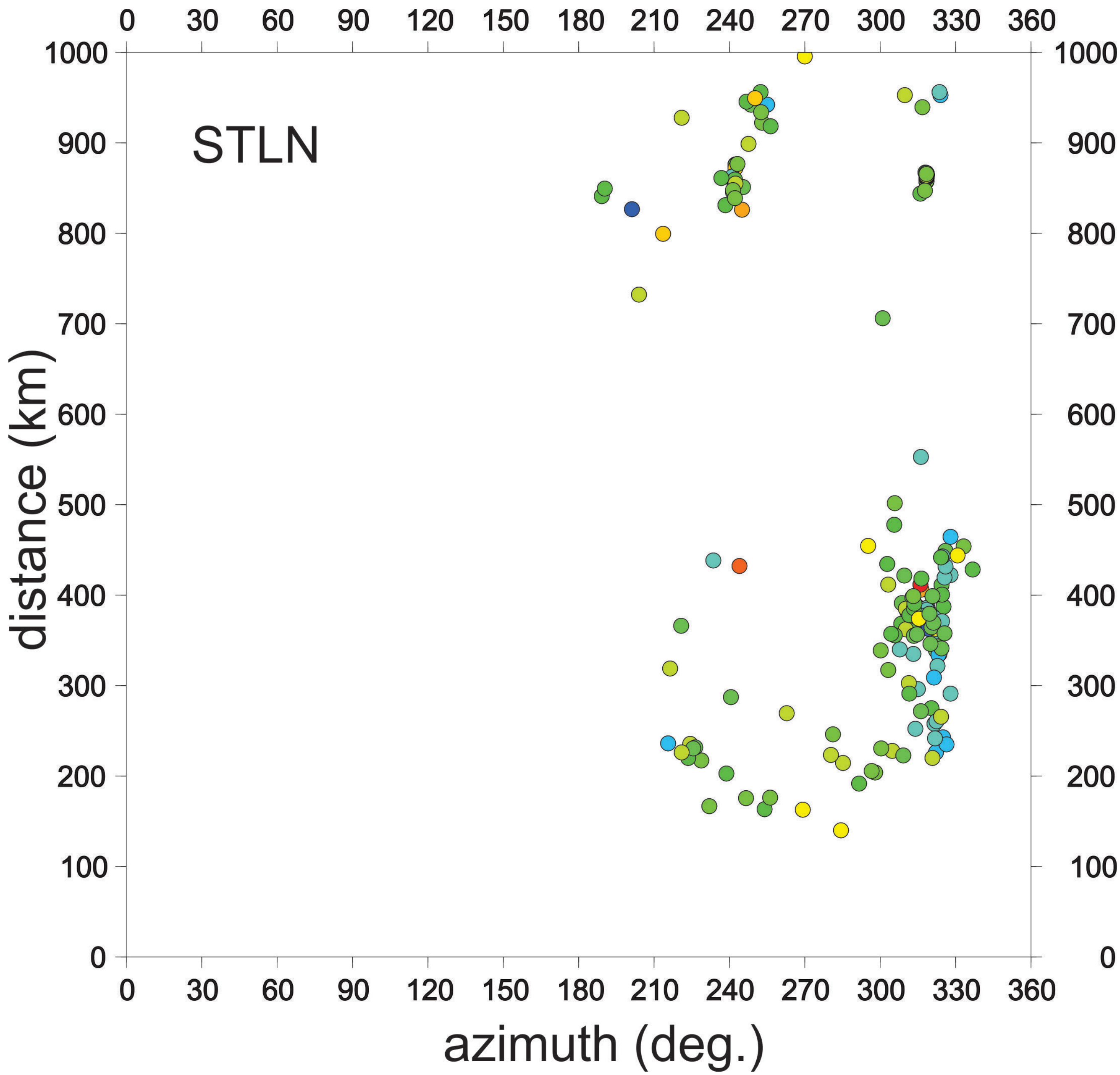


Figure 5lxxxii

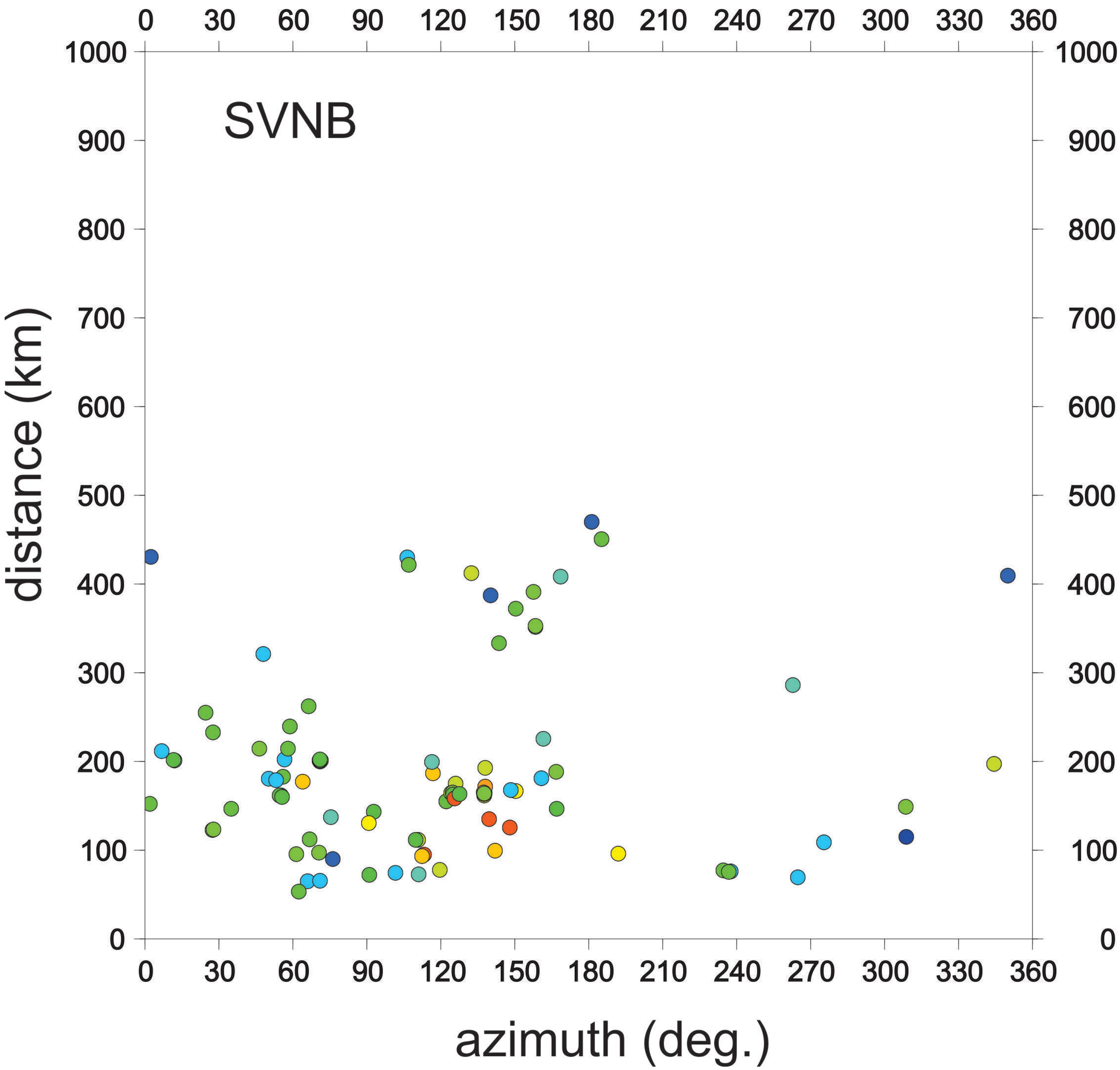


Figure 5lxxxiii

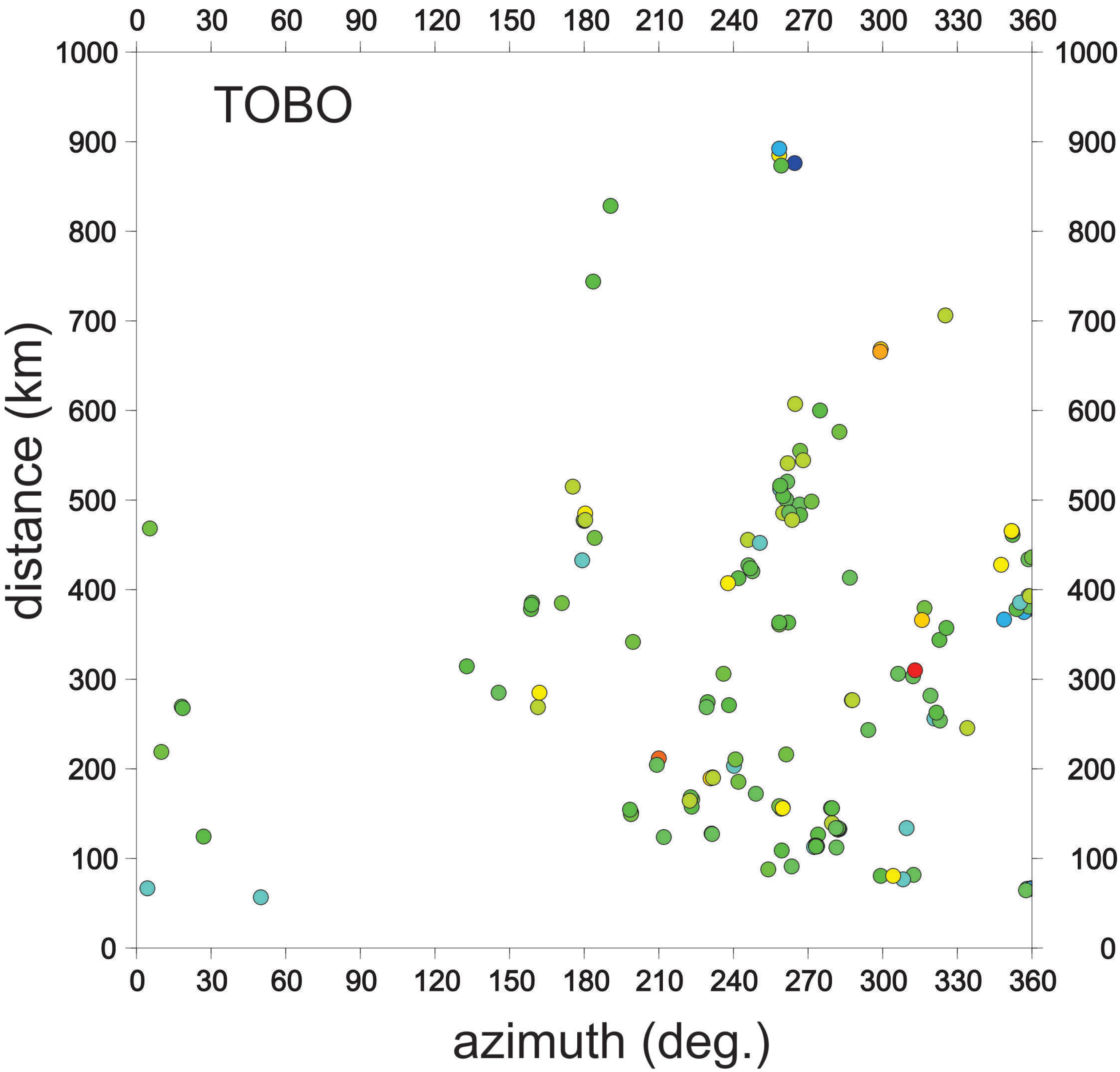


Figure 5lxxxiv

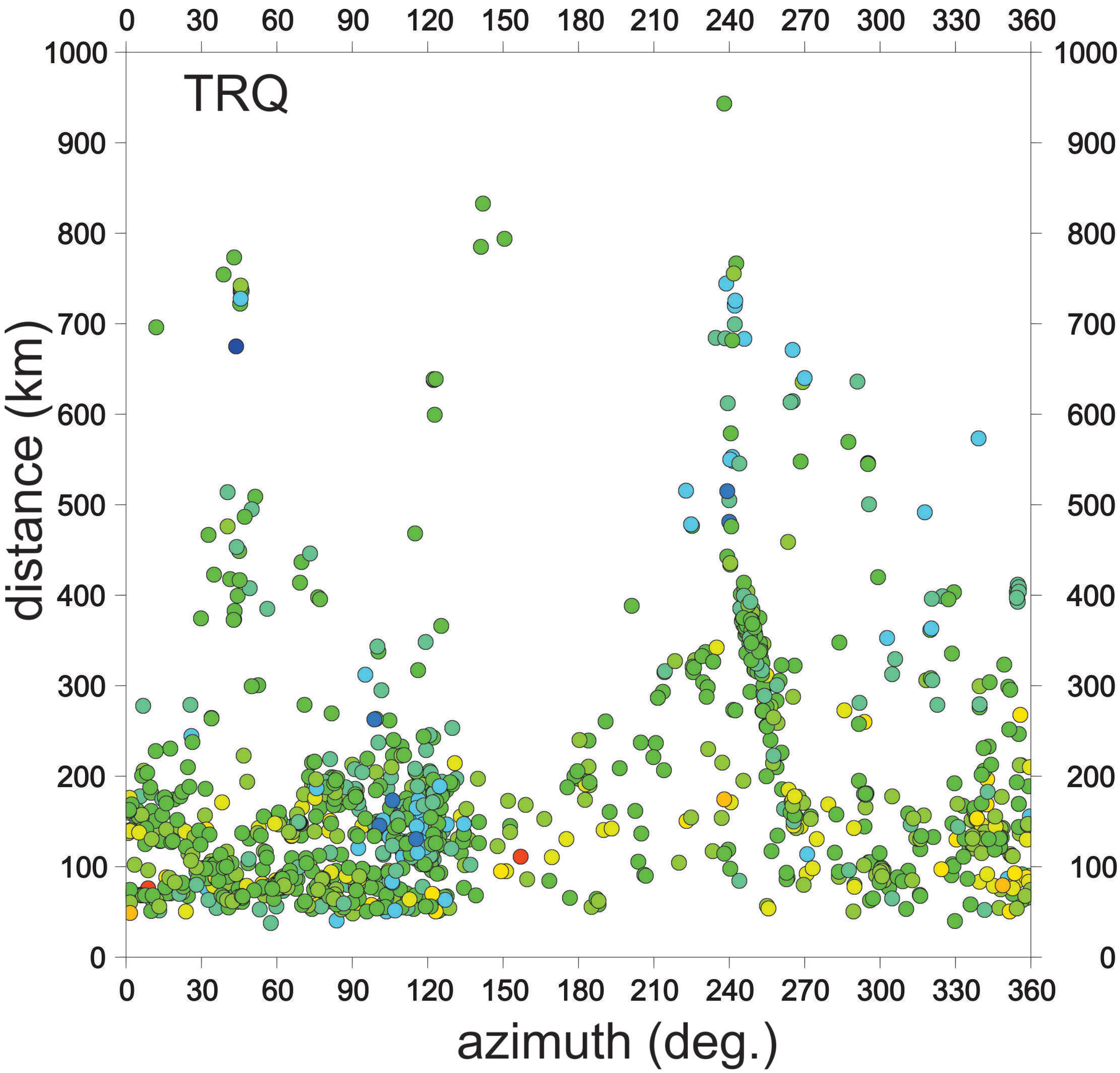


Figure 5lxxxv

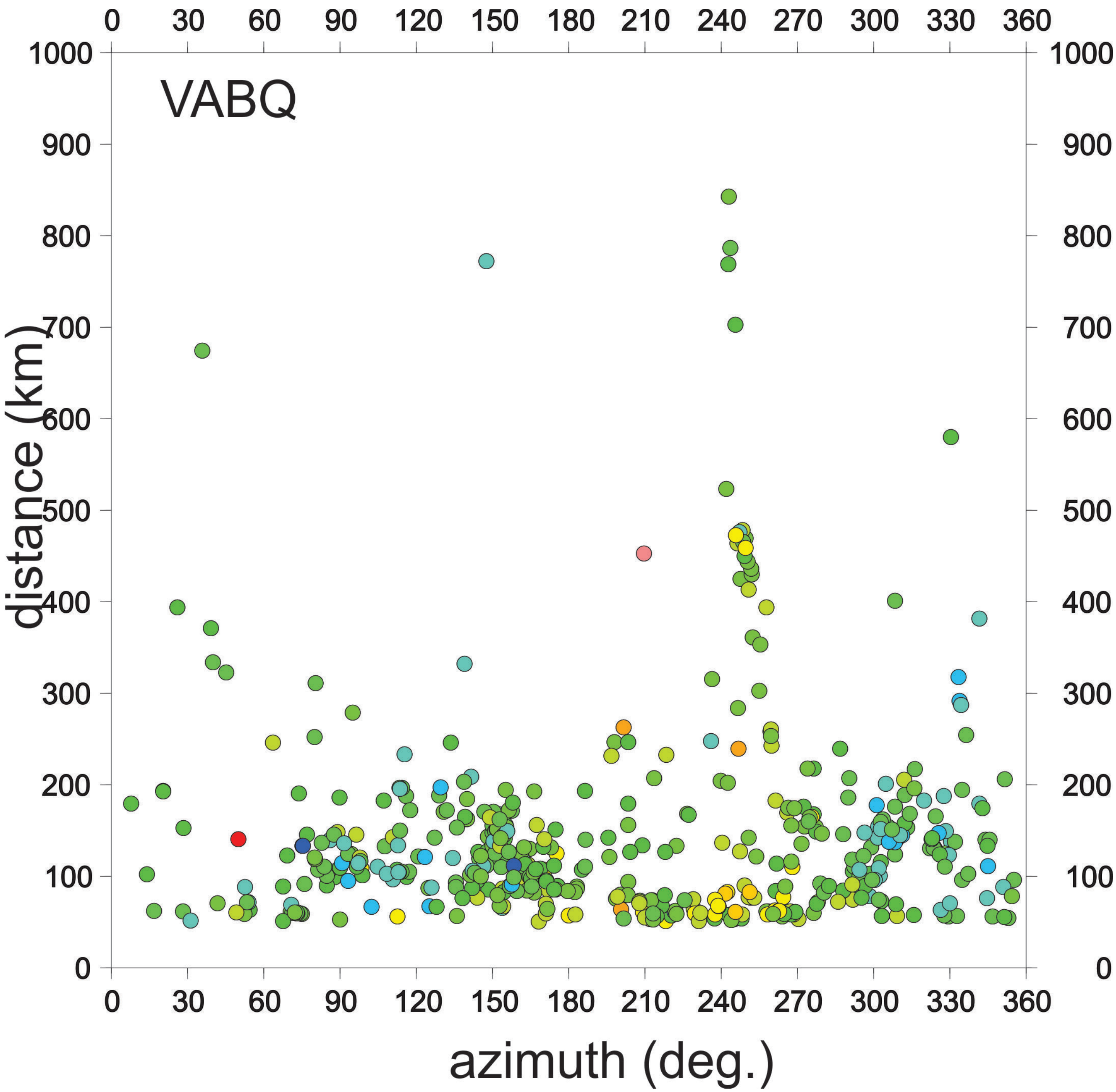


Figure 5lxxxvi

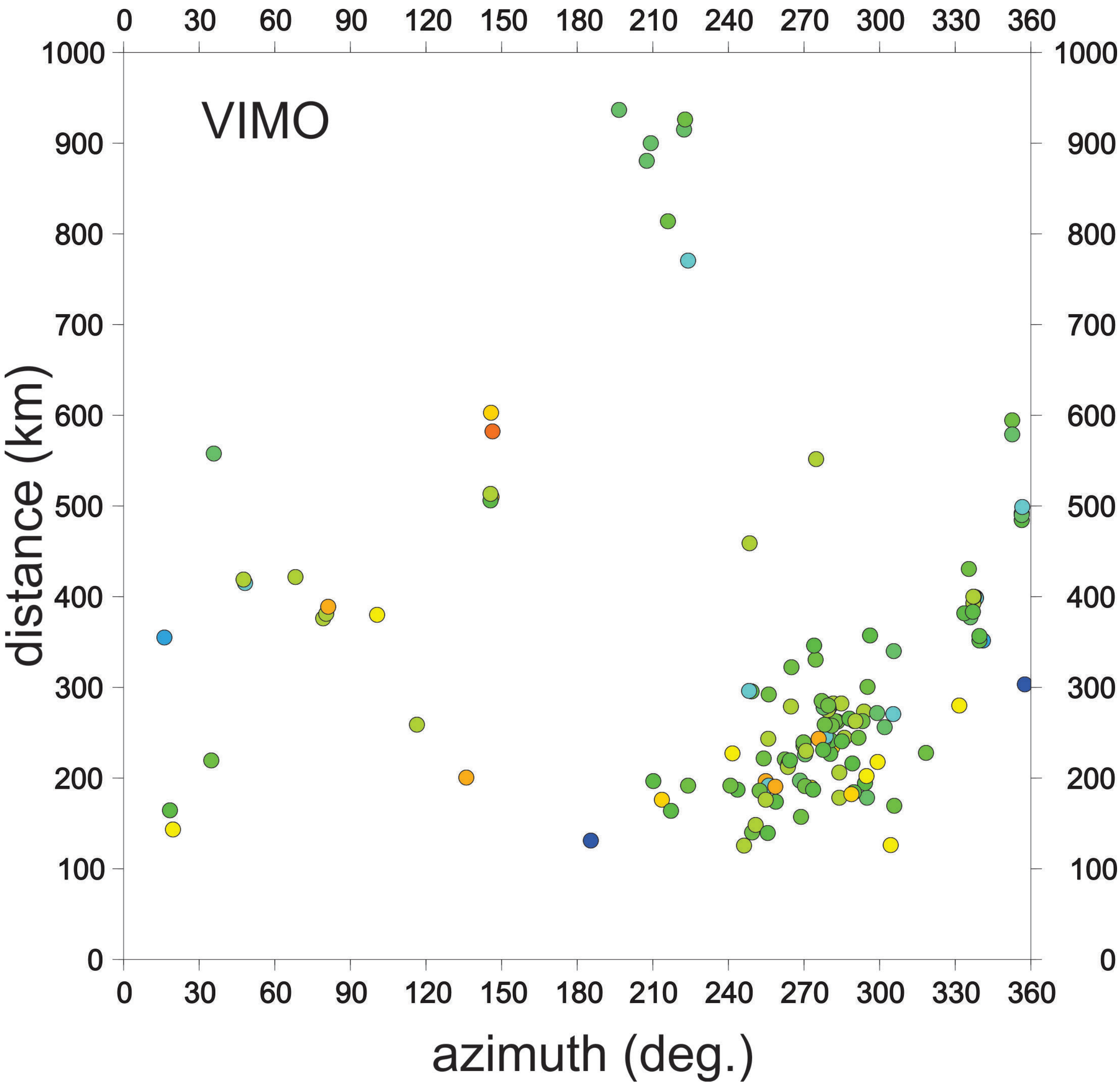


Figure 5lxxxvii

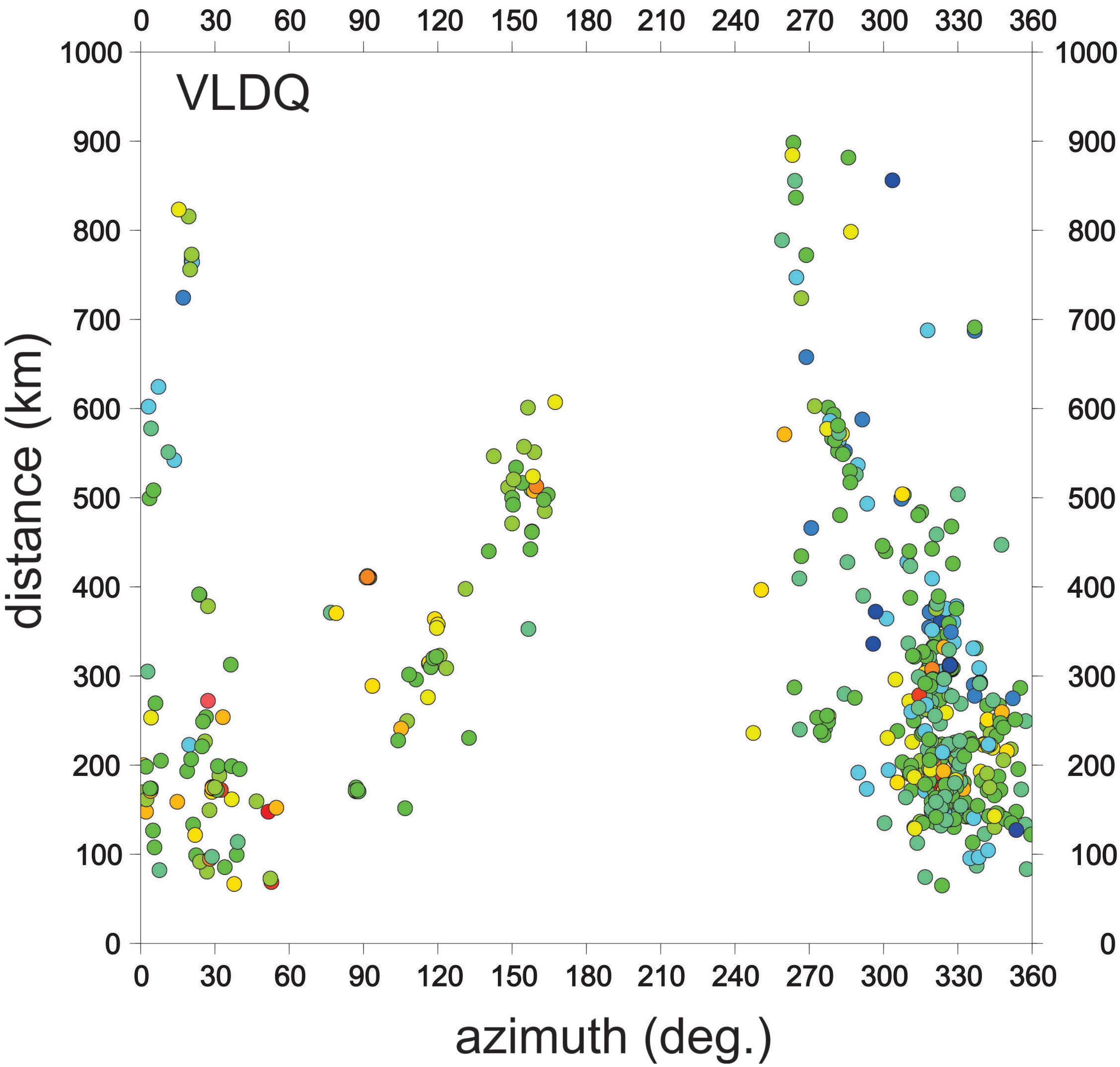


Figure 5lxxxviii

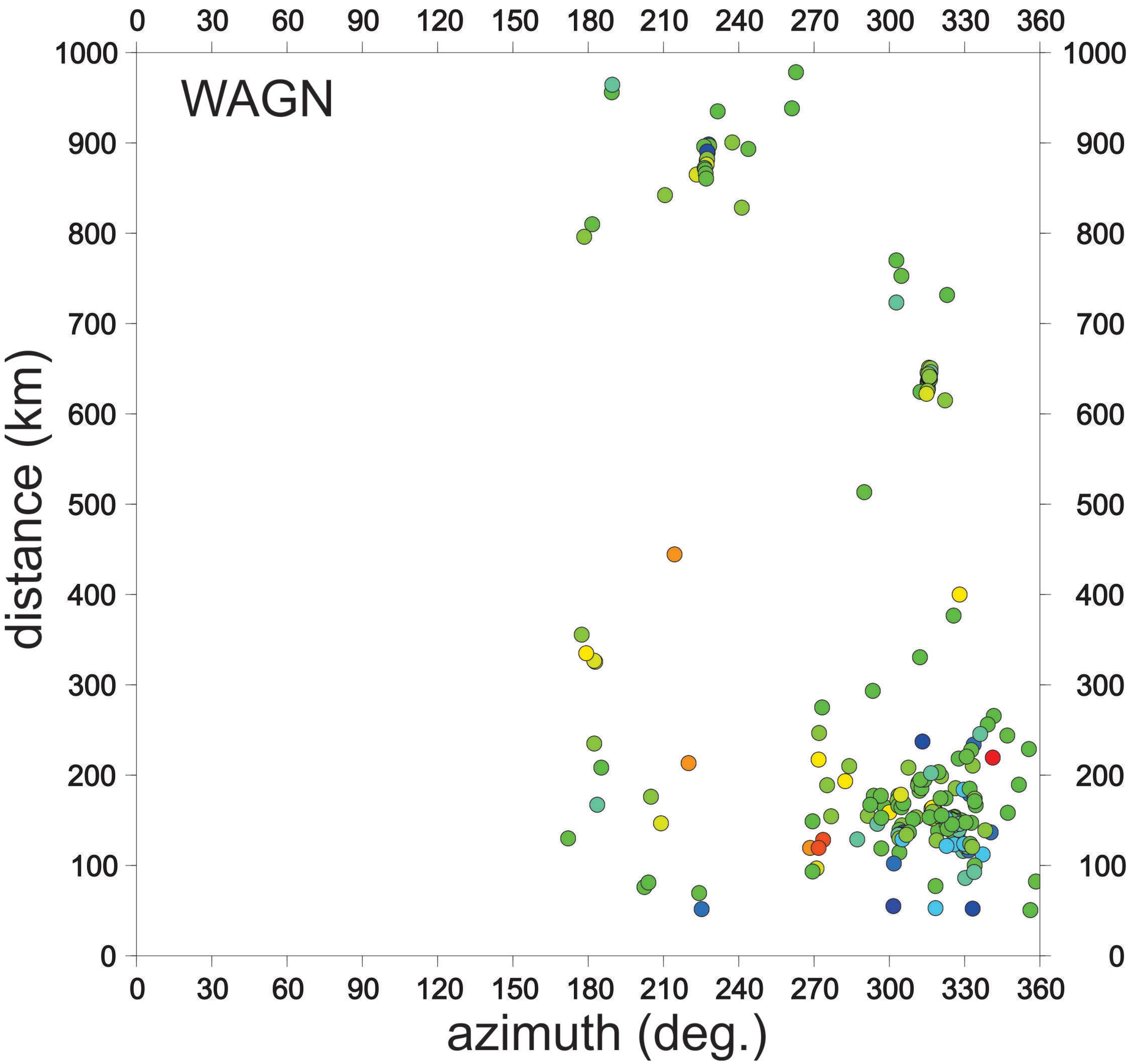
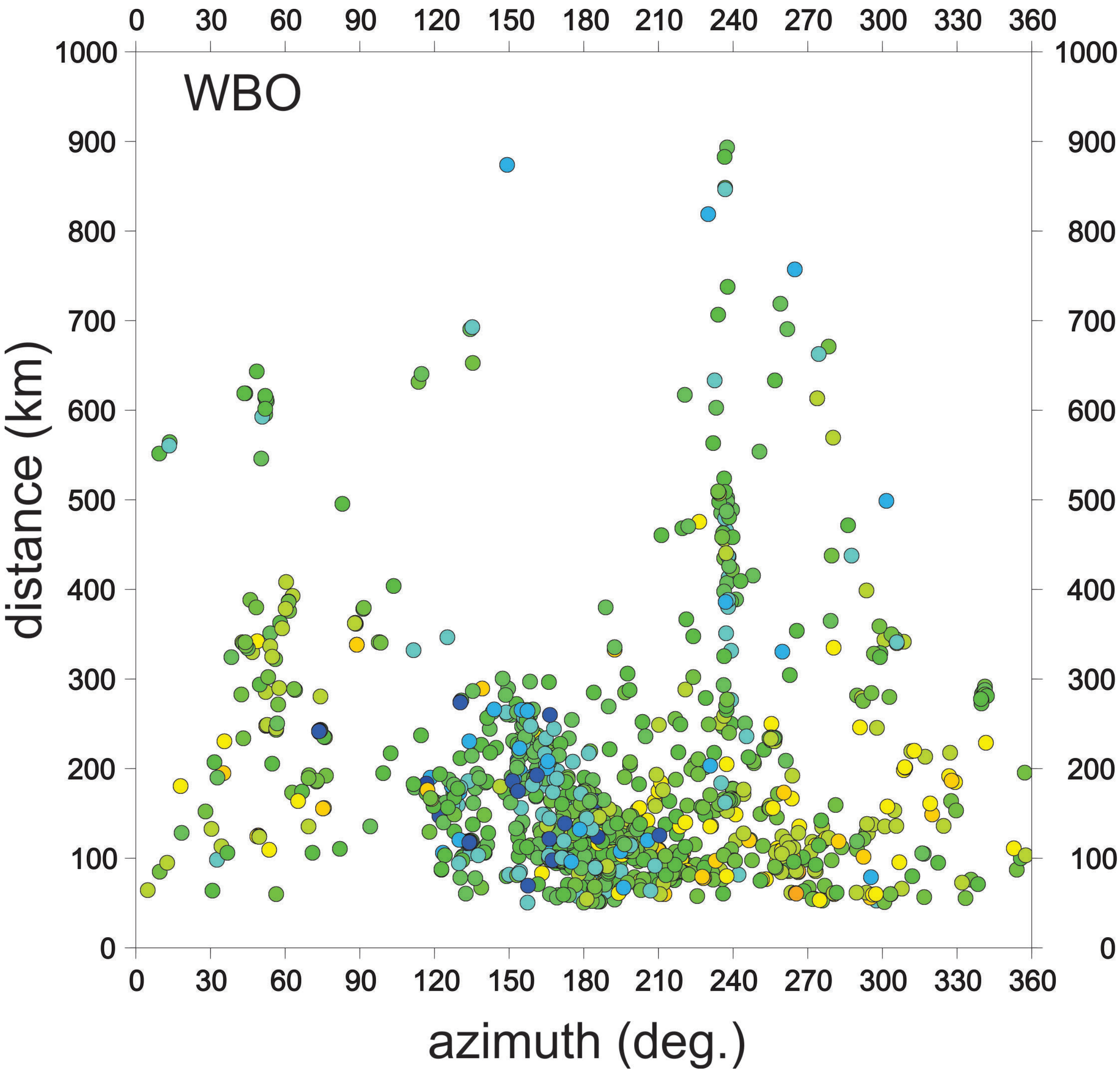


Figure 5lxxxix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azimuth (deg.)
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Figure 5xc

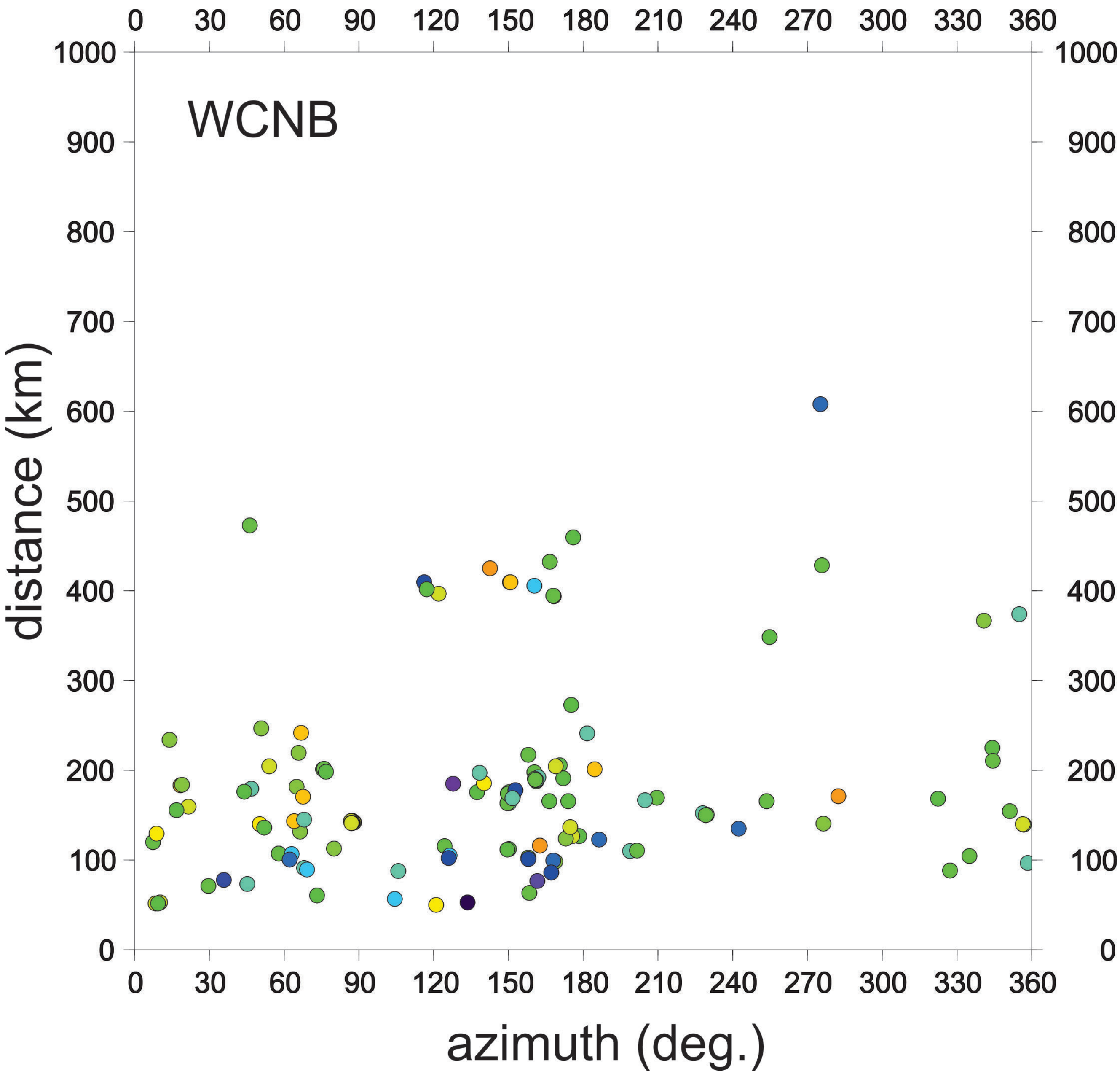
WCNB
distance (km)
azimuth (deg.)
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Figure 5xci

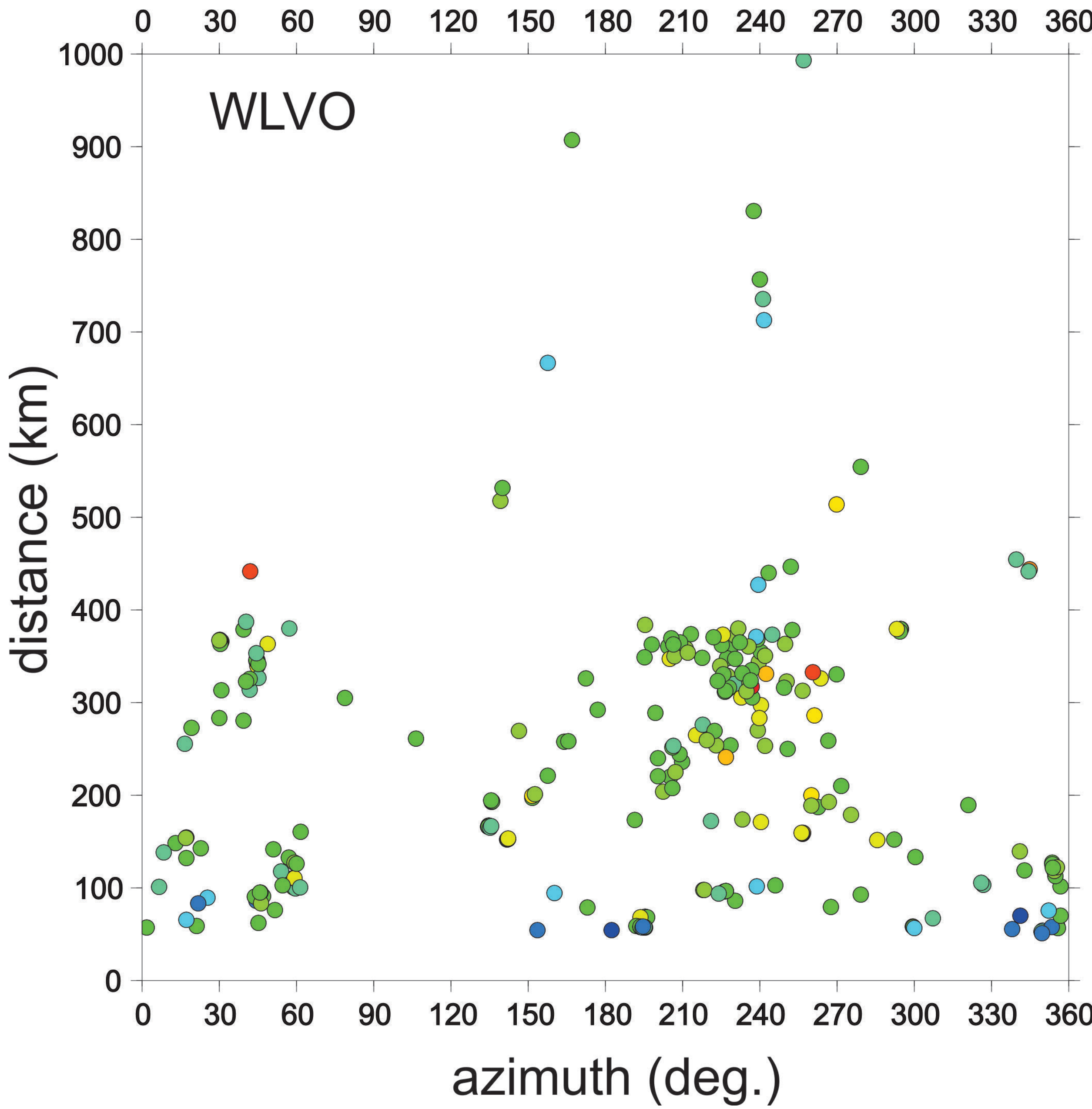


Figure 5xcii

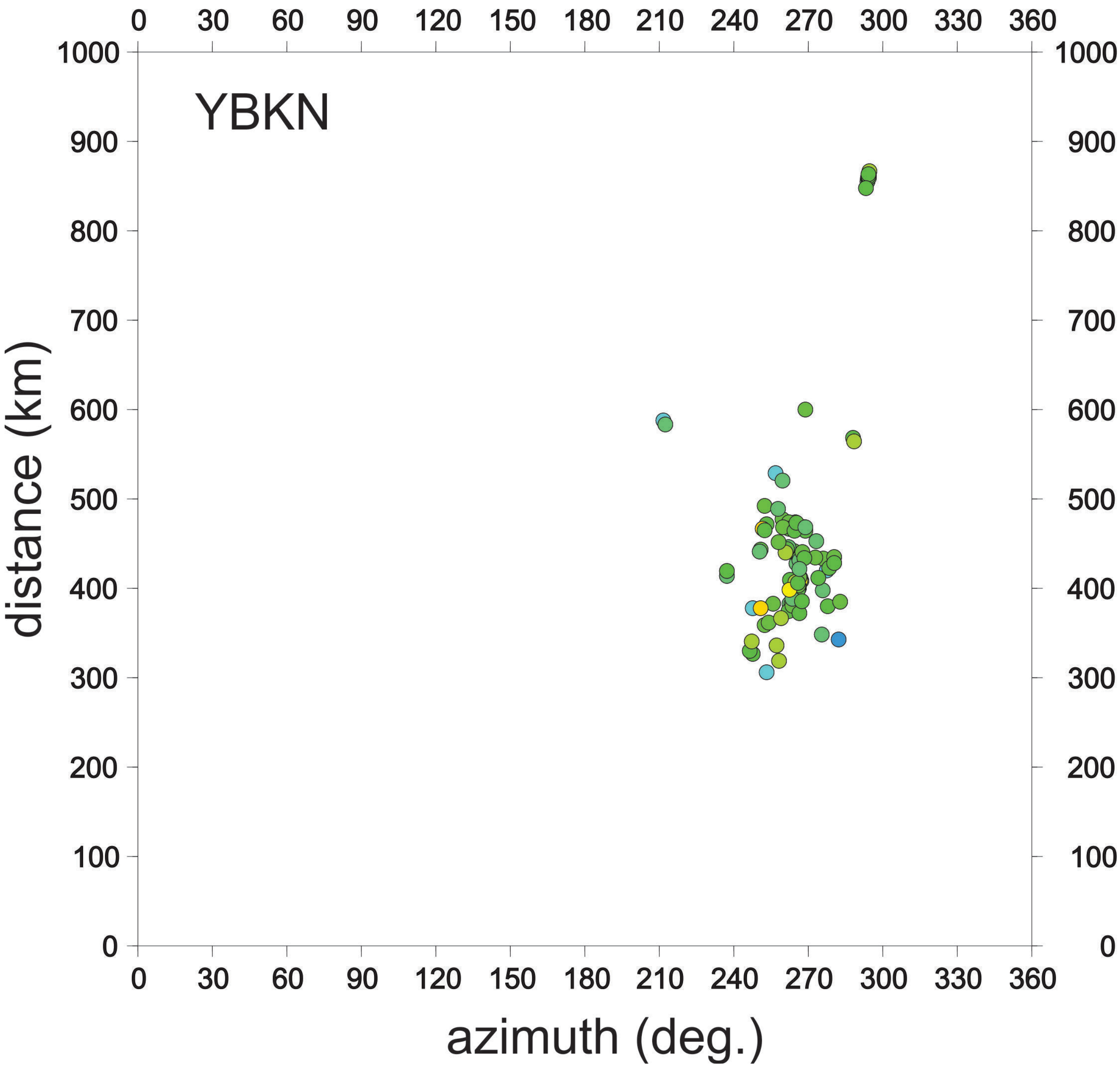


Figure 5xcii

Figure 5: Magnitude residuals after the station correction has been applied shown as a function of azimuth and epicentral distance. The color scheme is the same as in previous figures. Plots are shown for stations whose corrections are based on one hundred or more individual station magnitudes. Many points may plot at the same place. Residuals are plotted in chronological order. i) A11, ii) A16, iii) A21, iv) A54, v) A61, vi) A64, vii) ACTO, viii) AKVQ, ix) ALFO, x) ALGO, xi) AP3N, xii) ARVN, xiii) BANO, xiv) BATG, xv) BCLQ, xvi) BELQ, xvii) BMRO, xviii) BUKO, xix) BULN, xx) BWLO, xxi) CHEG, xxii) CNQ, xxiii) CRLO, xxiv) DAQ, xxv) DPQ, xxvi) EEO, xxvii) ELNB, xxviii) FRB, xxix) GAC, xxx) GGN, xxxi) GIFN, xxxii) GRQ, xxxiii) GSQ, xxxiv) GTO, xxxv) HKNB, xxxvi) ICQ, xxxvii) ILON, xxxviii) INUQ, xxxix) IVKQ, xl) JOSN, xli) KAPO, xlii) KB1O, xliii) KGNO, xliv) KILO, xlv) KLBO, xlvi) KUGN, xlvii) KUQ, xlviii) LAIN, xlix) LBNH, l) LG4Q, li) LMN, lii) LMQ, liii) MALO, liv) MATQ, lv) MEDO, lvi) MNQ, lvii) MNT-

MNTQ, lviii) MOQ, lix) MPPO, lx) MRHQ, lxi) MTHQ, lxii) NATG, lxiii) NUNN, lxiv) ORIO, lxv) OTT, lxvi) PECO, lxvii) PEMO, lxviii) PKME, lxix) PKRO, lxx) PLIO, lxxi) PLVO, lxxii) QCQ, lxxiii) QILN, lxxiv) RES, lxxv) RSPO, lxxvi) SADO, lxxvii) SCHQ, lxxviii) SEDN, lxxix) SMQ, lxxx) SRLN, lxxxi) SRNB, lxxxii) STLN, lxxxiii) SVNB, lxxxiv) TOBO, lxxxv) TRQ, lxxxvi) VABQ, lxxxvii) VIMO, lxxxviii) VLDQ, lxxxix) WAGN, xc) WBO, xci) WCNB, xcii) WLVO, xciiii) YBKN

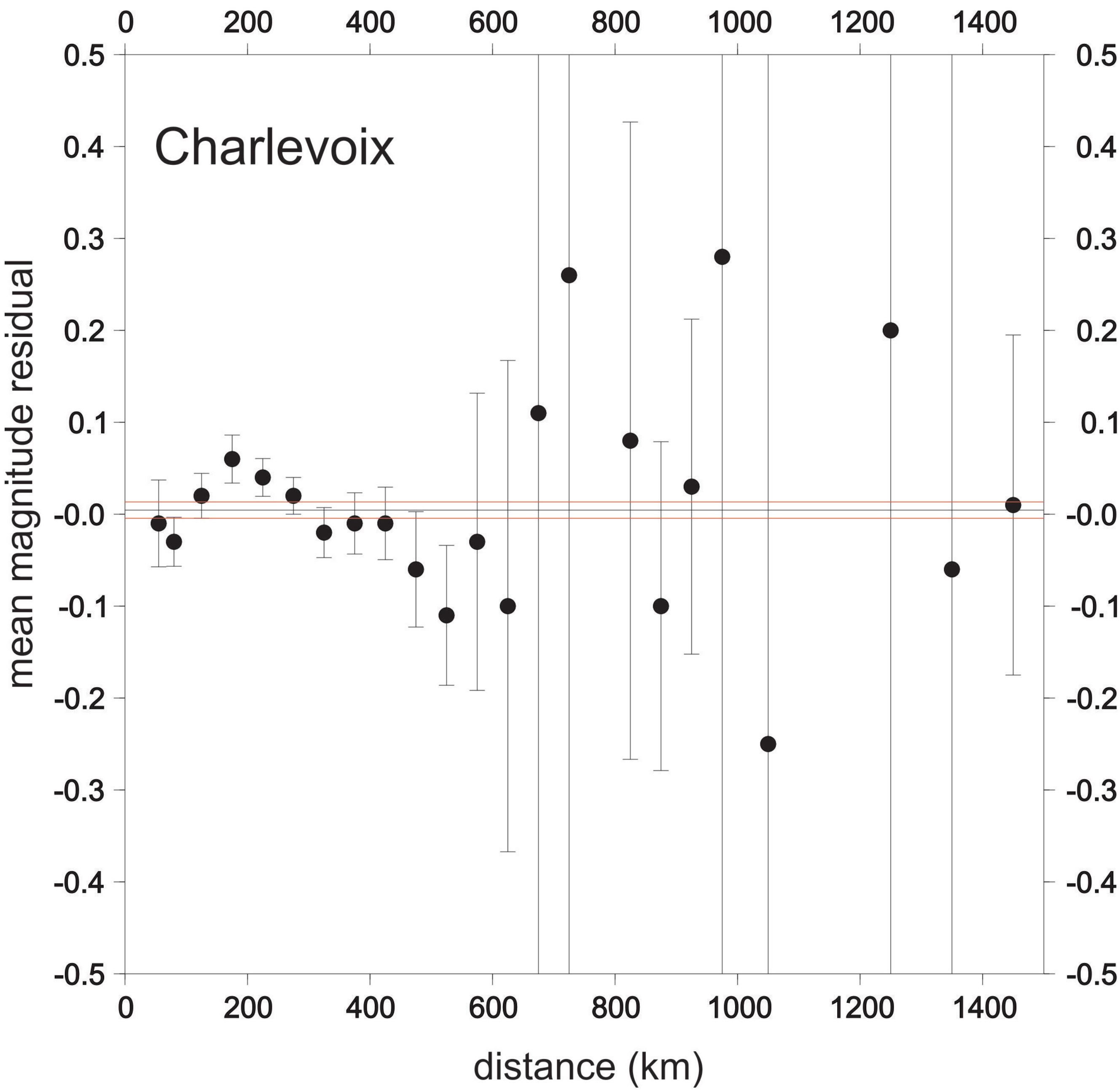
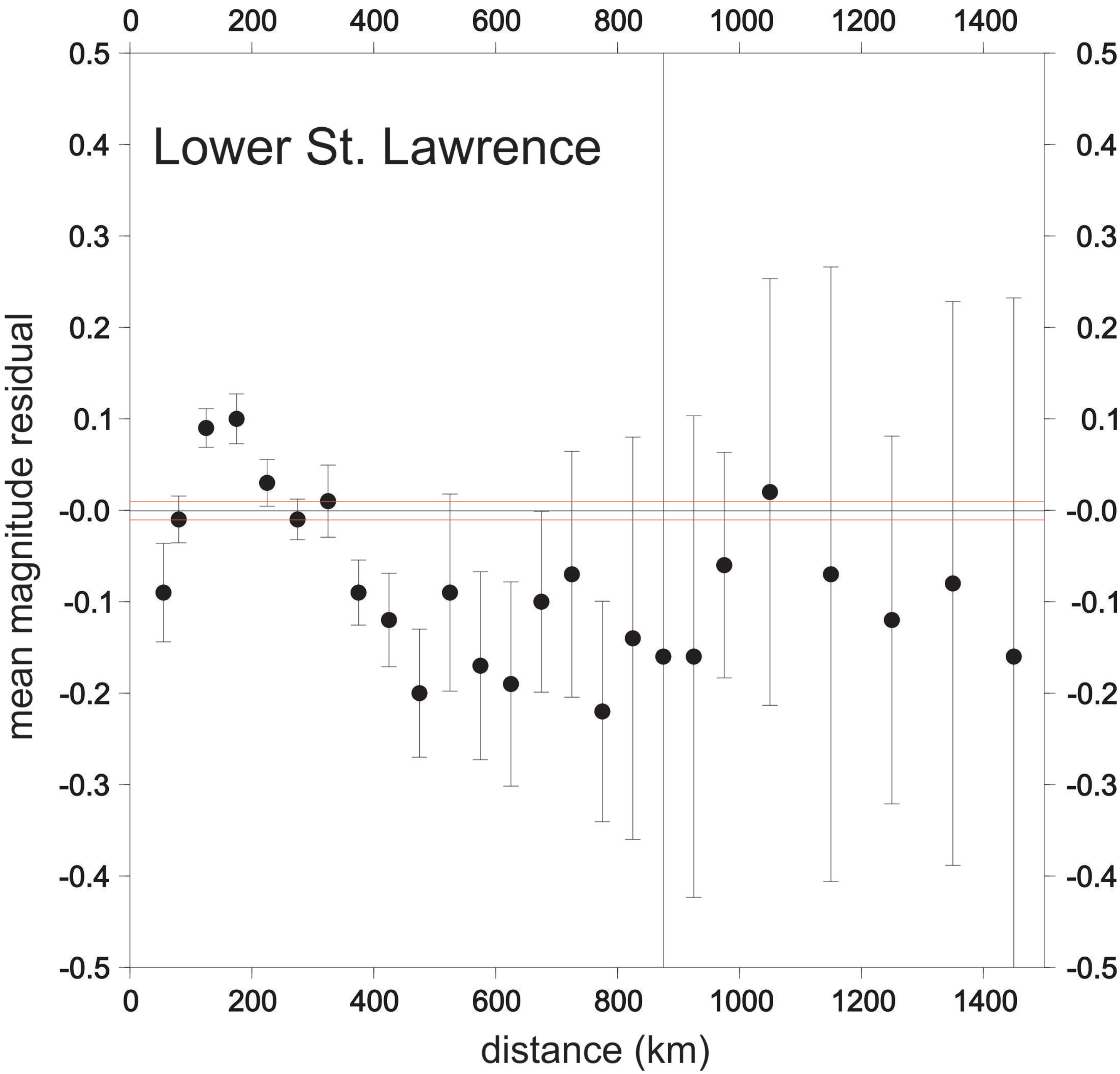

Charlevoix
mean magnitude residual
distance (km)
0
200
400
600
800
1000
1200
1400
0.5
0.4
0.3
0.2
0.1
-0.0
-0.1
-0.2
-0.3
-0.4
-0.5

Figure 6a


Lower St. Lawrence
mean magnitude residual
distance (km)
0
200
400
600
800
1000
1200
1400
0.5
0.4
0.3
0.2
0.1
-0.0
-0.1
-0.2
-0.3
-0.4
-0.5
Figure 6b

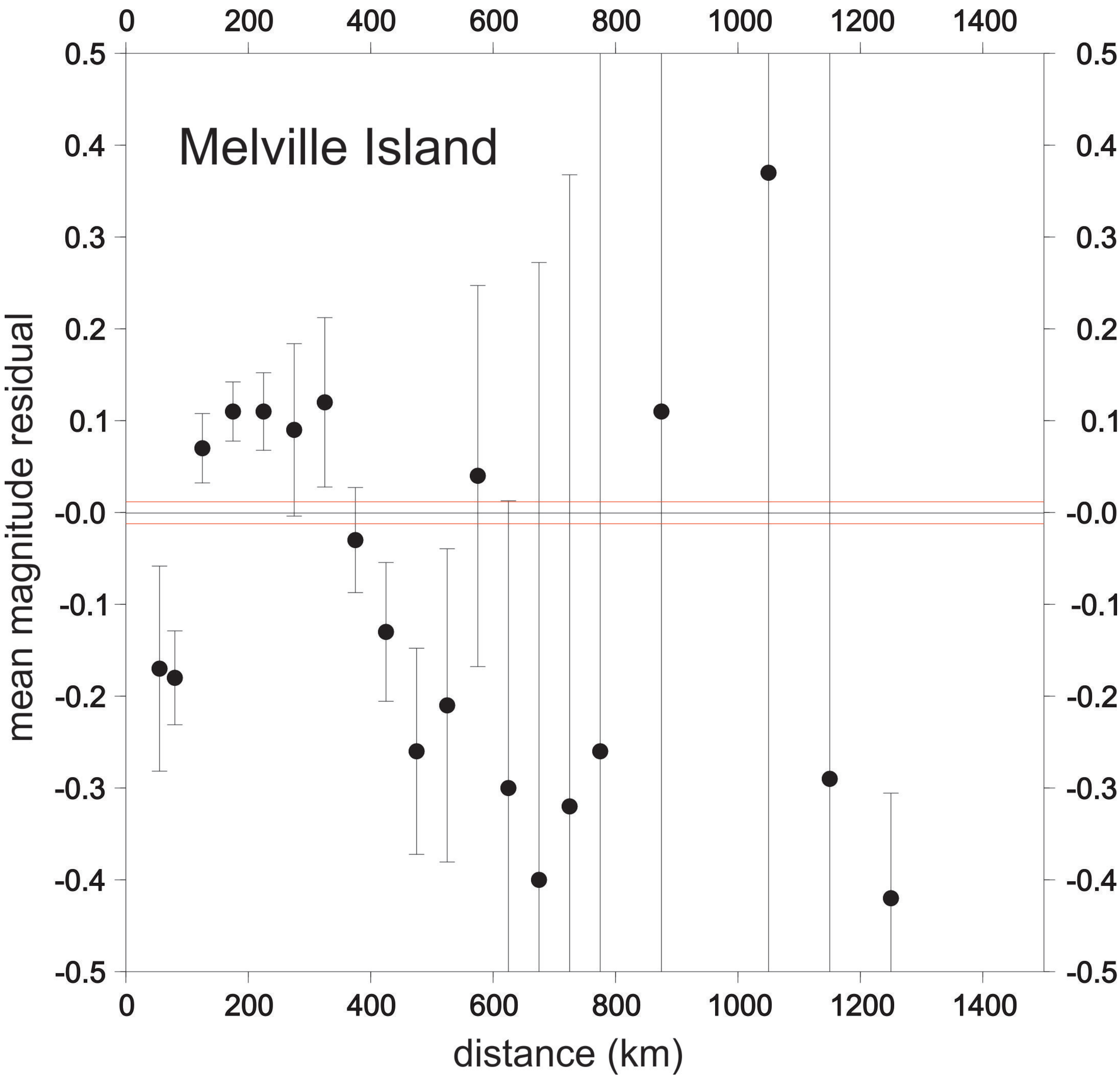
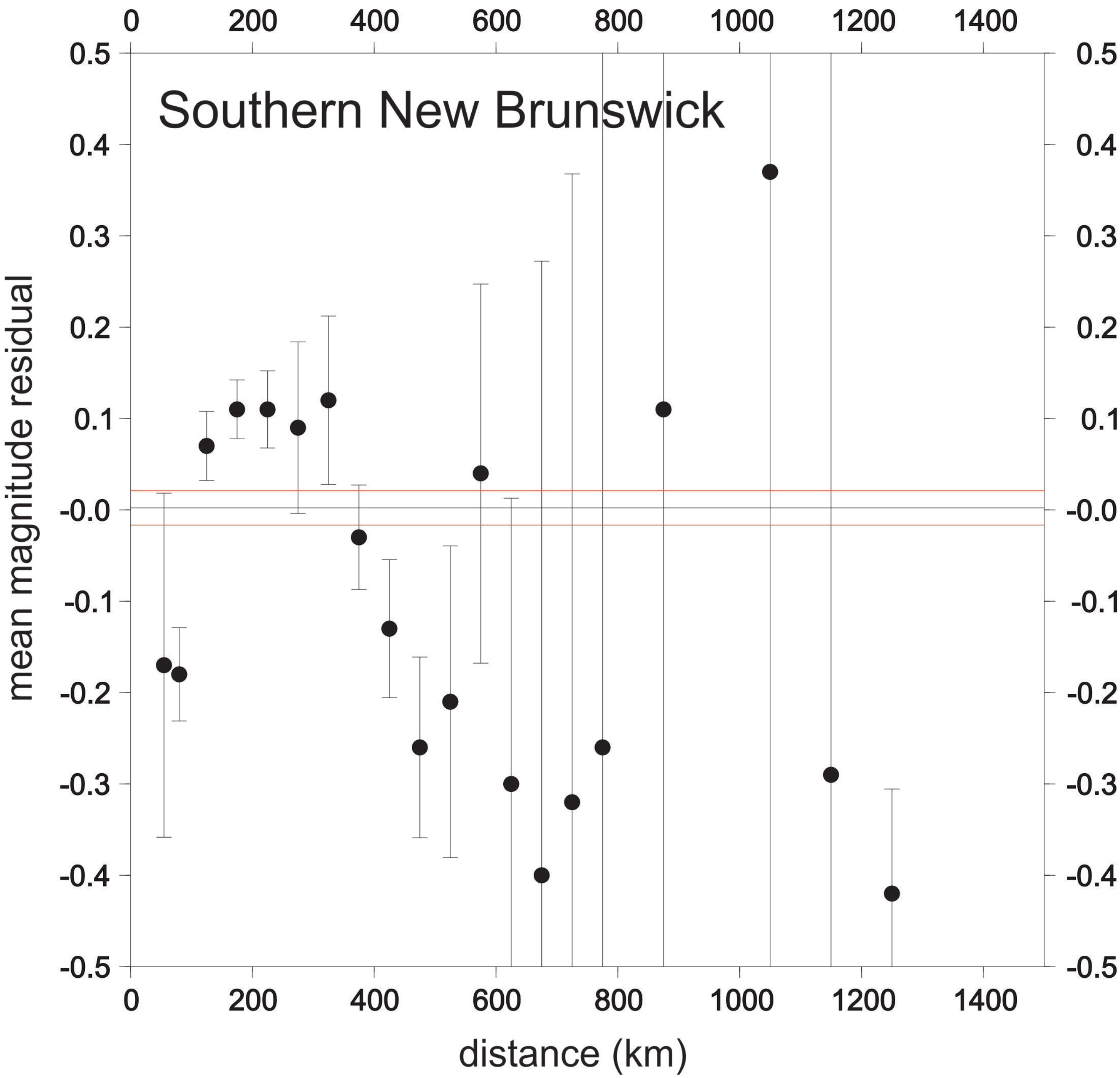

Melville Island
mean magnitude residual
distance (km)
0
200
400
600
800
1000
1200
1400
0.5
0.4
0.3
0.2
0.1
-0.0
-0.1
-0.2
-0.3
-0.4
-0.5

Figure 6c



Southern New Brunswick
mean magnitude residual
distance (km)
0
200
400
600
800
1000
1200
1400
0.5
0.4
0.3
0.2
0.1
-0.0
-0.1
-0.2
-0.3
-0.4
-0.5

Figure 6d

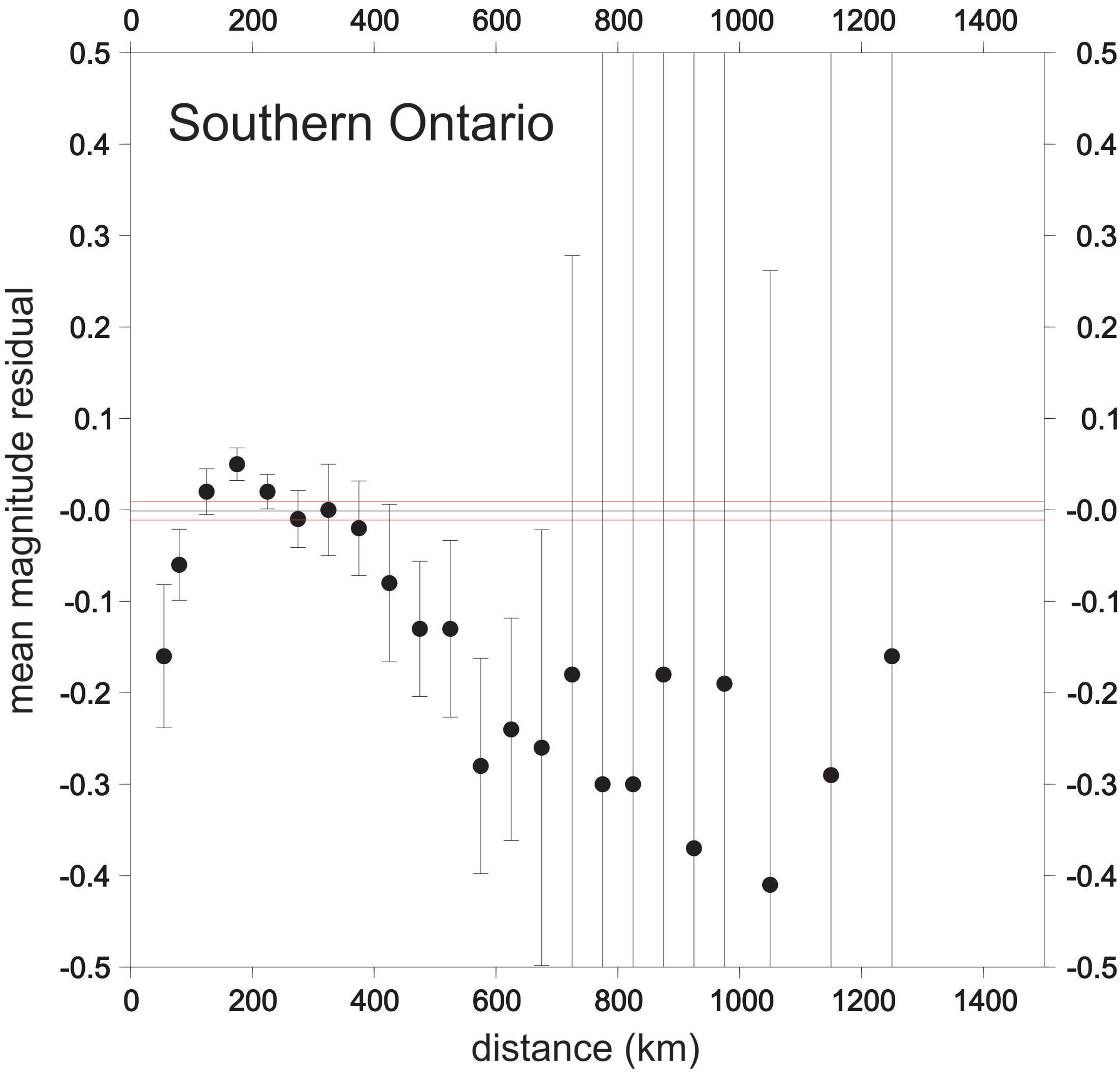

Southern Ontario
mean magnitude residual
distance (km)
0
200
400
600
800
1000
1200
1400
0.5
0.4
0.3
0.2
0.1
-0.0
-0.1
-0.2
-0.3
-0.4
-0.5

Figure 6e

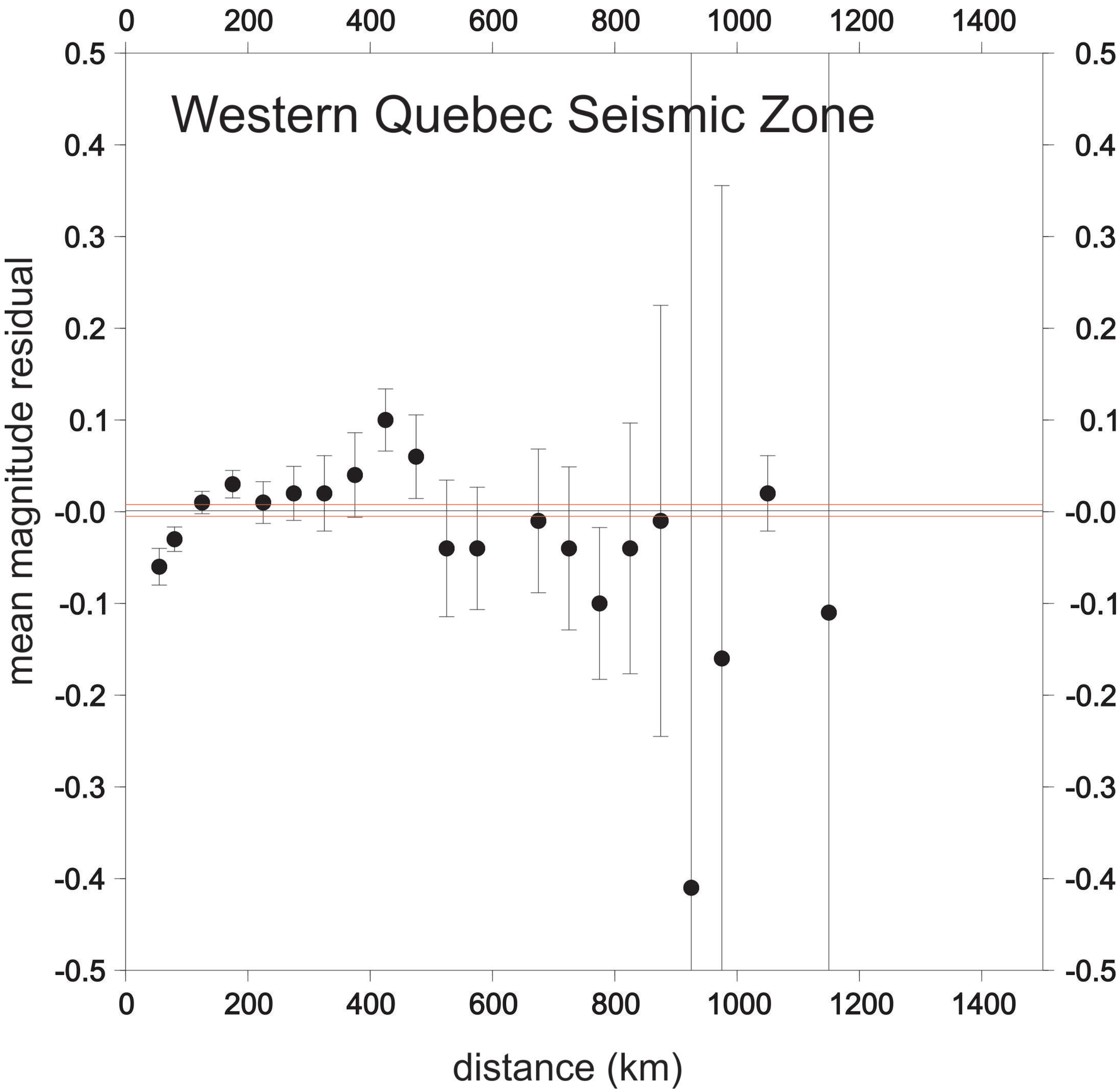


Figure 6f

Figure 6. Mean magnitude residuals for selected regional groups of stations for distance windows as discussed in the text. The points are plotted at the midpoint of the window. The stations for each group are discussed in the text. Error bars show the 99% confidence intervals. The black and red horizontal lines show the mean and 99% confidence values for the region, respectively. a) Charlevoix, b) Lower St. Lawrence, c) Melville Island, d) southern New Brunswick, e) southern Ontario and f) Western Quebec Seismic Zone.

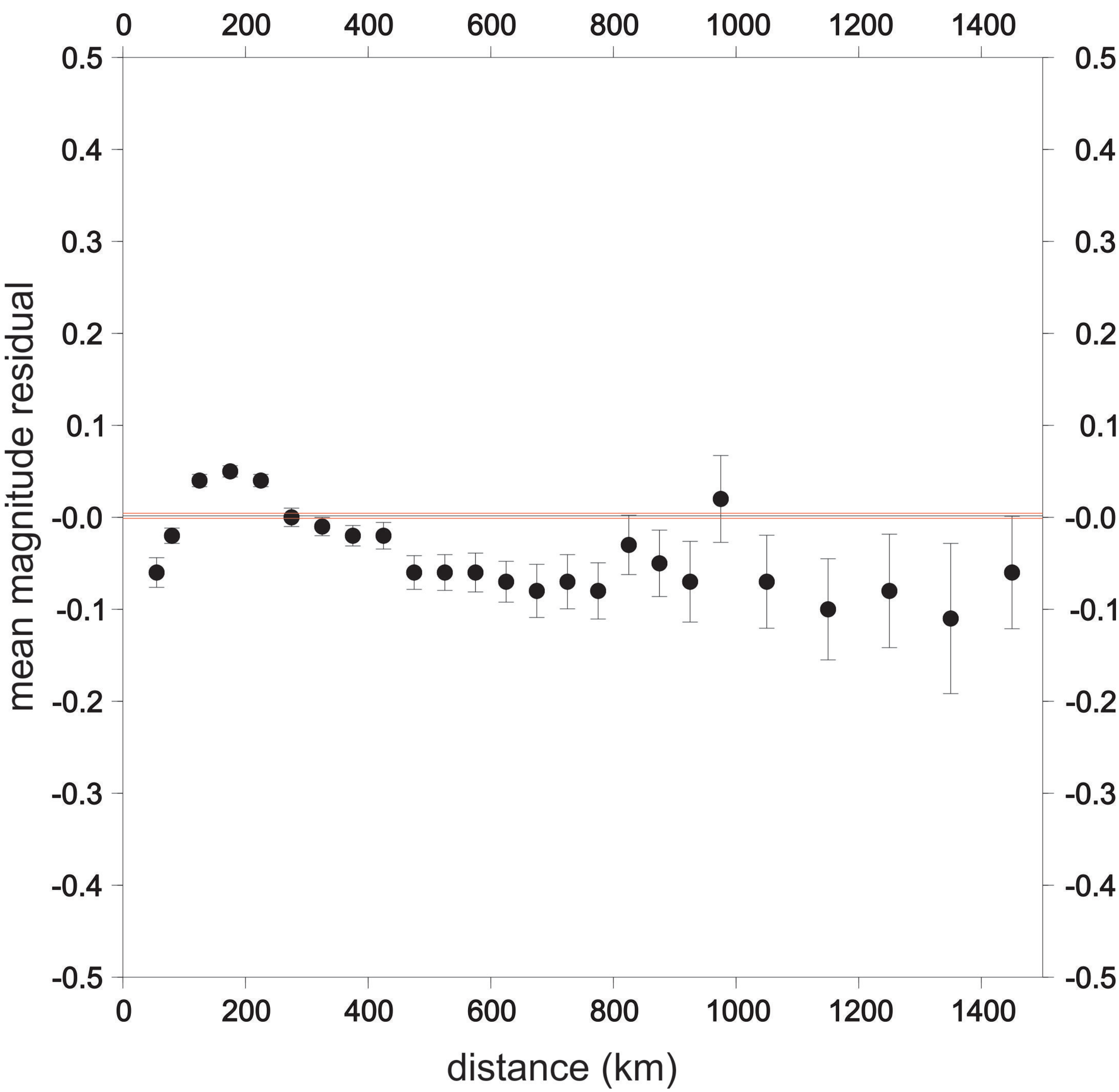


Figure 7: Magnitude residuals from stations averaged by distance. Points are plotted at the center of the window used. Windows are 50-60km, 60-100 km, then in 50 km increments to 1000 km and 100 km increments from 1000-1500 km. Error bars represent 99% confidence intervals. The black and red horizontal lines represent the mean and 99% confidence intervals, respectively, for all stations for which there were one hundred or more individual magnitude values.

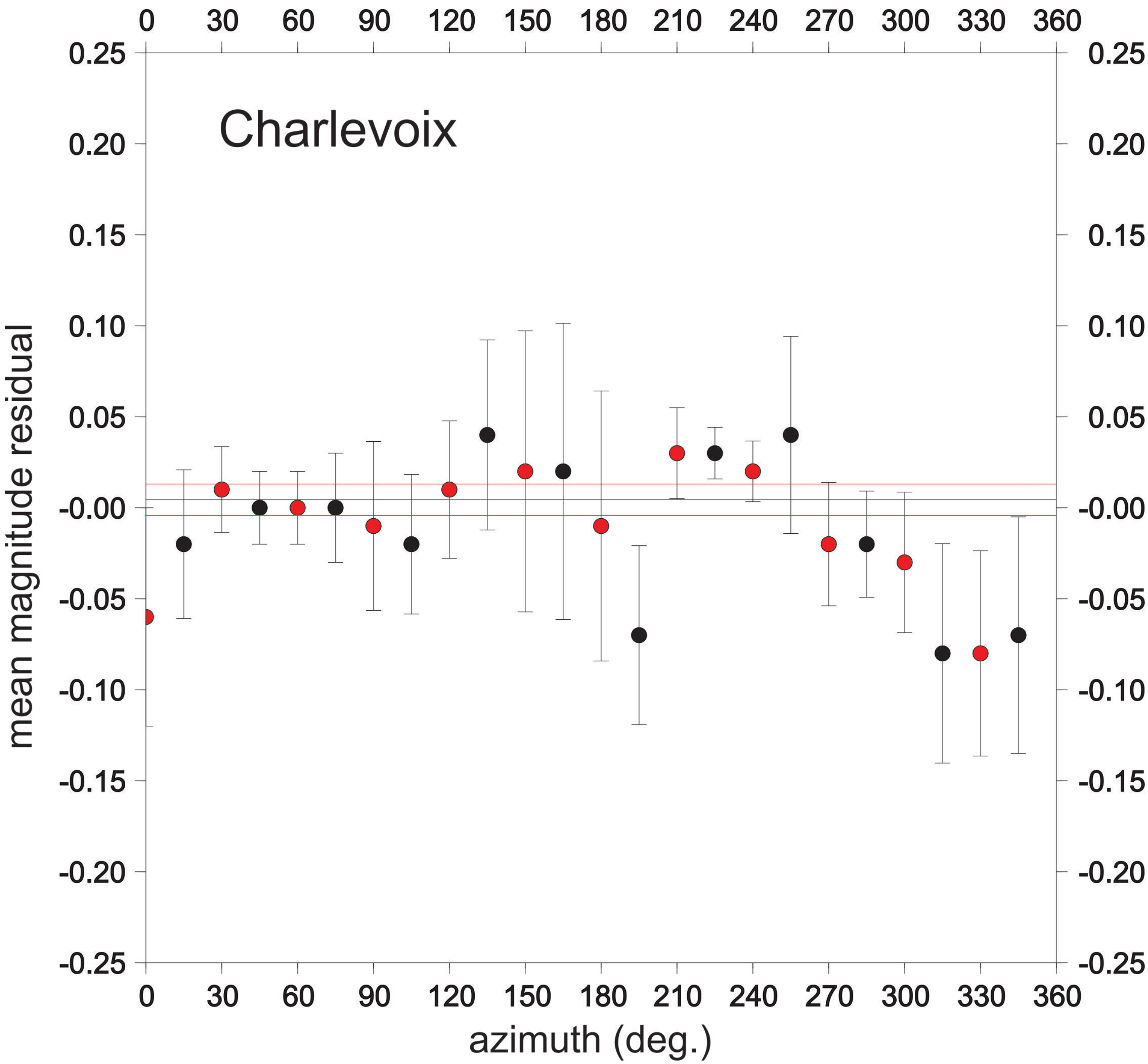

Charlevoix
mean magnitude residual
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
0.25
0.20
0.15
0.10
0.05
-0.00
-0.05
-0.10
-0.15
-0.20
-0.25

Figure 8a

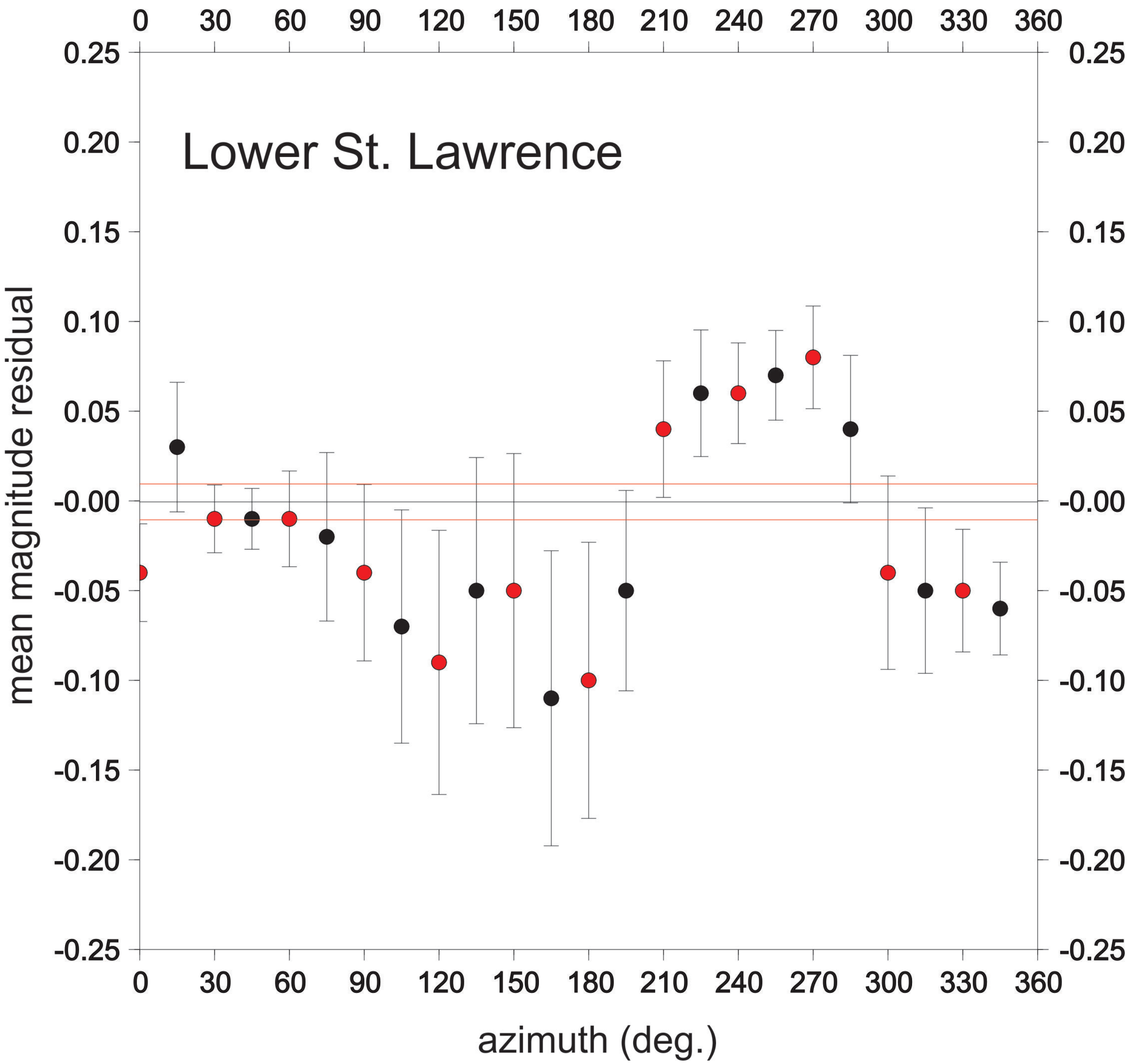

Lower St. Lawrence
mean magnitude residual
azimuth (deg.)
0.25
0.20
0.15
0.10
0.05
-0.00
-0.05
-0.10
-0.15
-0.20
-0.25
0 30 60 90 120 150 180 210 240 270 300 330 360

Figure 8b

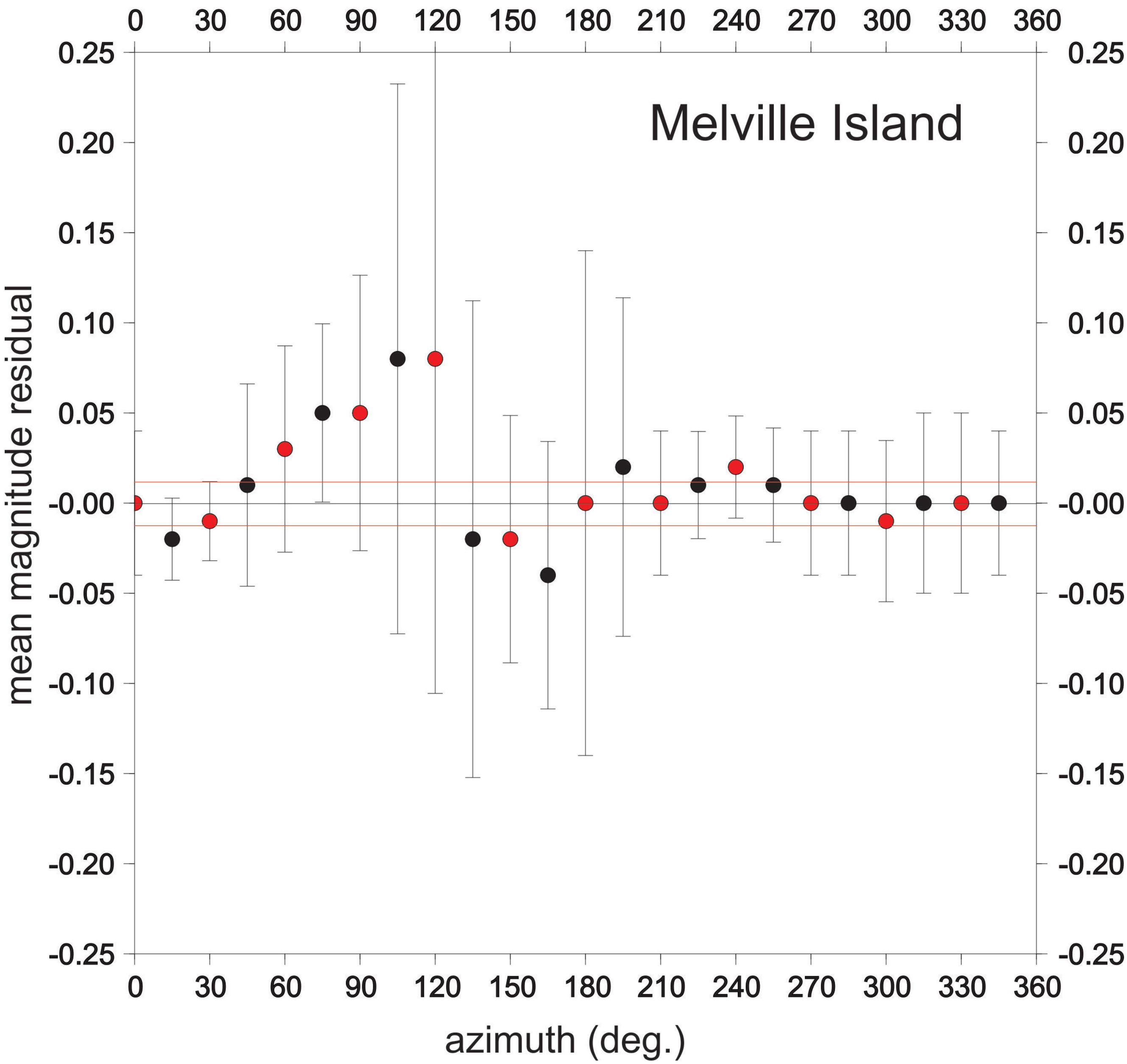

Melville Island
mean magnitude residual
azimuth (deg.)
0.25
0.20
0.15
0.10
0.05
-0.00
-0.05
-0.10
-0.15
-0.20
-0.25
0
30
60
90
120
150
180
210
240
270
300
330
360

Figure 8c

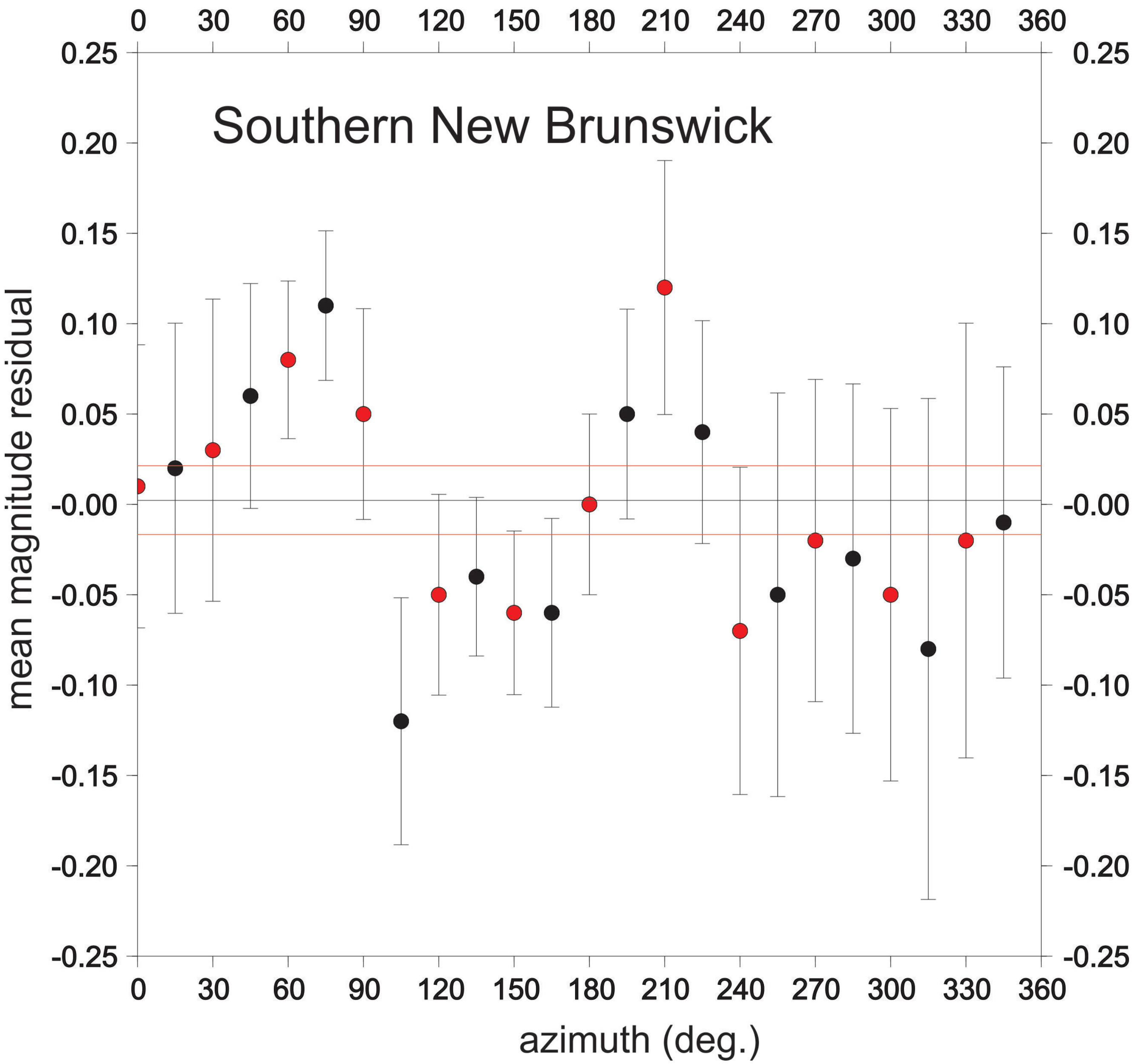

Southern New Brunswick
mean magnitude residual
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
0.25
0.20
0.15
0.10
0.05
-0.00
-0.05
-0.10
-0.15
-0.20
-0.25

Figure 8d

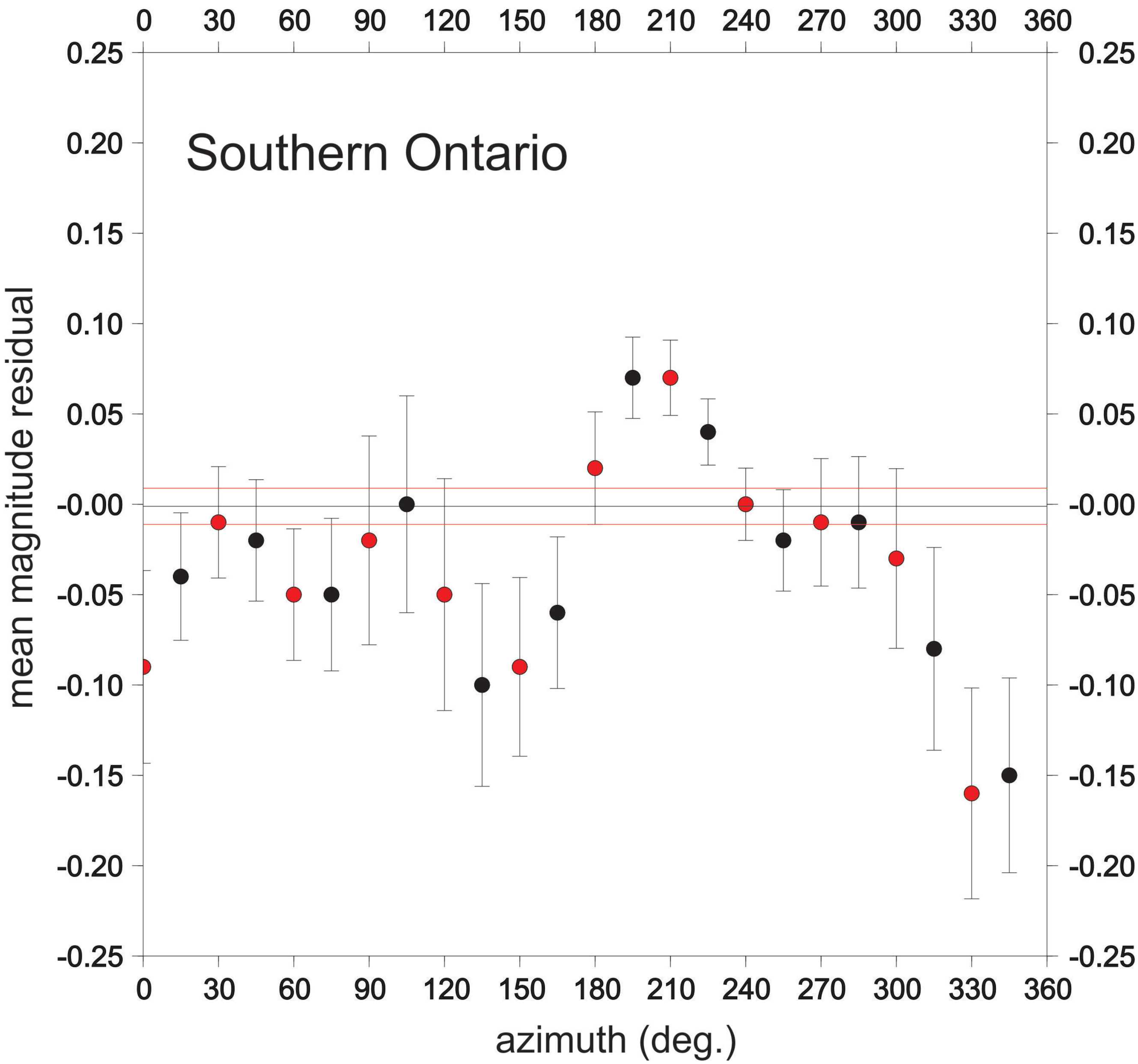

Southern Ontario
mean magnitude residual
azimuth (deg.)
0
30
60
90
120
150
180
210
240
270
300
330
360
0.25
0.20
0.15
0.10
0.05
-0.00
-0.05
-0.10
-0.15
-0.20
-0.25

Figure 8e

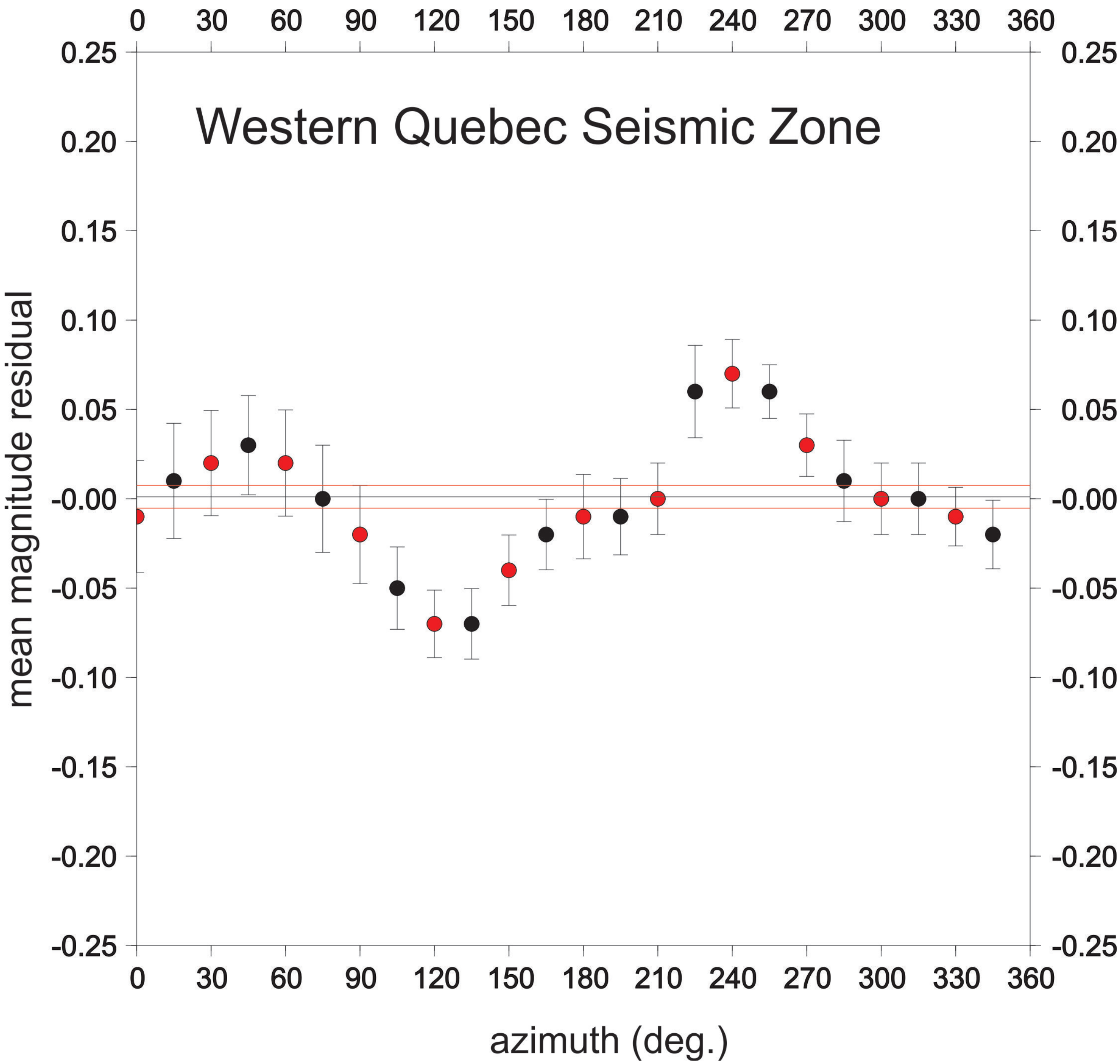
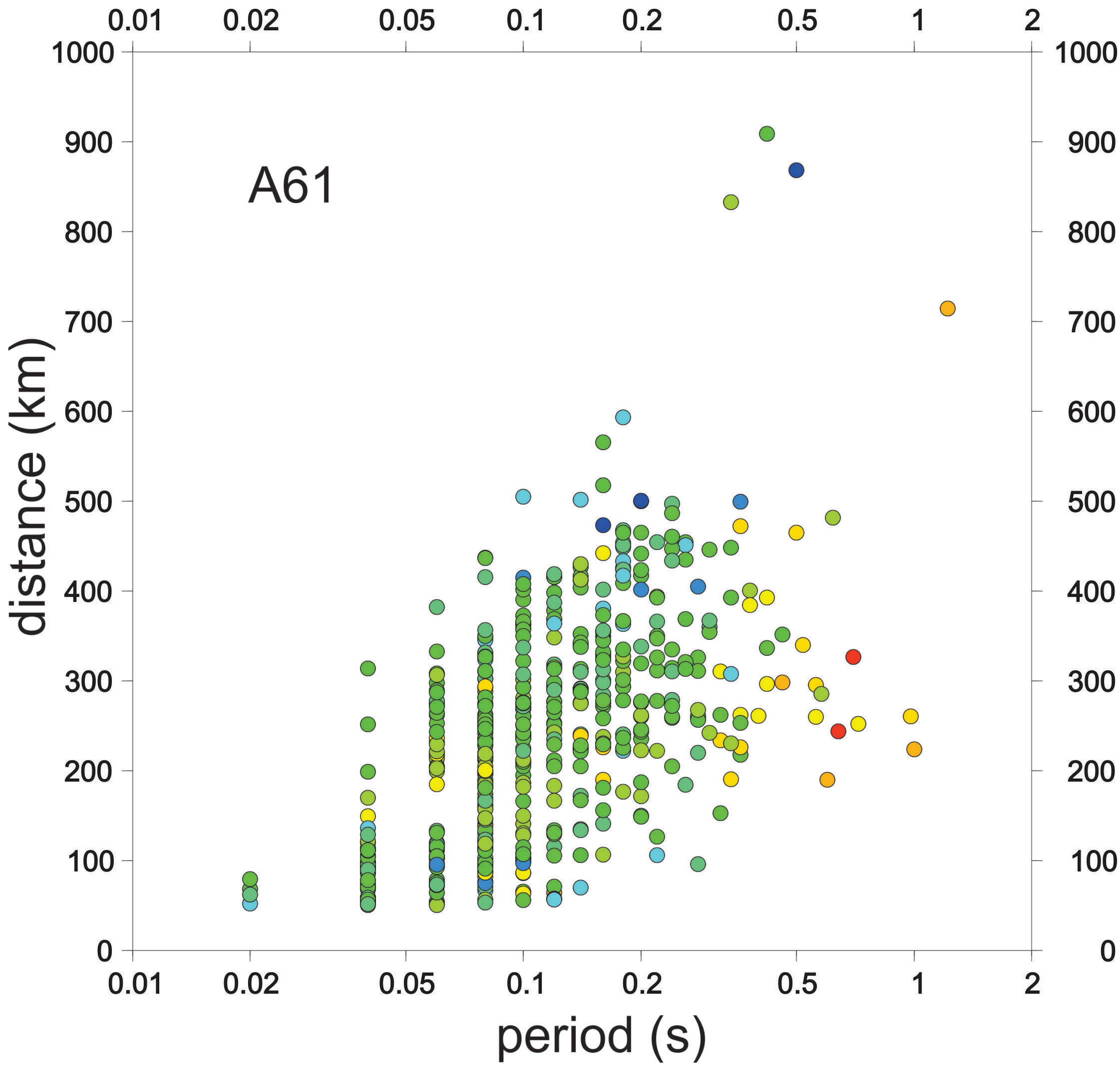
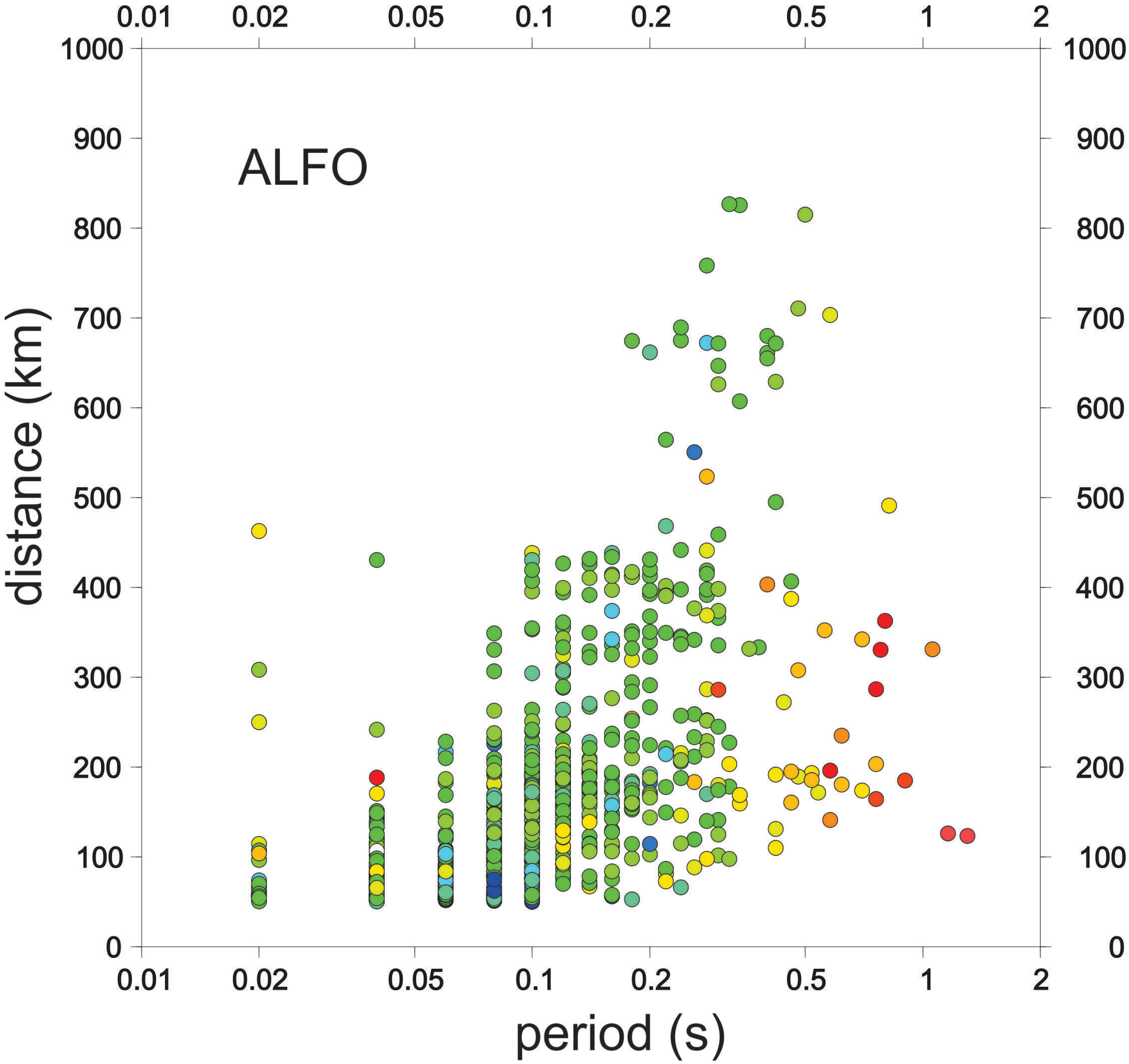


Figure 8f

Figure 8. Mean magnitude residuals for selected regional groups of stations for azimuthal windows as discussed in the text. The points are plotted at the midpoint of the window. The stations for each group are discussed in the text. Error bars show the 99% confidence intervals. The black and red horizontal lines show the mean and 99% confidence values for the region, respectively. a) Charlevoix, b) Lower St. Lawrence, c) Melville Island, d) southern New Brunswick, e) southern Ontario and f) Western Quebec Seismic Zone.


A61
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
0
100
200
300
400
500
600
700
800
900
1000
Figure 9a.



ALFO
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
0
100
200
300
400
500
600
700
800
900
1000

Figure 9b

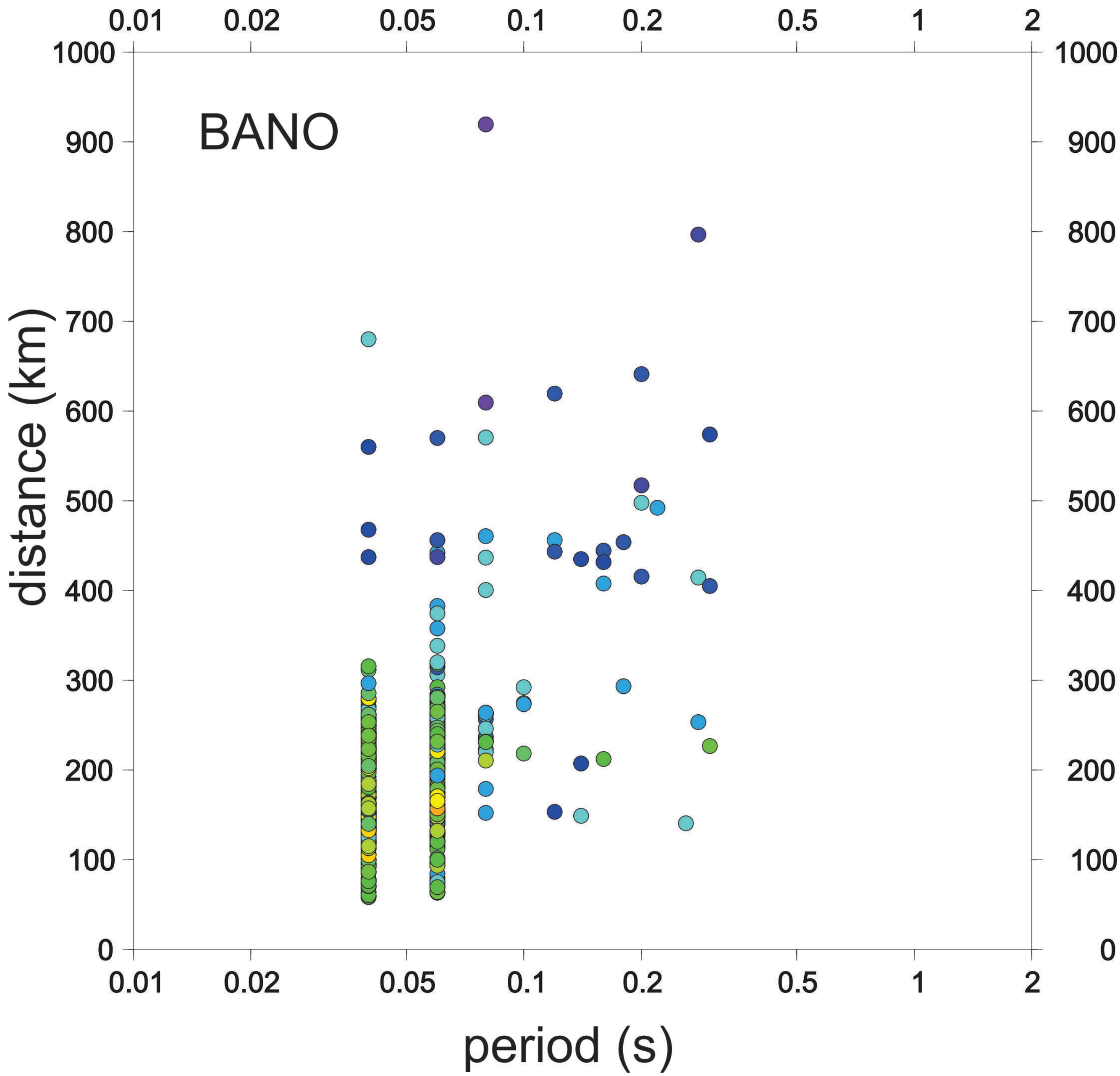
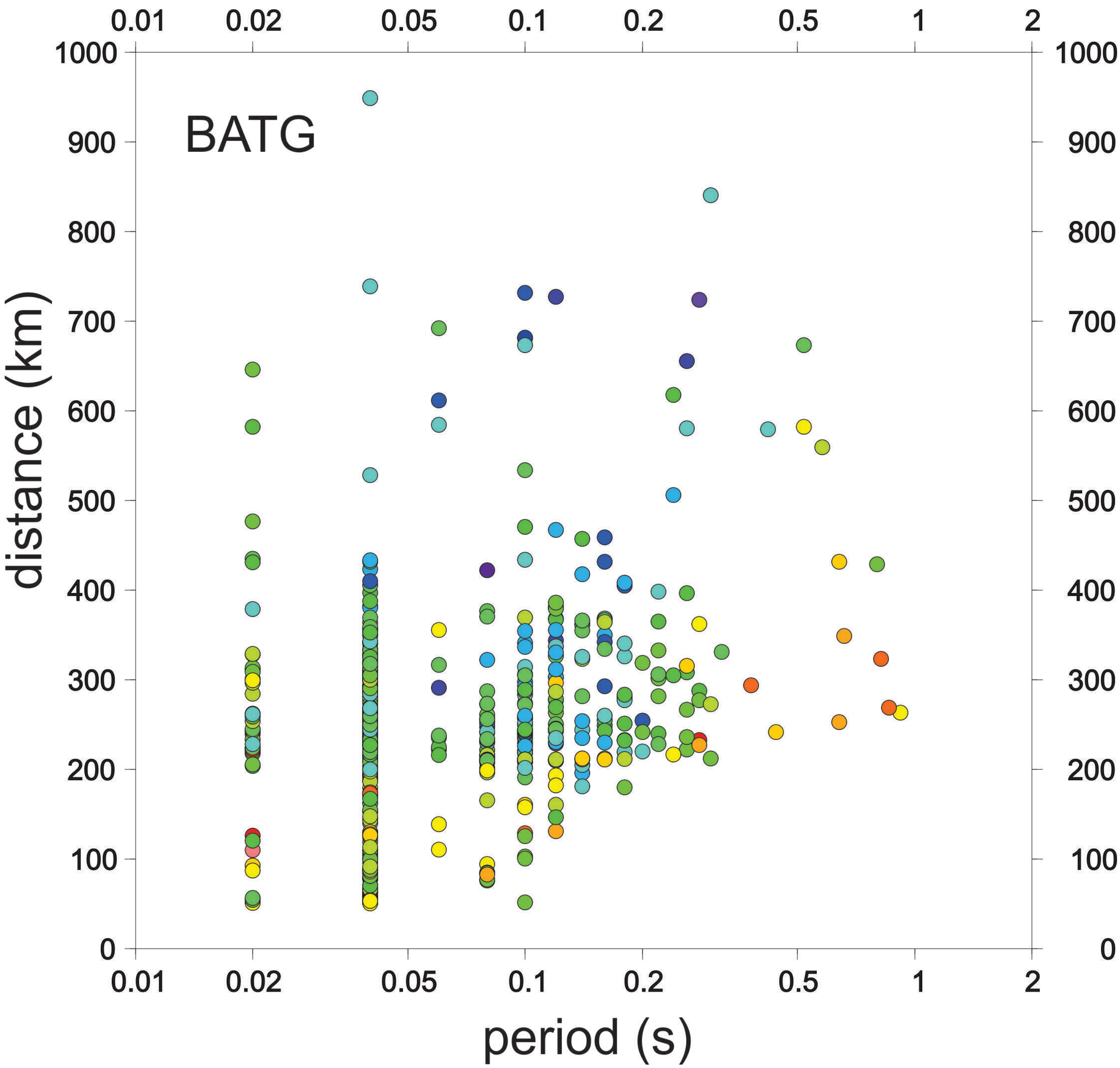

BANO
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
1000
900
800
700
600
500
400
300
200
100
0

Figure 9c.



BATG
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
0
100
200
300
400
500
600
700
800
900
1000

Figure 9d

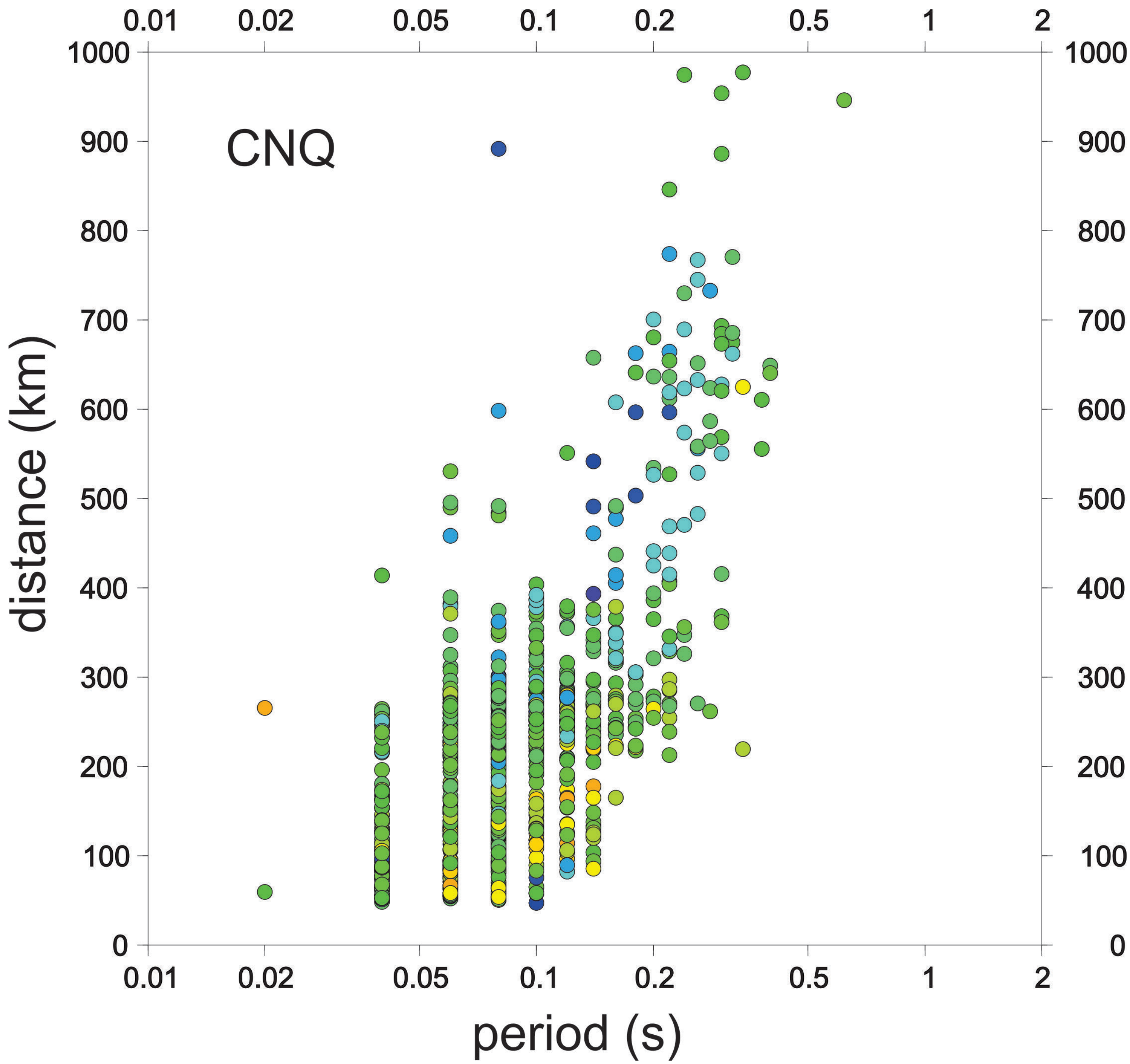

CNQ
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
0
100
200
300
400
500
600
700
800
900
1000

Figure 9e

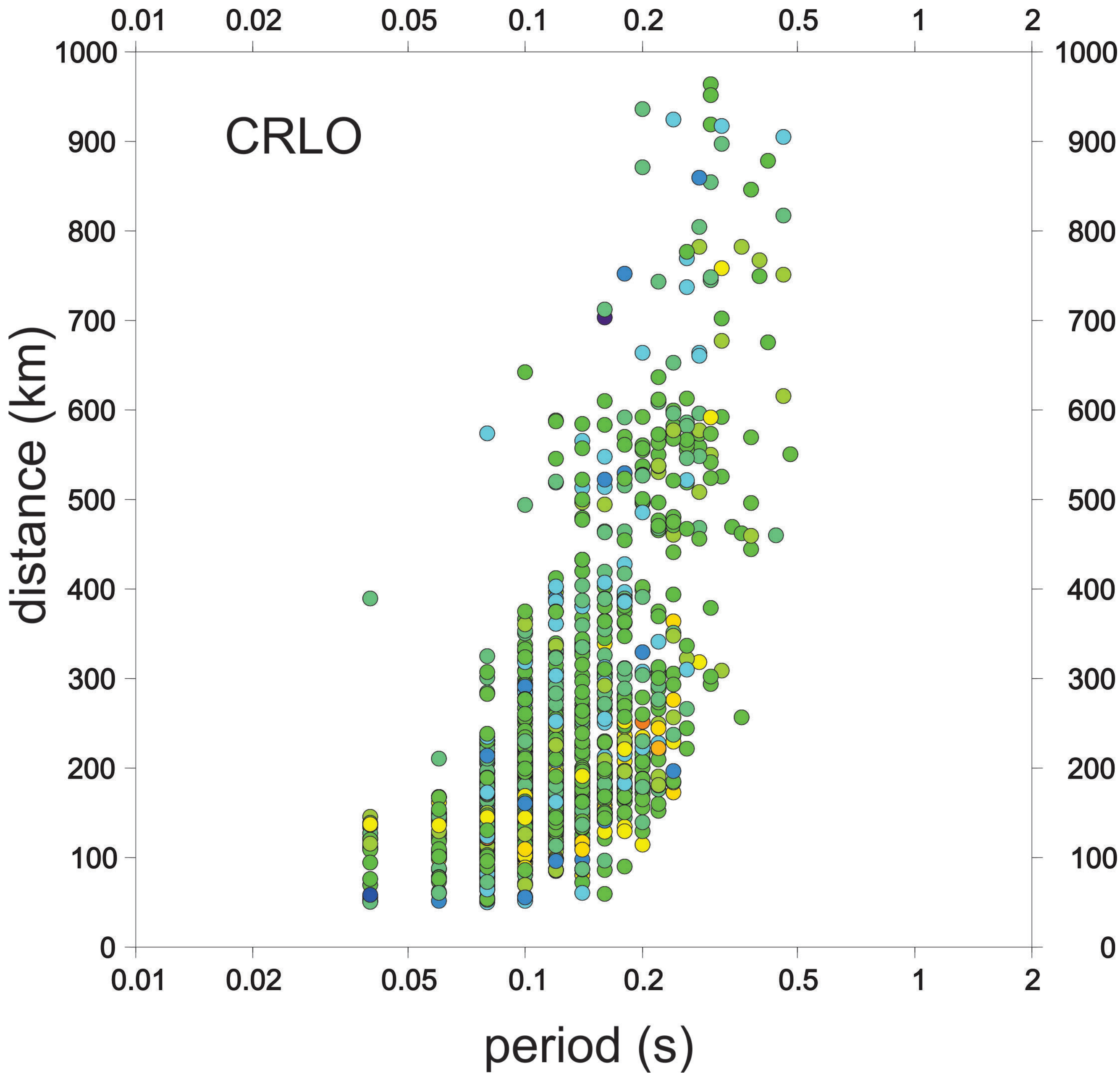
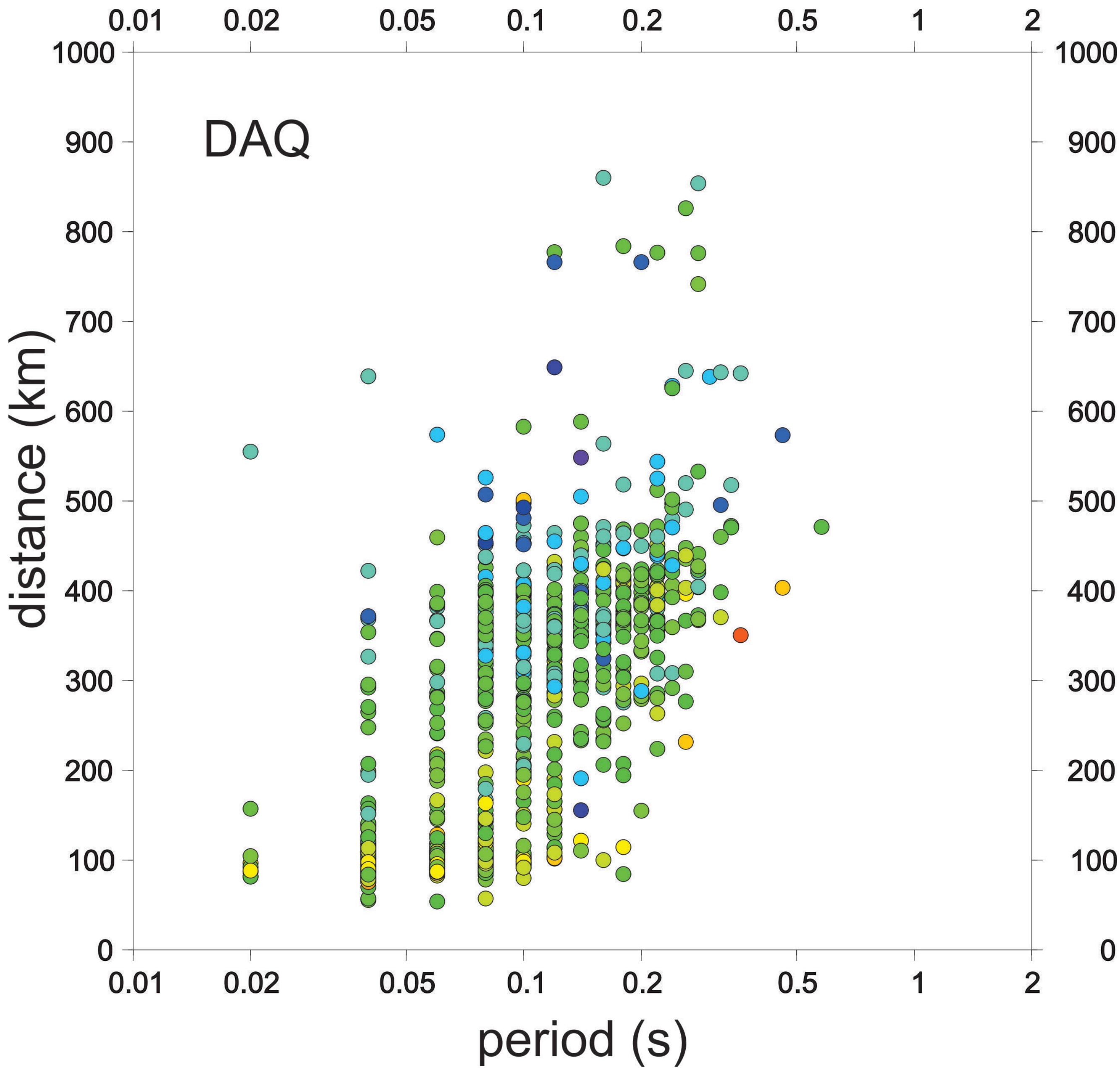
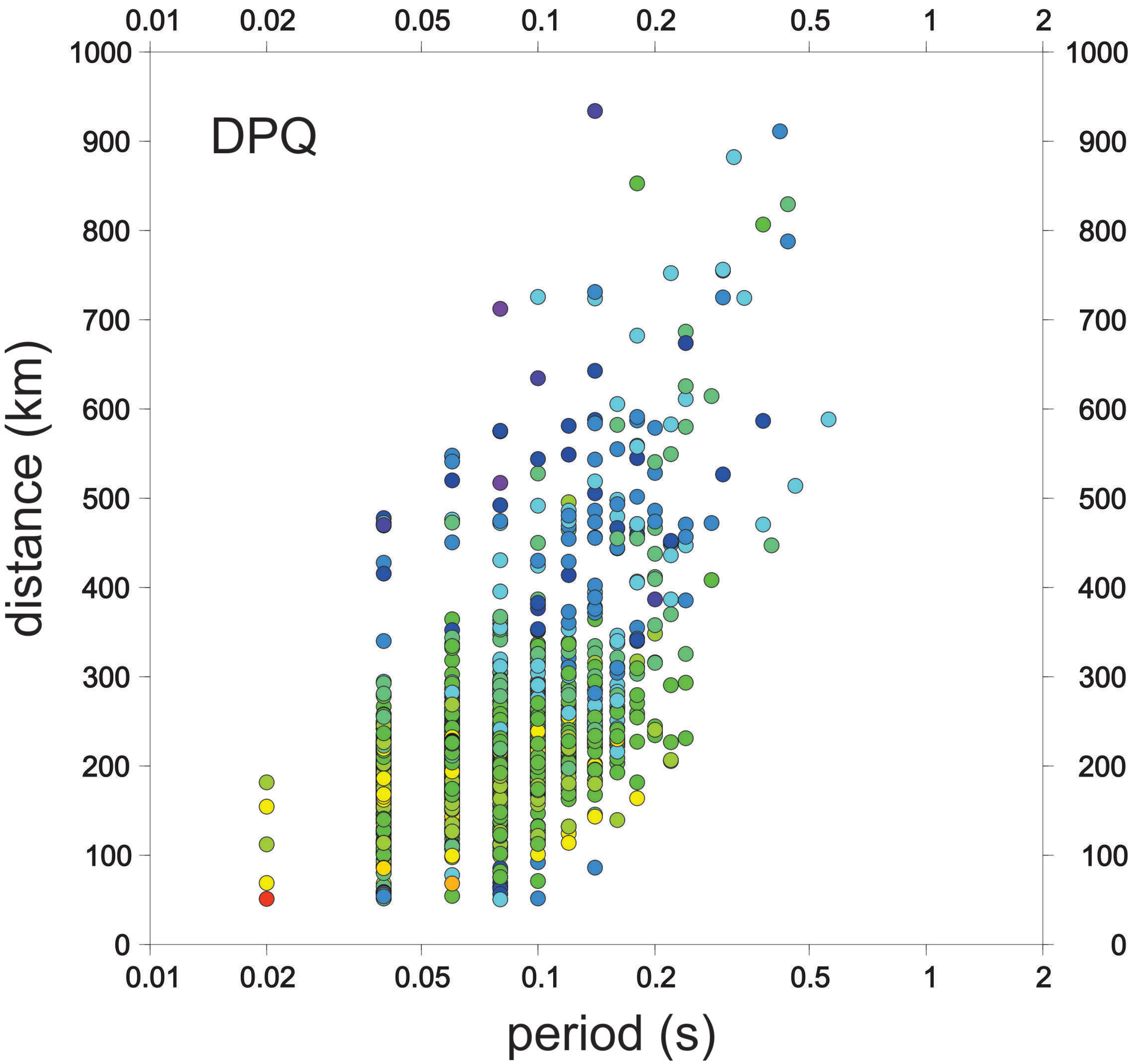

CRLO
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
0
100
200
300
400
500
600
700
800
900
1000

Figure 9f



0.01
0.02
0.05
0.1
0.2
0.5
1
2
1000
900
800
700
600
500
400
300
200
100
0
DAQ
distance (km)
period (s)

Figure 9g



DPQ
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
0
100
200
300
400
500
600
700
800
900
1000

Figure 9h

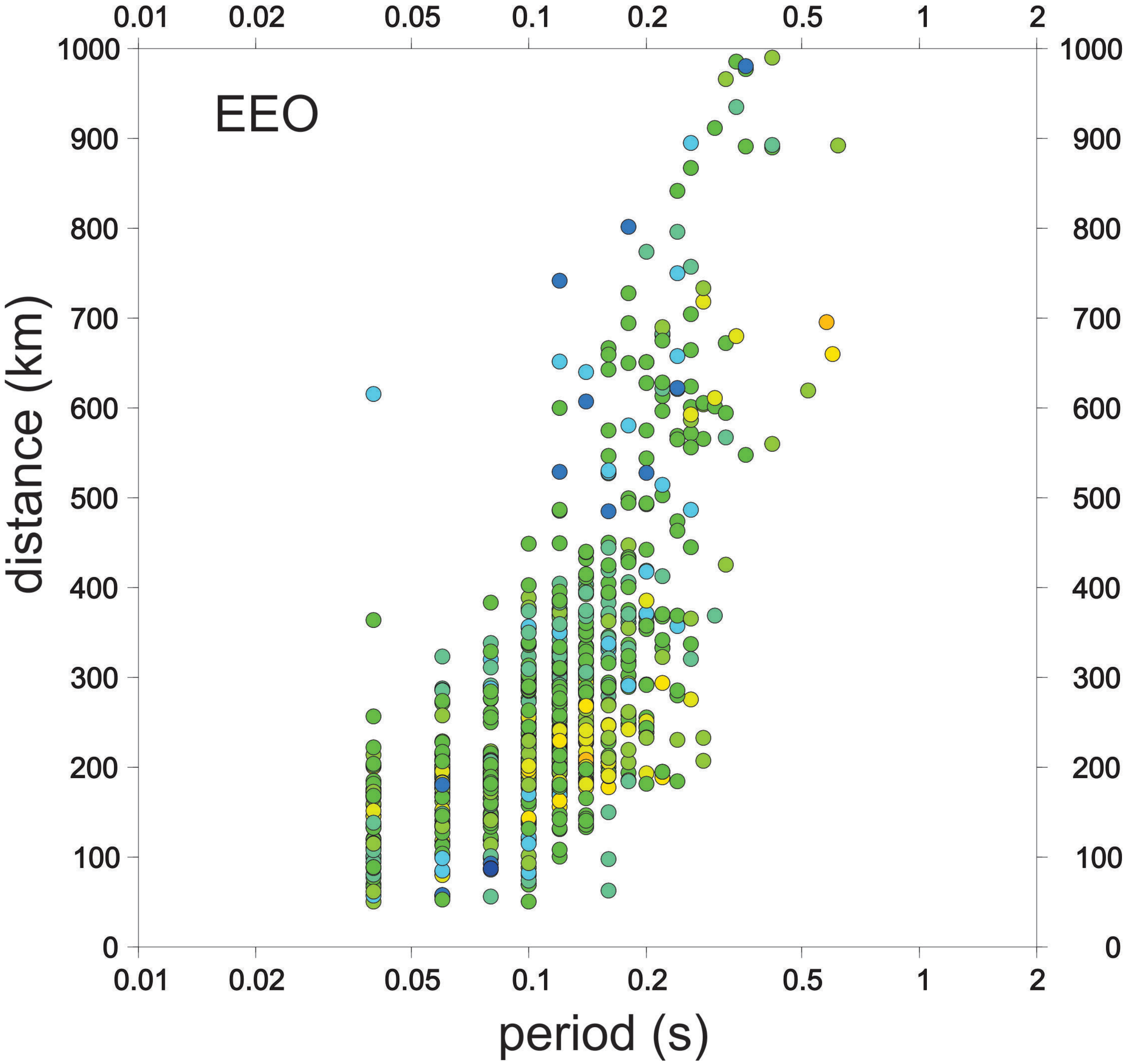
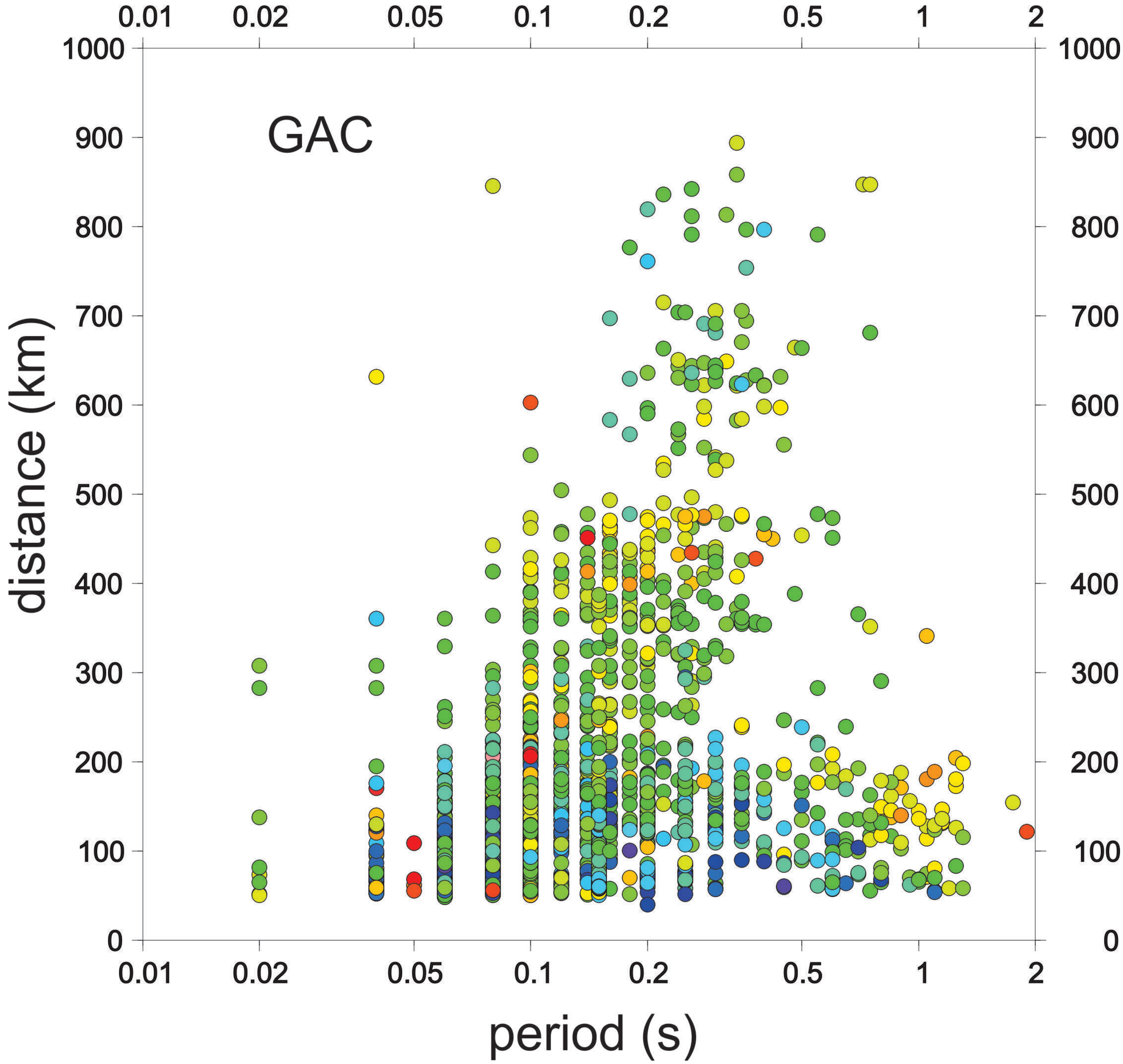

EEO
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
0
100
200
300
400
500
600
700
800
900
1000

Figure 9i



GAC
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
0
100
200
300
400
500
600
700
800
900
1000

Figure 9j

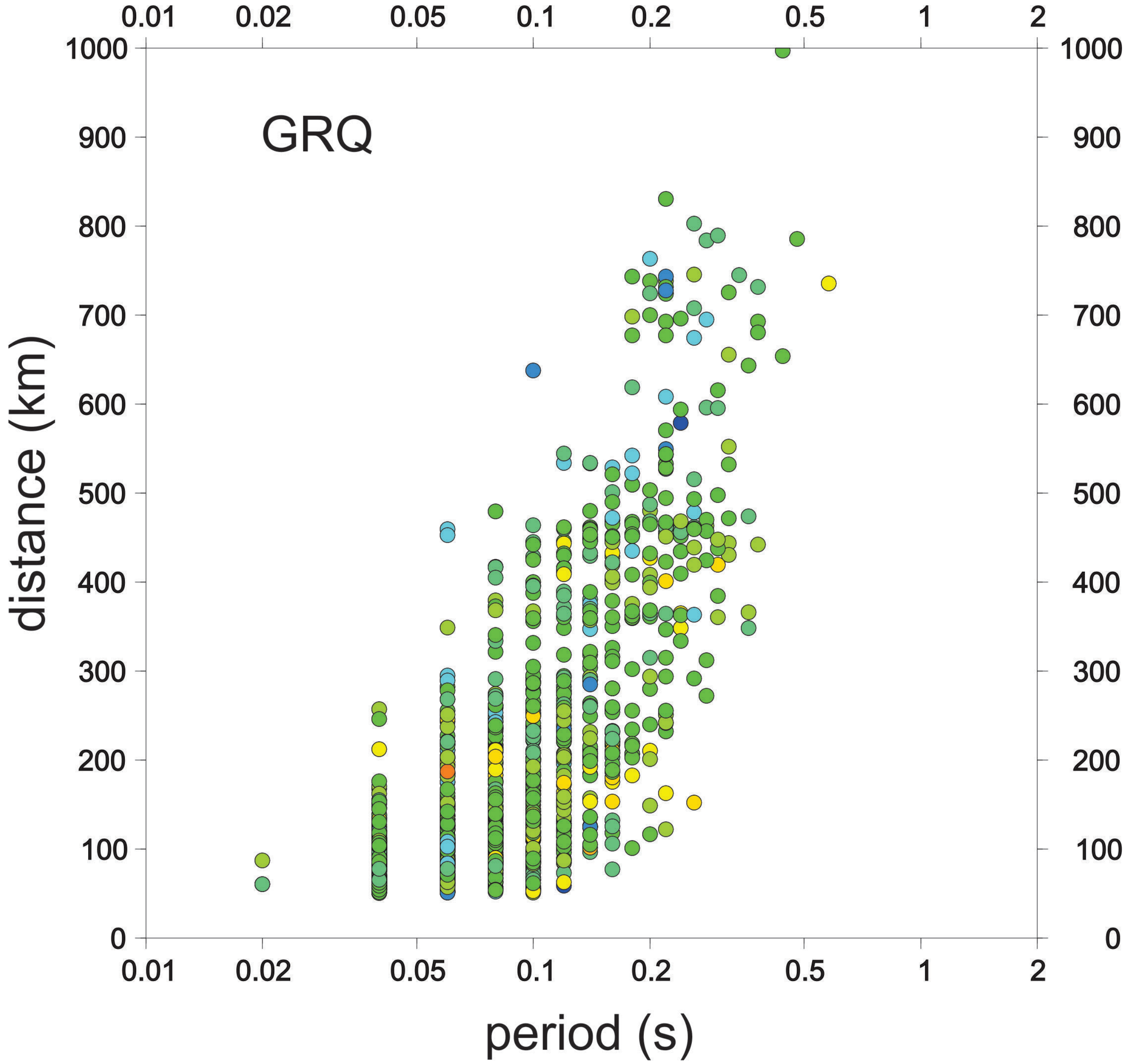
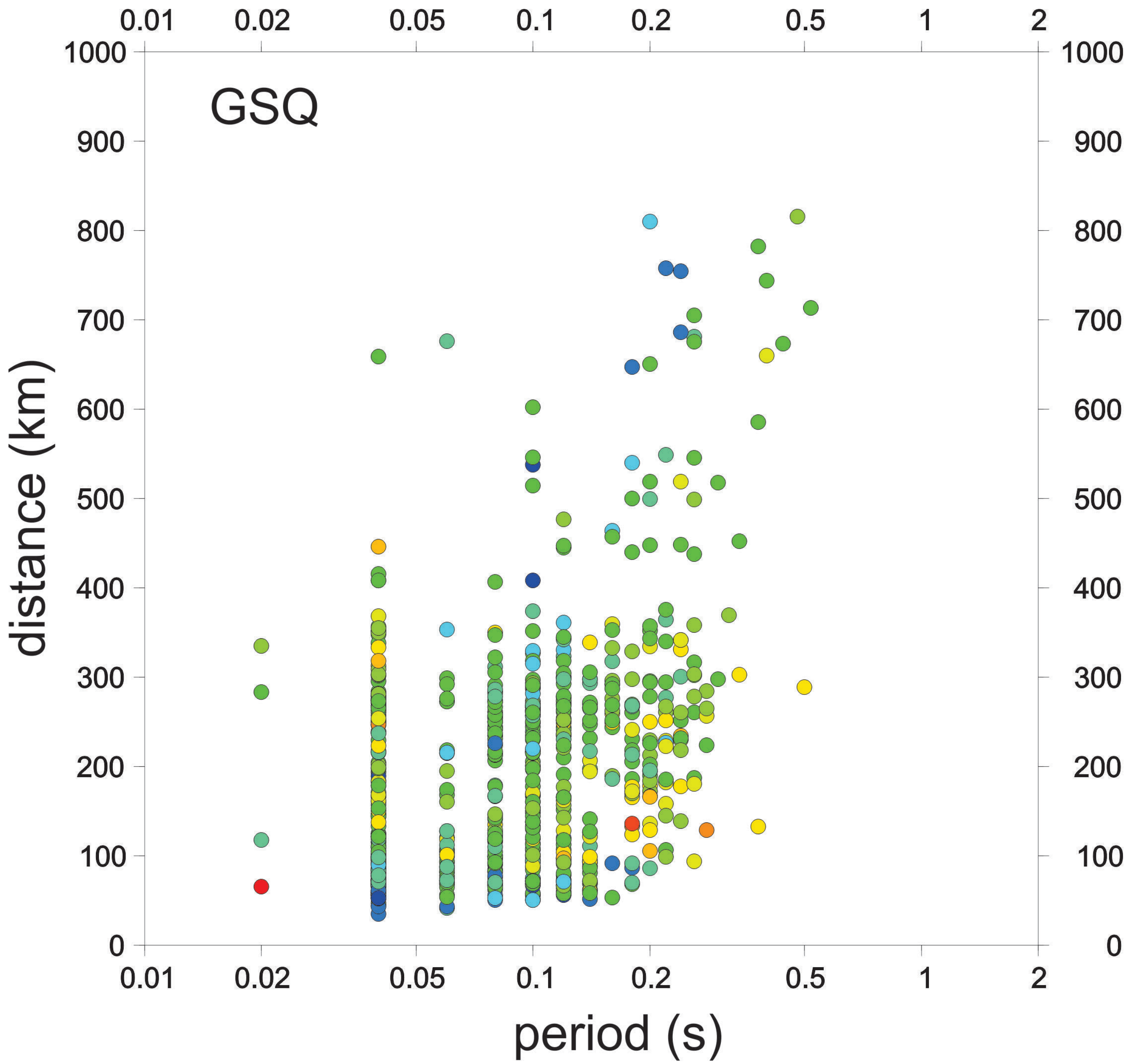
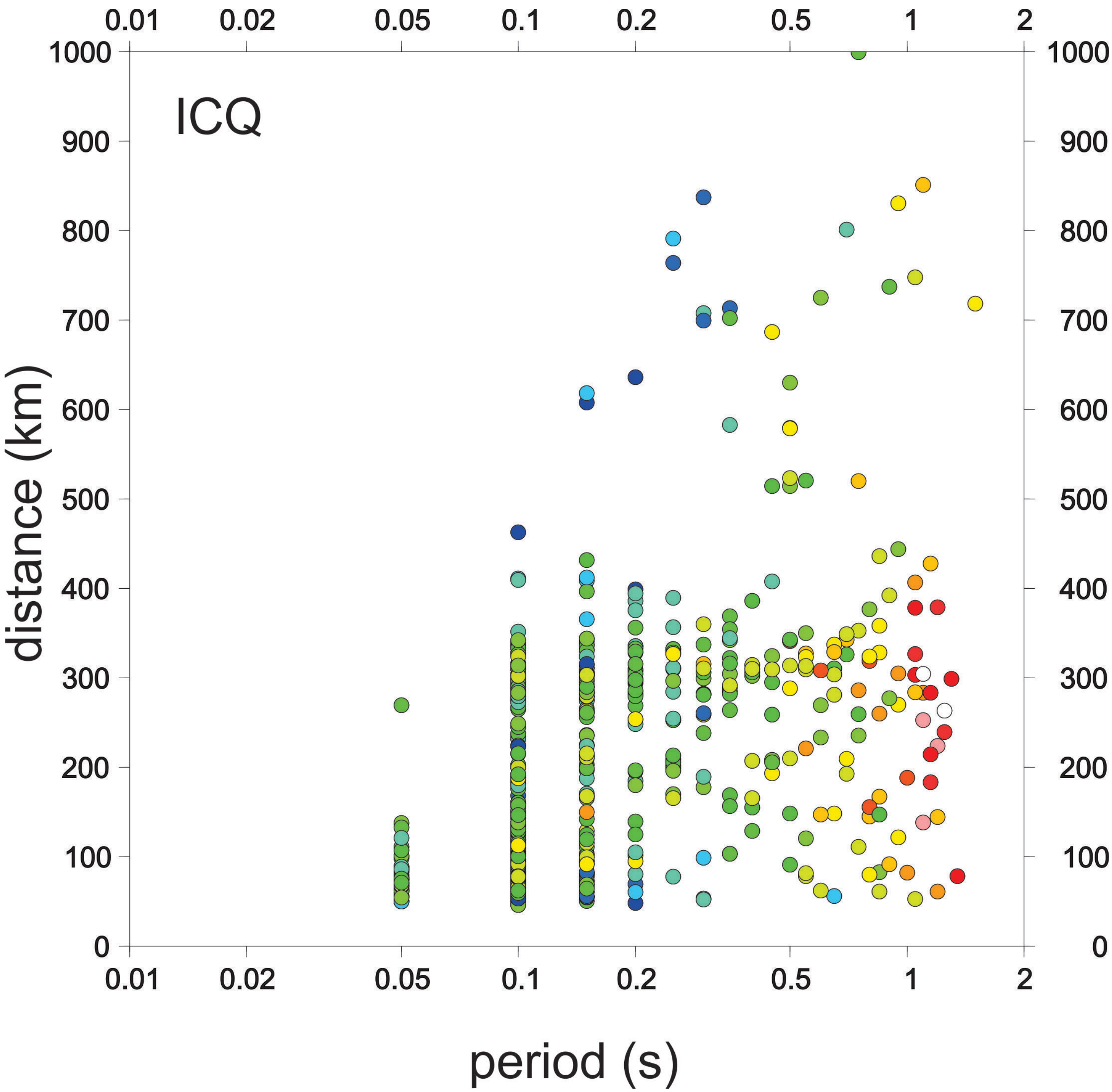

GRQ
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
0
100
200
300
400
500
600
700
800
900
1000

Figure 9k



GSQ
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
1000
900
800
700
600
500
400
300
200
100
0

Figure 9l


ICQ
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
1000
900
800
700
600
500
400
300
200
100
0
Figure 9m

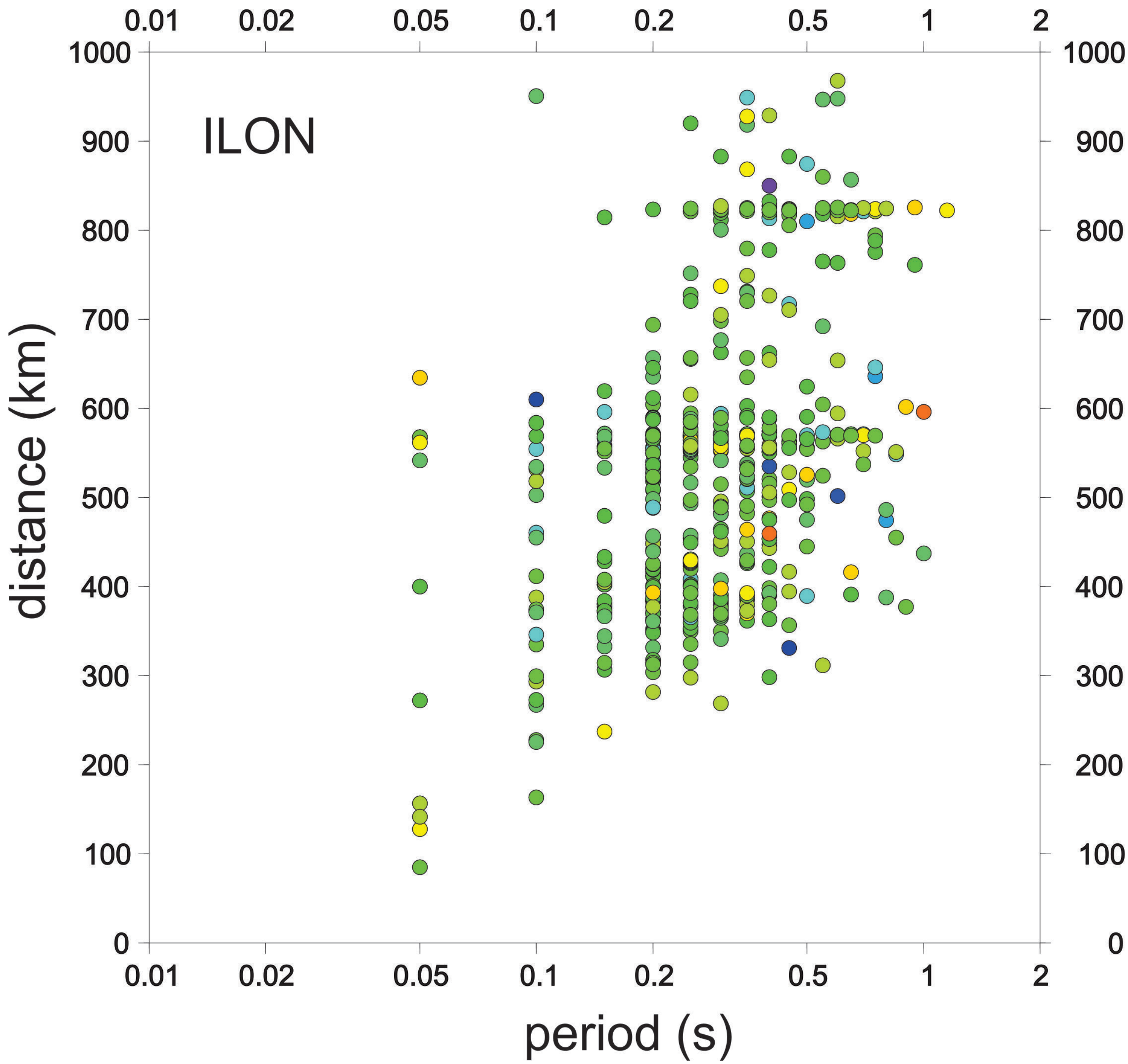

ILON
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
0
100
200
300
400
500
600
700
800
900
1000

Figure 9n

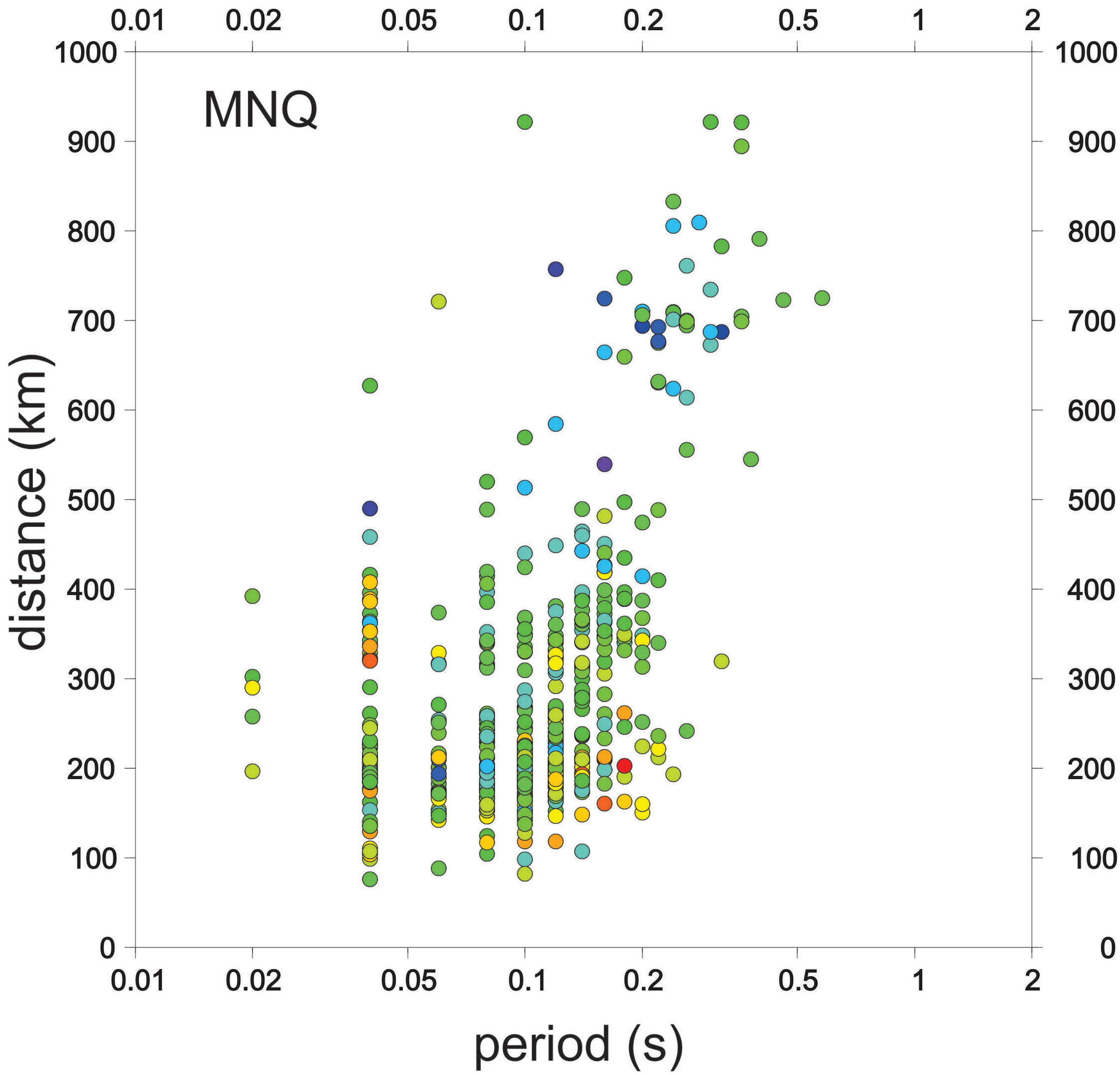
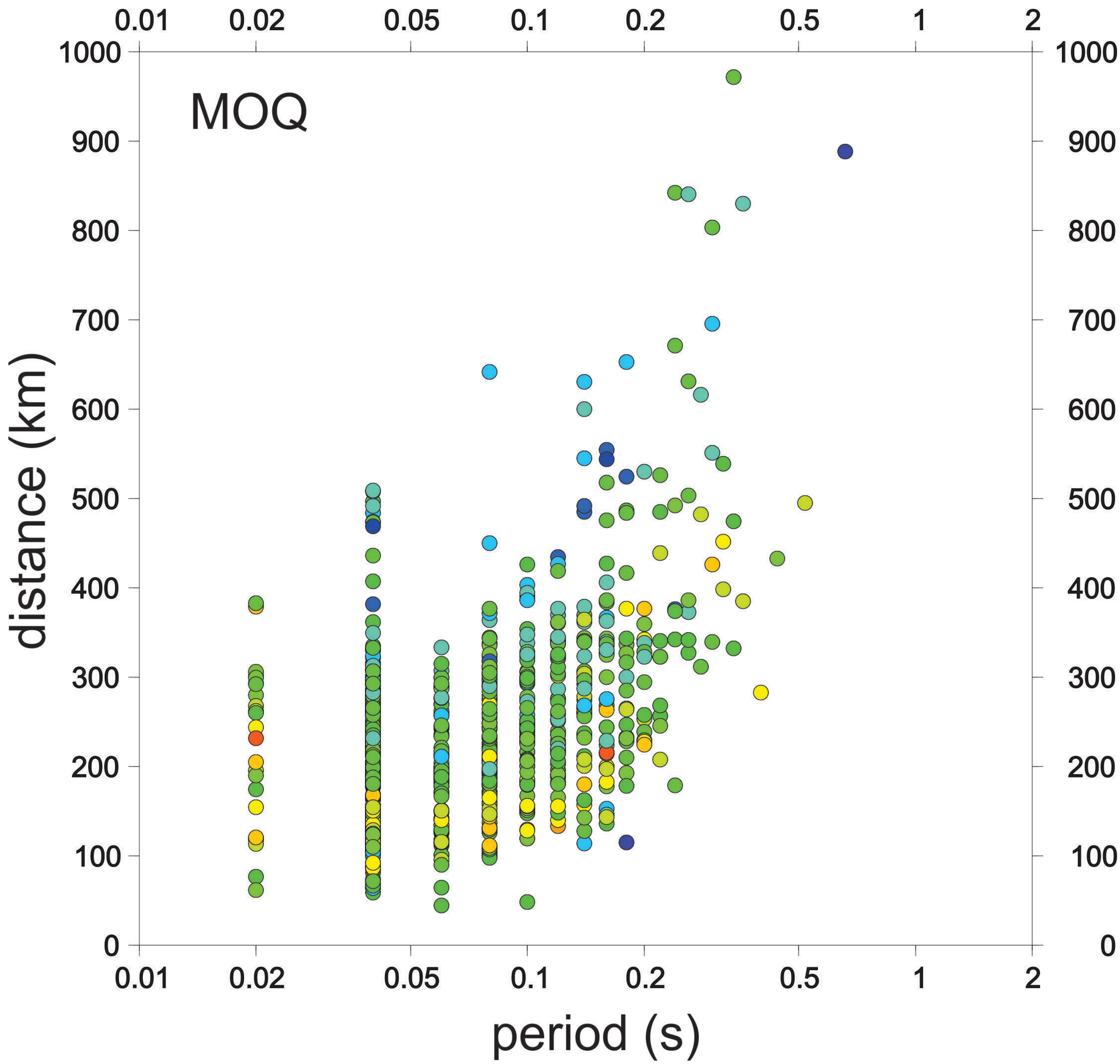

MNQ
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
0
100
200
300
400
500
600
700
800
900
1000

Figure 9o



MOQ
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
0
100
200
300
400
500
600
700
800
900
1000

Figure 9p

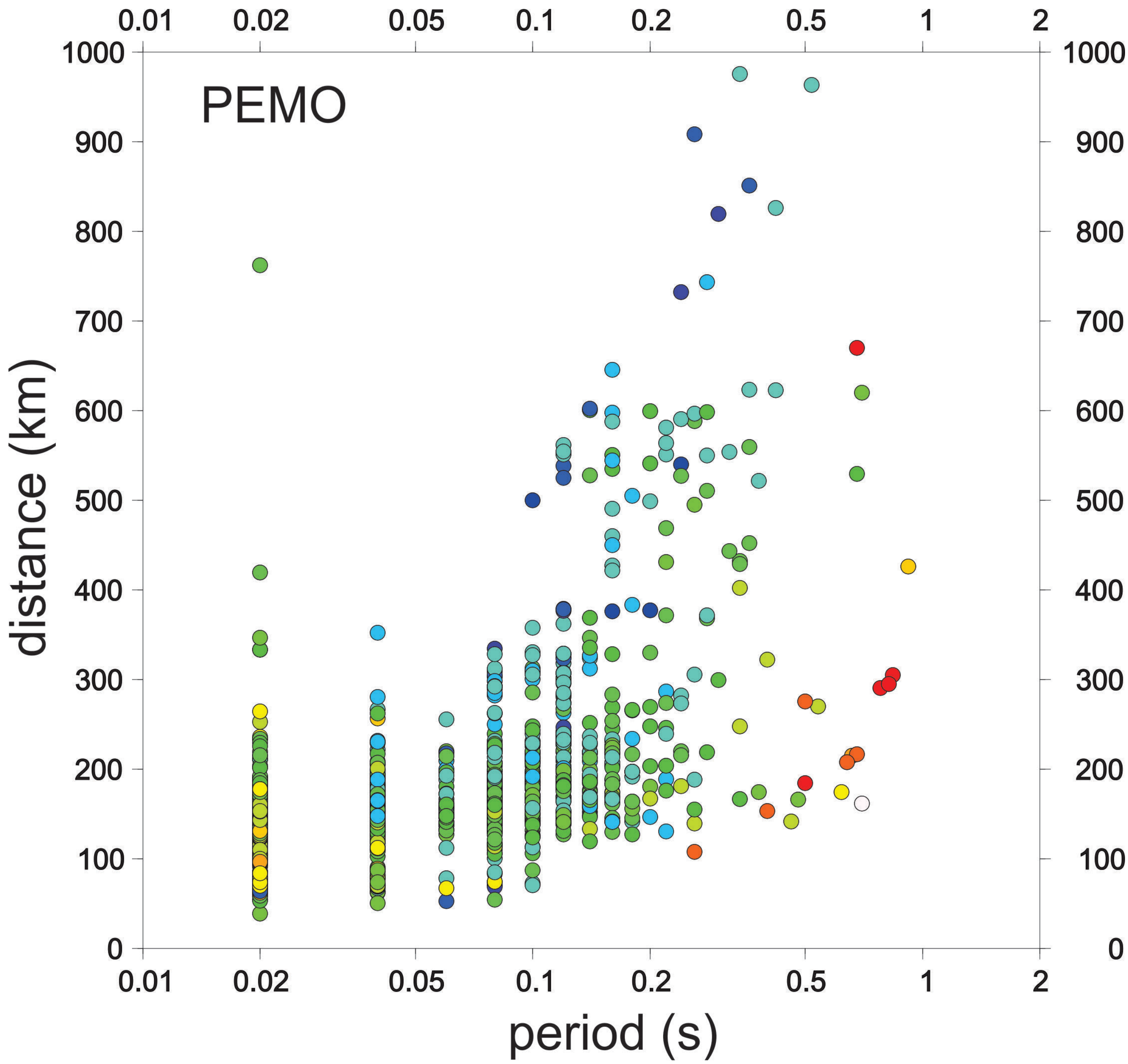
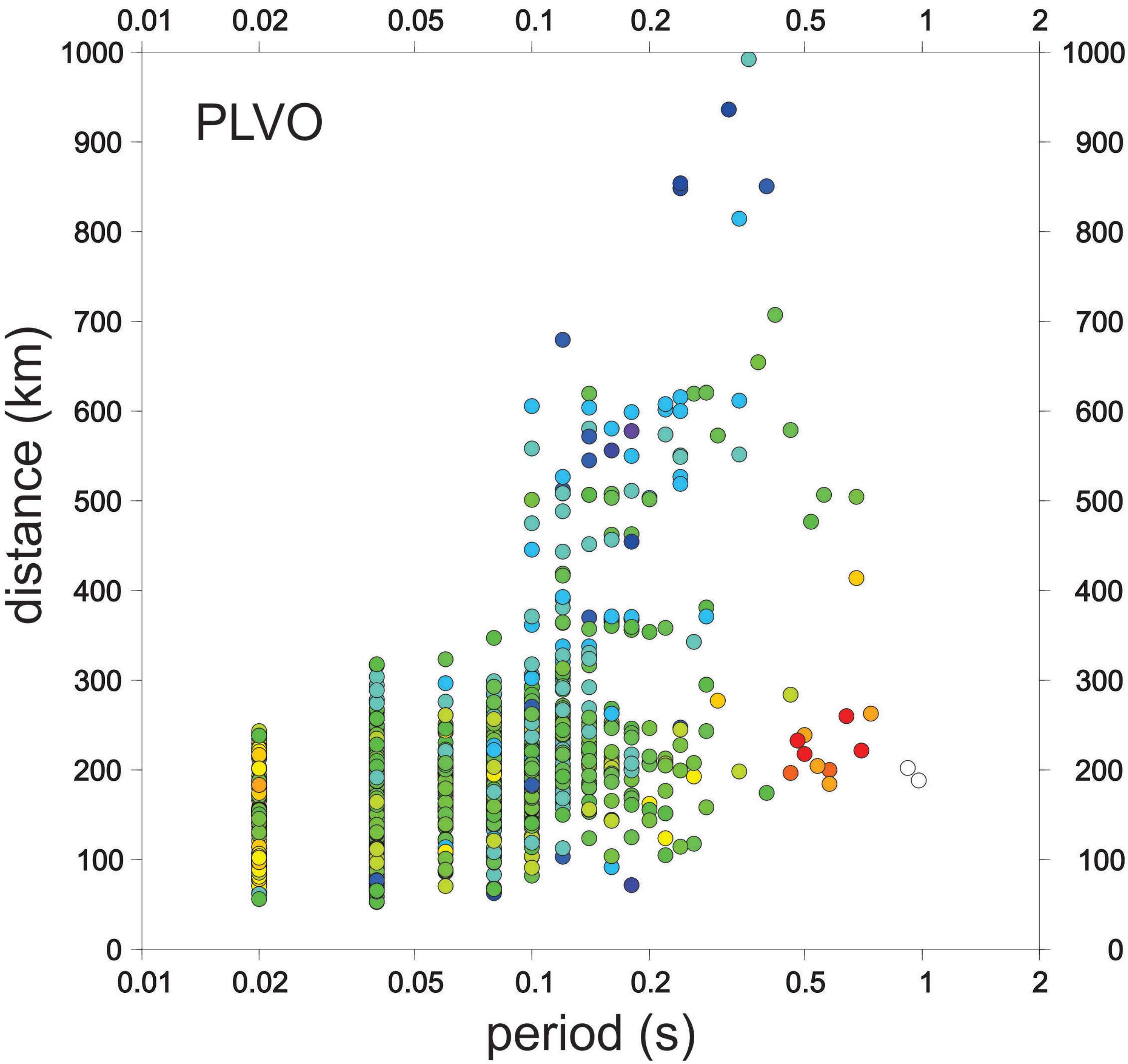

PEMO
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
0
100
200
300
400
500
600
700
800
900
1000

Figure 9q



PLVO
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
0
100
200
300
400
500
600
700
800
900
1000

Figure 9r

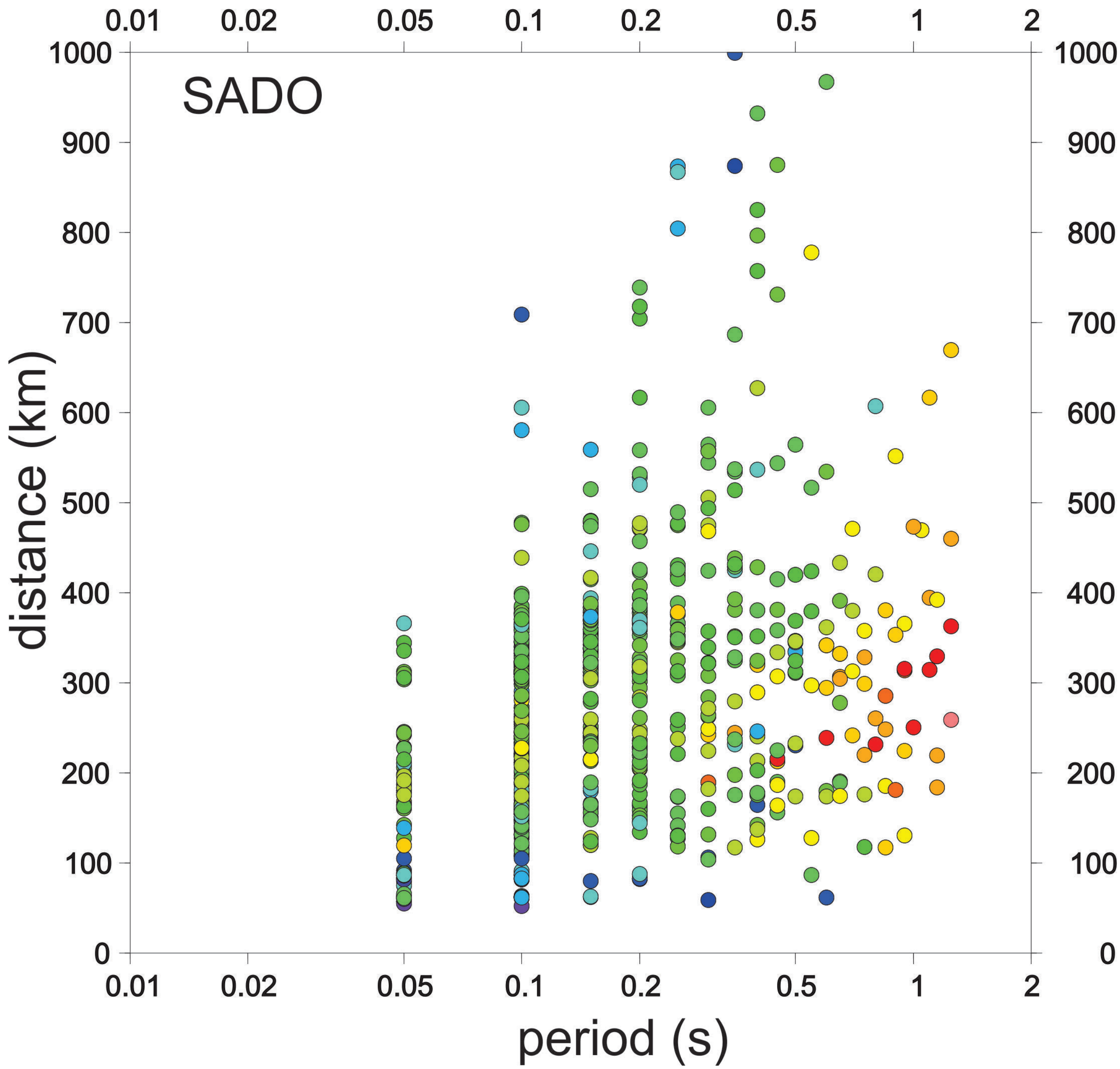
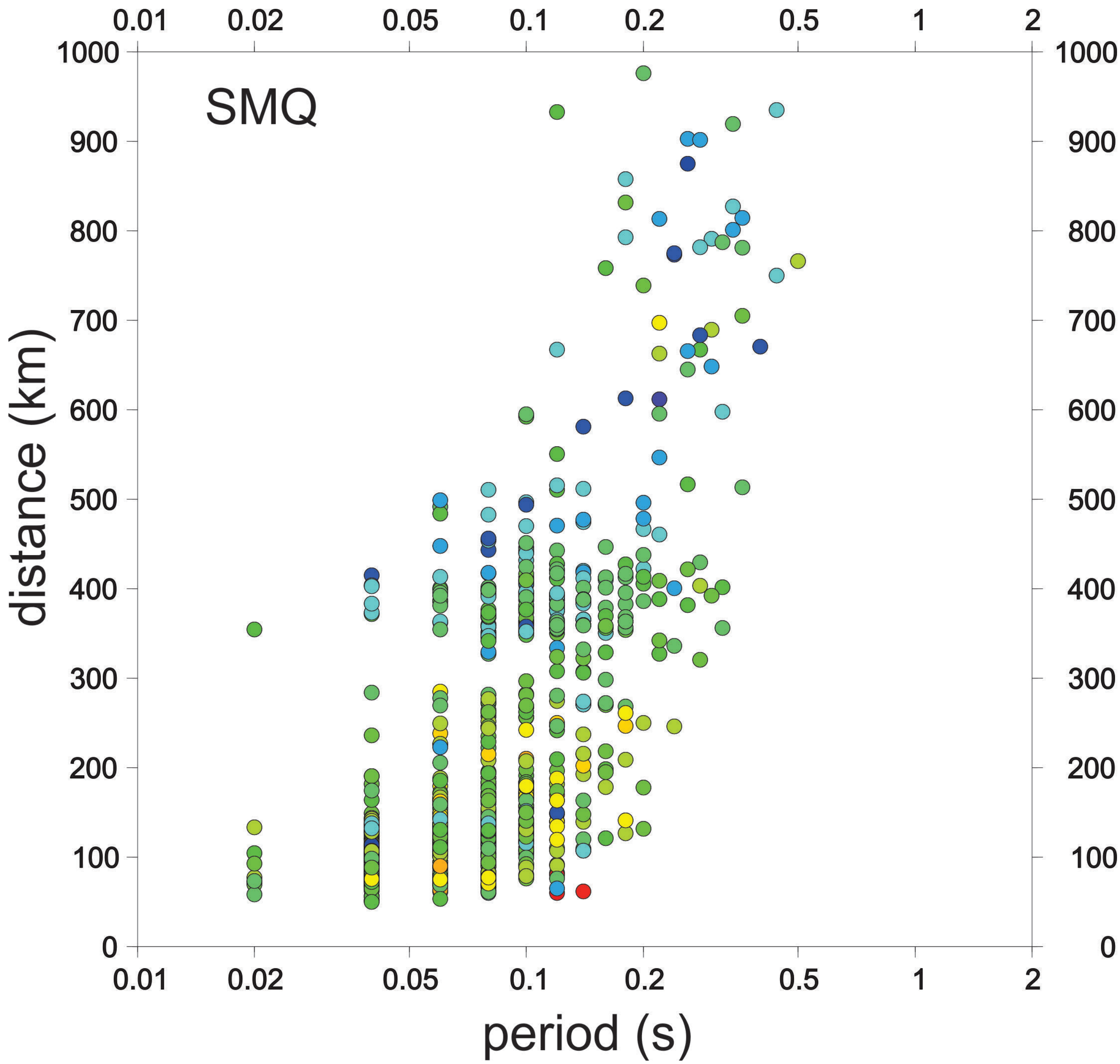

SADO
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
1000
900
800
700
600
500
400
300
200
100
0

Figure 9s



SMQ
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
0
100
200
300
400
500
600
700
800
900
1000

Figure 9t

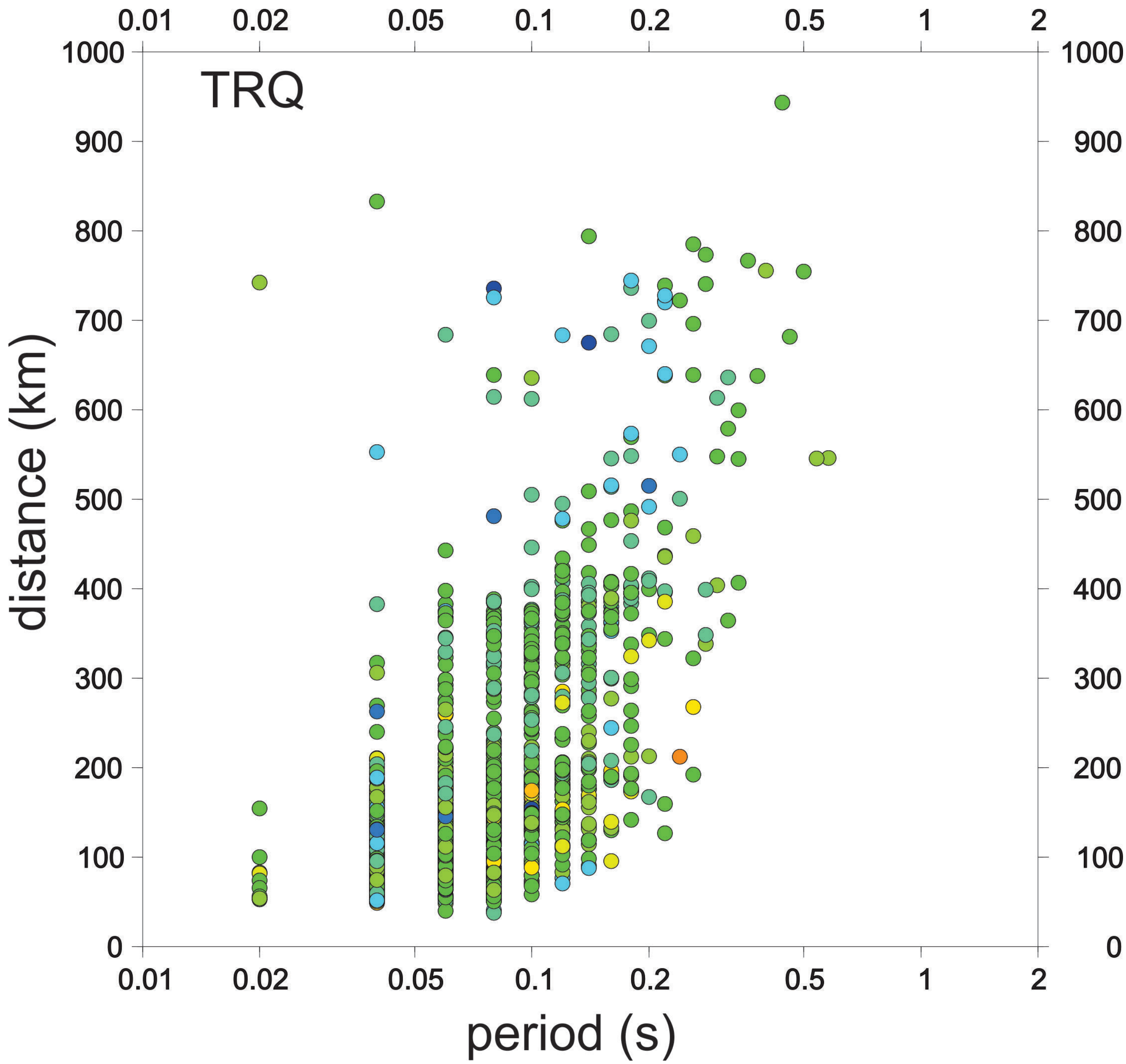
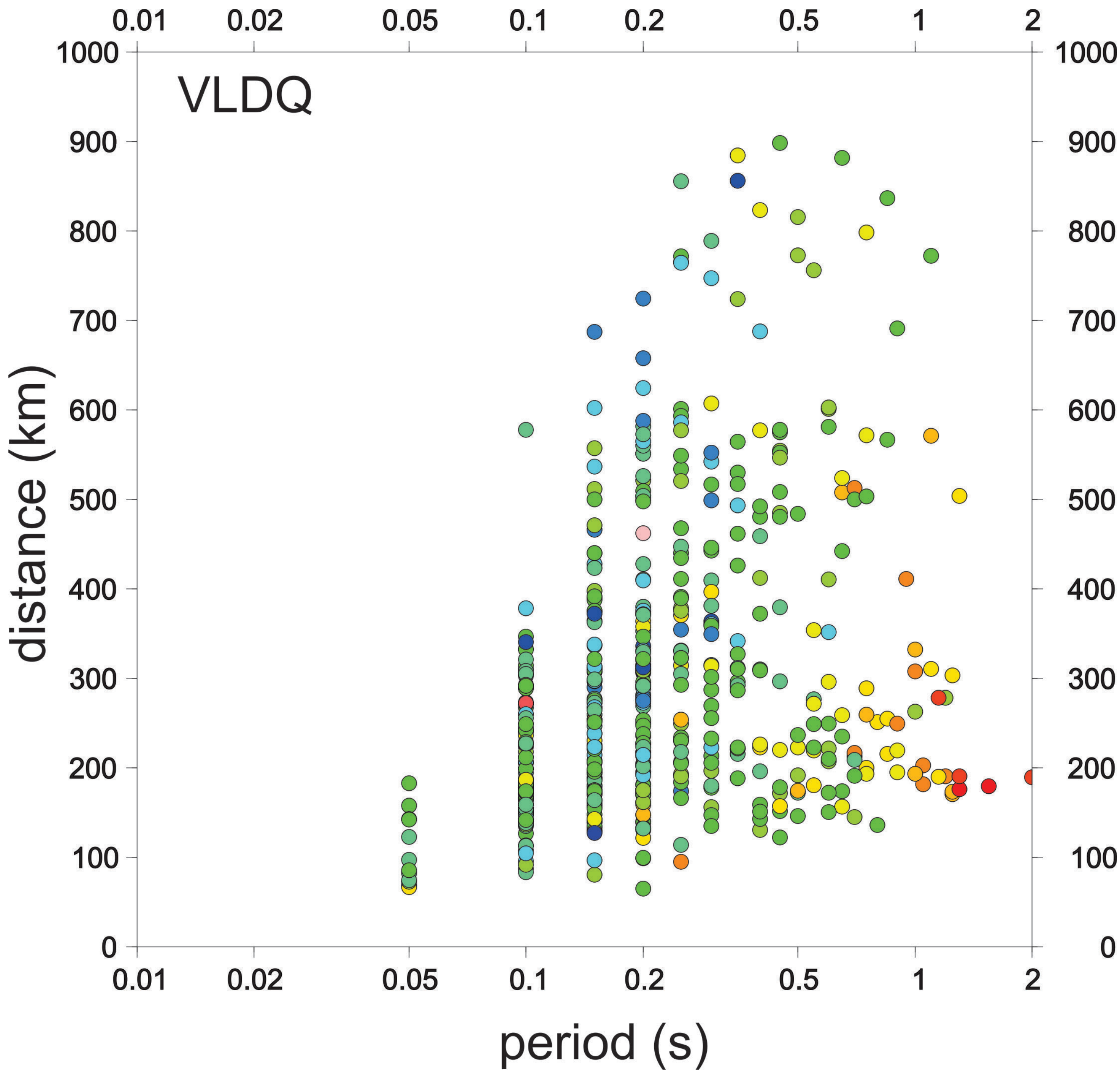

TRQ
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
0
100
200
300
400
500
600
700
800
900
1000

Figure 9u


VLDQ
distance (km)
period (s)
0.01
0.02
0.05
0.1
0.2
0.5
1
2
0
100
200
300
400
500
600
700
800
900
1000
Figure 9v

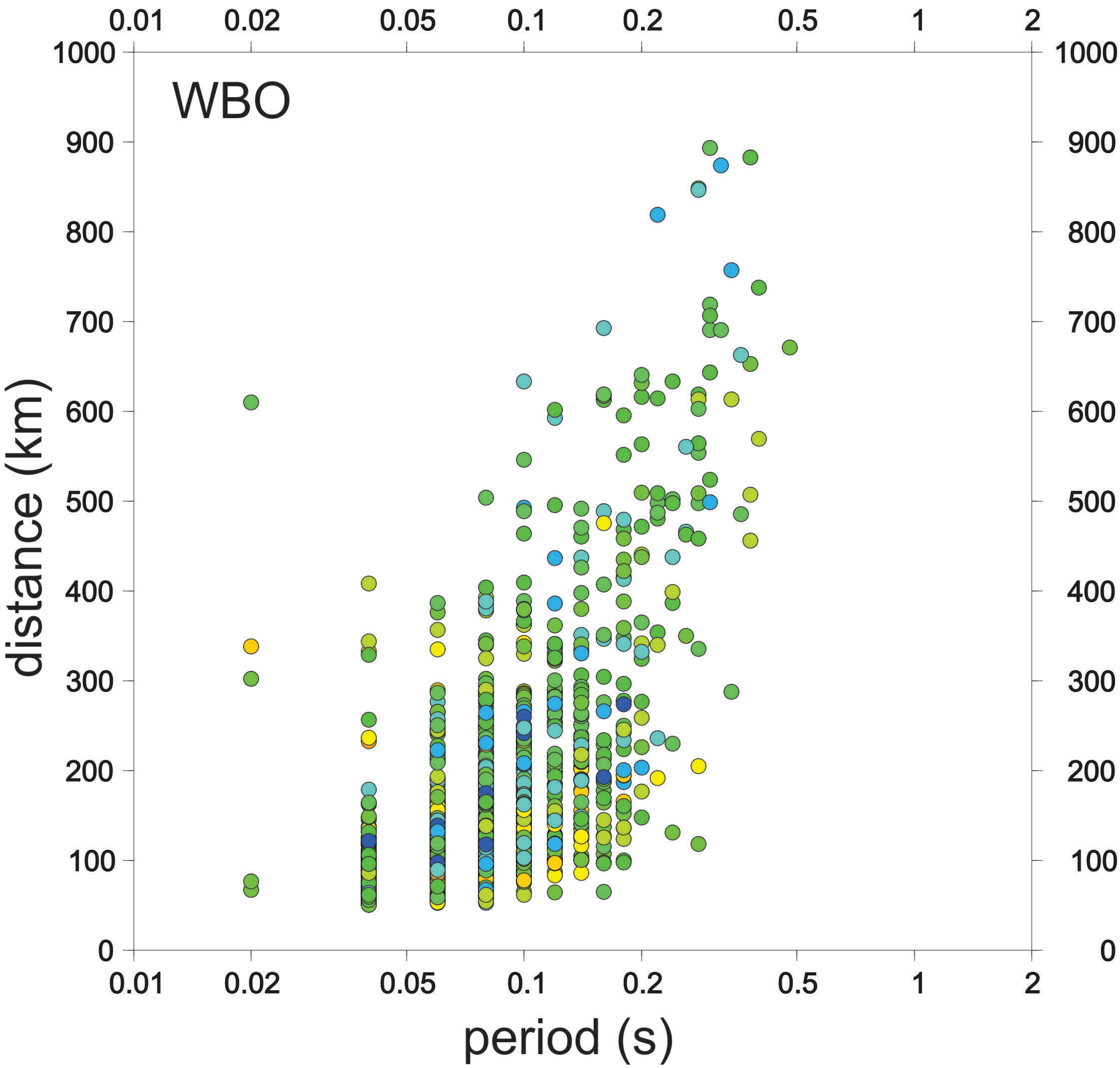


Figure 9w

Figure 9: Magnitude residuals after the station correction has been applied shown as a function of period and distance. The color scheme is the same as in Figure 1. For those stations with more than one instrument at the same site, all are shown and the instrument specific corrections were applied. a) A61, b) ALFO , c) BANO, d) BATG, e) CNQ, f) CRLO, g) DAQ, h) DPQ, i) EEO, i) GAC, k) GRQ, l) GSQ, m) ICQ, n) ILON, o) MNQ, p) MOQ, q) PEMO, r) PLVO, s) SADO, t) SMQ, u) TRQ, v) VLDQ DQ and w) WBO

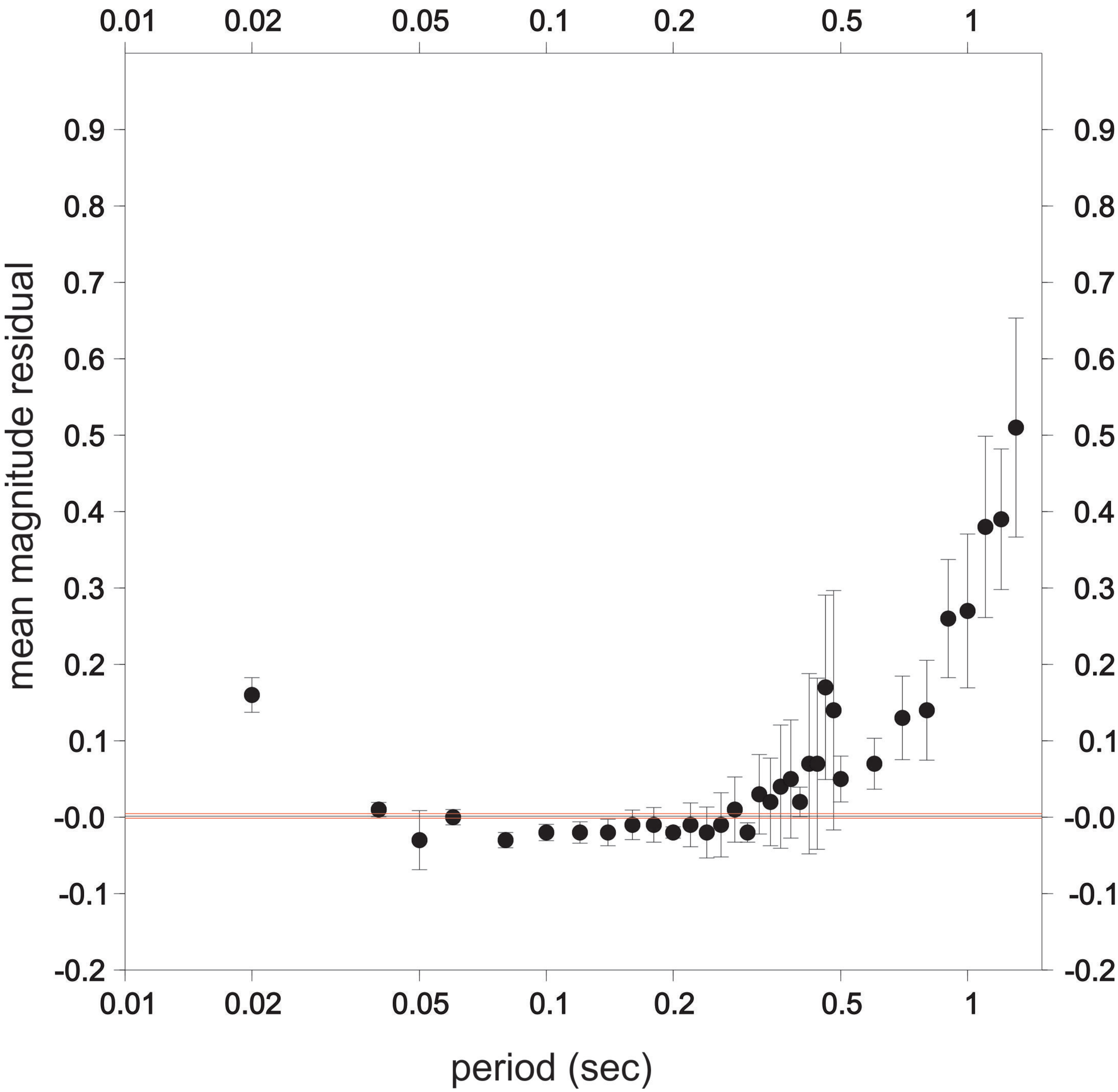


Figure 10. Mean magnitude residuals for the combined group of regional data sets discussed in the text plotted by period. Error bars show the 99% confidence intervals. The black and red horizontal lines show the mean and 99% confidence values for the complete data set, respectively.