Systematic Analysis of Earthquake Sequences of Southeastern Canada

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ABSTRACT

Significant clusters of earthquakes occur in southeastern Canada. The Geological Survey of Canada's earthquake database has been subdivided into groups of foreshock(s)-mainshock-aftershock(s) sequences. A statistical analysis of these sequences is made. Special analysis indicated that all foreshocks and more than half (62%) of associated events (possible aftershocks) can be considered as non-random events (real aftershocks). Using our catalogue and plots one can say in particular how many events of given magnitude have no aftershocks (or foreshocks), have just one aftershock (or foreshock) or have more than one aftershock (or foreshock). Some prognostic estimations are carried out. For example, probability that a magnitude 4.4 earthquake is a foreshock is only 6%; probability that a magnitude 4.4 earthquake will have at least one aftershock within 5 years is 48%, and the probability about 50% that this aftershock will be of magnitude 3.4 or greater.

INTRODUCTION

Eastern Canada is defined here to be the part of Canada east of the Cordillera and extending from the northern border of the United States to the Arctic Ocean. Seismicity of the southern part of eastern Canada was described by Smith (1962, 1966). Later Basham et al. (1979) analyzed seismic hazard in eastern Canada. Still later Hasegawa et al. (1985) reviewed crustal stresses in eastern Canada, and Hasegawa (1986) described eastern Canadian seismotectonics. The problems of eastern Canadian seismic hazard estimation was discussed by Basham and Adams (1989), and a recent review of eastern Canadian seismotectonics and seismicity was carried out by Adams and Basham (1989, 1991).

Most of the seismicity of the southern part of the continental region is contained in four zones: western Quebec, which includes a band of earthquakes along the Ottawa River and a band north of the river; Charlevoix which is the location of many strong and numerous small earthquakes; Lower St. Lawrence, a source of small earthquakes; and the northern Appalachians zone which includes one of the strongest events of the last 50 years - the Miramichi earthquake of 1982 (Adams and Basham, 1991). The Appalachian zone as defined includes some earthquakes in New England. Fig. 1 represents southeastern Canadian seismicity studied and shows the four zones mentioned above.

A significant cluster of earthquakes occurs mostly in western Quebec, extending to eastern Ontario across the Ottawa River. In this region there were several strong earthquakes with magnitudes about 6, and many smaller events with magnitude 4.3 or less. The Charlevoix zone is the most active in eastern Canada, being the source of several large (possibly up to magnitude 7) earthquakes over the last four hundred years. The Lower St. Lawrence zone has no known large earthquakes but has many earthquakes with magnitudes 3 and 4. The northern Appalachian region including most of New Brunswick and extending to New England had several known earthquakes with magnitudes between 5 and 6, and many events with magnitude above 3.

CRITERIA FOR FORESHOCKS-MAINSHOCKS-AFTERSHOCKS SELECTION

As the result of many years of instrumental observations many earthquake records were obtained. After interpretation of these records, a detailed catalogue (GSC's earthquake database) was compiled, which includes the information on all eastern Canadian earthquakes from 1534 to 1994. This catalogue contains standard data on time and earthquake coordinates, magnitude, source depth etc. But, to solve the problems of eastern Canadian earthquake statistical analysis and to make forecasts we need to sample event groups consisting of mainshocks and their foreshocks and aftershocks (if any present).

I considered earthquakes which had occurred in southeastern Canada during the period from 1935 to 1994. I excluded from consideration all events before 1935 because the catalogue for that period of time is not complete enough to fulfil objective research and make conclusions. The earthquake catalogue was subdivided into groups. Each group contains foreshock(s) (if any occurred) - mainshock(s) - aftershock(s) (if any occurred) for one mainshock. I examined mainshocks with magnitudes (m_{bLg}) not less than 3.0 and found 482 groups. To find the above mentioned groups I used the following criteria: first, the strongest event in the catalogue was considered to be a mainshock, and its foreshocks and aftershocks identified. Each successive mainshock was defined to be the strongest event remaining in the catalogue which had not yet been defined to be a foreshock, mainshock or aftershock. Foreshocks were defined by the following conditions:

$$(\varphi_f)^2 + (\lambda_m - \lambda_f)^2)^{1/2} < 0.05$$

$$(\text{date(msh)} - 3 \text{ months} < \text{date(fsh)}) < \text{date(msh)},$$

where φ_m, λ_m - latitude and longitude of the mainshock;

φ_f, λ_f - latitude and longitude of a foreshock;

date(msh) - date of the mainshock;

date(fsh) - date of a foreshock.

For the same mainshock all associated aftershocks were defined by the conditions:

$$((\varphi_m - \varphi_a)^2 + (\lambda_m - \lambda_a)^2)^{1/2} < 0.25$$

$$\text{date(msh)} < \text{date(afsh)} < (\text{date(msh)} + 5 \text{ years}),$$

where φ_a, λ_a - latitude and longitude of an aftershock;

date(afsh) - date of an aftershock

Then we take the next strongest event not yet identified as a foreshock, mainshock or aftershock to be a mainshock and find its foreshocks and aftershocks, etc. This procedure was done for all earthquakes. Finally, I compiled catalogue which consists of groups, each group includes the mainshock and its foreshock(s) and aftershock(s) (if any occurred). My catalogue contains the following new information about each earthquake sequence: the number of foreshocks and aftershocks, the magnitudes of largest foreshock and largest aftershock, the difference between the mainshock and each its foreshock (aftershock) magnitudes. I use this information for southeastern Canadian earthquakes statistical prognosis estimations.

In order to check up if there is a strong influence of incomplete data for the early periods of time, I repeated the analysis and most of the plots described below for the time period from 1970 to 1994. The comparison of plots for both cases (time periods of 1935-1994 and 1970-1994) showed their good conformity. So I shall describe the results for earthquakes of 1935-1994 time period.

ANALYSIS OF THE COMMON EARTHQUAKE ACTIVITY IN SOUTHEASTERN CANADA

In order to make statistical analysis of earthquakes sequences we plotted some figures. Fig. 2 shows the cumulative rate of all earthquakes versus magnitude value. The magnitude range from 1.5 to 3.0 includes the most earthquakes. The departure from a straight line relationship (Gutenberg-Richter law) near magnitude 3.0 reflects an incomplete catalogue for smaller magnitudes; this has some effect on deciding whether a (say) magnitude 3.5 earthquake has aftershocks or not. Fig. 3 shows the cumulative rate of mainshocks as a function of magnitude. We see that the number of earthquakes decreases as the earthquake magnitude increases; and magnitude 3.0 corresponds to the largest number of mainshocks (N=128). This result is in accordance with Gutenberg-Richter relationship.

REAL FORESHOCKS-AFTERSHOCKS OR ASSOCIATED EVENTS?

The question appears: which of the earthquakes in each group is a real foreshock or aftershock and which are just associated events which happened by chance? In order to find an answer to this question, I carried out the following analysis. I took the cumulative rate curves for different zones of seismic activity in eastern Canada (Basham et al., 1982), which show how many events of each magnitude occur in each zone per year on average, determined the zone rate for the magnitude corresponding to that of the foreshock (or aftershock) and then recalculated the cumulative rates for the specific areas and time intervals that corresponding to the spatial and temporal separation between each foreshock (or aftershock) and its mainshock. Then I supposed that if the expected cumulative rate for the foreshock (or aftershock) is less or equal 0.05 it is a real foreshock (or aftershock), effectively a 95% confidence level. Otherwise, I consider the earthquake just as associated one (i.e. not clear if it is causal or random). My analysis indicated that all of foreshocks and more than a half (62%) of associated events can be considered as non-random events (real aftershocks). Looking at these numbers one should take into account that 38% of aftershocks can be either random or non-random events. About 85% of all associated (possibly random) events are in the most active zone, Charlevoix. This is the only zone for which the number of associated events is more than the number of real related events (aftershocks). Using these results we shall make our following analysis for related (real) foreshocks and aftershocks.

Fig. 4 represents the time-distance plot for real aftershocks and associated events with magnitude not less than 1.5. One can see that the less the time and the distance differences between mainshock and aftershocks, the more real aftershocks occur. For mainshock-aftershock distance differences up to about 9 km there are only real aftershocks.

Figs. 5 and 6 show the difference between real aftershock (associated event) and mainshock magnitudes (M_m-M_a) versus the difference between real aftershock (associated event) and mainshock origin times (Fig. 4) or real aftershock (associated event) and mainshock epicentres (Fig. 5) for real aftershocks and associated events with magnitude not less than 1.5. One can see from these figures, that the closer an aftershock and mainshock (in time and (or) in distance), the higher the probability that this is a real aftershock, and vice versa.

ANALYSIS OF AFTERSHOCK ACTIVITY IN SOUTHEASTERN CANADA

The situation with aftershock activity is shown on Figs. 7-9. Fig. 7 shows the number of aftershock s versus mainshock magnitude. One of the earthquakes with m_{bLg}=5.7 (the Miramichi earthquake) has the largest number of aftershocks (N=447). In fact the activity continues to the present (1995), so for this earthquake only all aftershocks more than 5 years after the mainshock have been included. It can be seen that the number of aftershocks is not strongly dependent on the magnitude of the mainshock. Fig. 8 is the plot of largest aftershock magnitude for each mainshock which had aftershocks. It shows that usually the difference between a mainshock and its strongest aftershock magnitudes ranges within the limits from 0.1 (by definition) to 1.5. Table 1 represents the number of aftershocks without, with just one, or with more than one aftershock, and the total number of mainshocks for each magnitude value. Fig. 9 shows the percentage of mainshocks without aftershocks and with just one aftershock. In order to smooth the data for different magnitudes which depend on earthquake activity, we averaged data on Fig. 9 by a 5-point sliding window. Based on these data we can evaluate the probabilities that a mainshock with a given magnitude value would have no aftershocks or just one aftershock. For example, more than a half (~67%) of the mainshocks with magnitude 4.5 have no aftershocks in the catalogue, and about one tenth (~10%) of the mainshocks with magnitude 4.5 have just one aftershock. Thus about one fourth (~23%) of such mainshocks have more than one aftershock.

ANALYSIS OF FORESHOCK ACTIVITY IN SOUTHEASTERN CANADA

As a next step we considered the situation with foreshocks in the same region and during the same time period (Figs. 10-14).

Fig. 10 shows the strongest foreshock magnitude for each mainshock. As one can see from this figure, the magnitude difference between mainshock and strongest foreshock is usually 0.1 - 2.0.

Table 2 represents the number of mainshocks without, with just one or with more than one foreshock, and the total number of mainshocks for each magnitude value. Fig. 11 shows the percentage of mainshocks without foreshocks in the catalogue, with just one, or with more than one foreshock. One can see, for example, that about three fourths of Eastern Canadian earthquakes with magnitude 4.5 have no foreshocks, about one fourth has one foreshock and there no such earthquakes with more than one foreshock. Figs. 12 and 13 show the time lag of all foreshocks; x-axes are mainshock magnitudes (Fig.12) and foreshock magnitudes (Fig. 13). In particular one can see that about one third of foreshocks occurred on the same day as their mainshocks, and, for example, more than a half of foreshocks occurred less than 10 days before their mainshocks. It is interesting that there are no foreshocks with a lag from 10 to 40 days (see Figs. 12 and 13). If this is not due to statistical chance, it may represent a time of quiescence or seismic gap 10 to 40 days before mainshocks. I plan to do the analysis of clusters and gaps for Southeastern Canada in my future investigations. Fig. 14 represents the cumulative rate of foreshocks versus their time lag. This figure shows that the number of foreshocks steady decreases with logarithm of time. One can see from this plot that one fifth of the foreshocks occurred during the hour before the mainshock.

ANALYSIS OF SOME EARTHQUAKE SEQUENCES

As examples of using of our catalog we examined two strong earthquakes with their foreshocks and aftershocks. Firstly, we consider the Saguenay earthquake of 25-Nov-1988, with a magnitude m_{bLg}=6.5. This earthquake had one foreshock on 23-Nov-1988 with m_{bLg}=4.6 and 61 aftershocks, with maximal aftershock magnitude m_{bLg}= 4.1 on 26-Nov-1988. There were no associated events for this earthquake, just real aftershocks. Almost all aftershocks occurred during 4 months after the mainshock, four aftershocks occurred during the period from 4 months up to 1 year after the mainshock, and two more aftershocks occurred 3 years later than the mainshock. So there was a quiescence after the mainshock during about 2 years.

Fig. 15 is the plot of foreshock, mainshock, aftershock magnitudes versus number of days from the date of the foreshock. Fig. 16 shows the cumulative number of aftershocks for various differences between mainshock and aftershock magnitudes.

Using this plot one can evaluate the probability of aftershock which differs from its mainshock by a certain value of magnitude. For example, this plot shows that the Saguenay earthquake had 59 aftershocks with magnitude 3.5 or less and just 16 aftershocks with magnitude 1.5 or less.

Secondly, let us consider the Miramichi earthquake dated 09-Jan-1982 (m_{bLg}=5.7). It had two foreshocks with magnitudes of 3.7 (on 28-Nov-1981) and 1.8 (on 06-Jan-1982), and 447 aftershocks. There were no associated events for Miramichi earthquake, just real aftershocks.

One strong aftershock, with a magnitude of 5.3, occurred on the same day as the mainshock, and the strongest aftershock (which could be considered to be a second mainshock), with a magnitude of 5.5, occurred two days later (on 11-Jan-1982). Other strong aftershocks, with the magnitudes of 3.5-4.8, occurred approximately every 150-200 days for the first three years and thereafter - approximately every 300-400 days. Fig. 17 shows the plot of foreshocks, mainshock, aftershocks magnitudes versus the number of days from the date of the first foreshock. Fig. 18 shows the cumulative number of aftershocks for the Miramichi earthquake versus the difference between the mainshock and aftershock magnitudes (M_m-M_a). This plot shows, for example, that for Miramichi earthquake there were 313 aftershocks with magnitude 2.7 or less and just 39 aftershocks with magnitude 1.7 or less.

CONCLUSIONS

I have conducted analysis of southeastern Canadian earthquakes which occurred since 1935. I created the new catalogue which contains foreshock(s)-mainshock-aftershock(s) sequences for each earthquake during the period from 1935 to 1994. Using this catalogue I made the plots which permit to conduct statistical analysis of southeastern Canadian earthquakes; to make probability estimations of foreshock-aftershock activity, that can be useful for forecasting purposes. Having my catalogue and plots one can estimate the probability of a certain aftershock value, the probability of the fact that a strong aftershock would occur within a certain period of time after the mainshock or that the mainshock of given magnitude would not have any foreshocks (aftershocks) or would have exactly one foreshock (aftershock), etc. Fig. 19 shows the probability of the fact that an event of given magnitude will be followed by a larger quake at the same location within 3 months (circles), and the probability it will be followed by any aftershocks (stars) within five years. Fig. 20 shows the probability that if the aftershock would occur it would be of magnitude within 0.5 (triangles) or 1.0 (diamonds) magnitude units of the mainshock, or that, if the event (foreshock) would be followed by a larger quake (mainshock), the magnitude of that quake (mainshock) will be by 0.5 (stars) or by 1.0 (circles) units more than initial event magnitude. In order to smooth the data for different magnitudes which depend on earthquake activity, I averaged data on Figs. 15 and 16 by a 5 point sliding window. Using these plots one can make some useful estimations. For example, when a magnitude 4.1 earthquake occurs in eastern Canada, the public can be comforted to know there is only a 2% chance of a larger quake within 3 months (Fig. 15), and the probability only about 2% that the subsequent event will be of magnitude 4.6 or greater (Fig. 16). Meanwhile, when a magnitude 4.1 earthquake occurs in Eastern Canada there is about 50% chance of at least one aftershock within five years, and the probability about 12% that this aftershock will be of magnitude 3.6 or greater.

The next step in this direction may evidently involve application of investigations and, in particular, monitoring of earthquakes clusters and gaps, which may be useful for long-term prediction. Moreover, the comparison with geological and geophysical data would give us new possibilities of seismic regime study and ensure further progress in the seismic hazard problem solution.

ACKNOWLEDGMENTS

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TABLES

Table 1. The number of mainshocks without, with just one or with more than one aftershock, and the total number of mainshocks.

Table 2. The number of mainshocks without, with just one or with more than one foreshock, and the total number of mainshocks.

Table 1

THE NUMBER OF MAINSHOCKS WITHOUT, WITH JUST ONE OR WITH MORE THAN ONE AFTERSHOCK, AND THE TOTAL NUMBER OF MAINSHOCKS

mainshock magnitude Mm	the number of mainshocks A=0	A=1	A>1	N(total)
3.0	49	11	9	69
3.1	35	13	9	57
3.2	24	8	11	43
3.3	19	8	14	41
3.4	32	9	7	48
3.5	18	8	10	36
3.6	10	6	12	28
3.7	15	6	8	29
3.8	9	4	8	21
3.9	8	1	8	17
4.0	9	2	7	18
4.1	7	3	5	15
4.2	3	2	7	12
4.3	9	1	3	13
4.4	4	1	3	8
4.5	2	1	1	4
4.6	2	0	1	3
4.7	3	0	0	3
4.8	2	0	0	2
4.9	2	0	2	4
5.0	1	1	2	4
5.1	0	0	0	0
5.2	1	0	0	1
5.3	0	0	0	0
5.5	0	0	0	0
5.6	0	0	1	1
5.7	0	0	1	1
5.8	0	0	0	0
6.2	0	0	1	1
6.5	0	0	1	1

Table 2

THE NUMBER OF MAINSHOCKS WITHOUT, WITH JUST ONE OR WITH MORE THAN ONE FORESHOCK, AND THE TOTAL NUMBER OF MAINSHOCKS

mainshock magnitude	the number of mainshocks			
Mm	F=0	F=1	F>1	N(total)
3.0	67	2	0	69
3.1	56	1	0	57
3.2	40	3	0	43
3.3	40	1	0	41
3.4	46	1	1	49
3.5	34	2	0	36
3.6	26	2	0	28
3.7	29	0	0	29
3.8	21	0	0	22
3.9	15	2	0	17
4.0	17	1	0	18
4.1	14	1	0	15
4.2	12	0	0	12
4.3	13	0	0	13
4.4	7	0	1	8
4.5	3	1	0	4
4.6	3	0	0	3
4.7	3	0	0	3
4.8	2	0	0	2
4.9	4	0	0	4
5.0	4	0	0	4
5.1	0	0	0	0
5.2	1	0	0	1
5.3	0	0	0	0
5.5	0	0	0	0
5.6	1	0	0	1
5.7	0	0	1	1
5.8	0	0	0	0
6.2	1	0	0	1
6.5	0	1	0	1

FIGURE CAPTIONS

Figure 1. The map of seismicity of southeastern Canada.

Figure 2. The cumulative number of all southeastern Canada earthquakes occurred from 1935 up to 1994 versus the magnitude value.

Figure 3. The cumulative number of mainshocks with different magnitude values.

Figure 4. The difference between real aftershocks (circles) and mainshocks origin time versus the distance between real aftershock and mainshock epicentres (for aftershock magnitudes not less than 1.5).

Associated events are plotted as squares.

Figure 5. The difference between real aftershock (circles) and mainshock magnitude versus the difference between real aftershock (associated event) and mainshocks origin time (for aftershocks magnitudes not less than 1.5).

Associated events are plotted as squares.

The events in the top right corner of the plot are the aftershocks of the Miramichi earthquake.

Figure 6. The difference between real aftershock (circles) and mainshock magnitude versus the difference between real aftershocck and mainshock epicentres (for aftershock magnitudes not less than 1.5).

Associated events are plotted as squares.

Figure 7. The number of aftershocks for each mainshock.

Figure 8. The magnitude of maximum aftershock for each mainshock.

Figure 9. Percentage of earthquakes without aftershocks, with just one aftershock

will be followed by an aftershock with magnitude within 0.5 (triangles) or 1.0 (diamonds) magnitude un its of mainshock.

Figure 1. The map of seismicity of southeastern Canada.

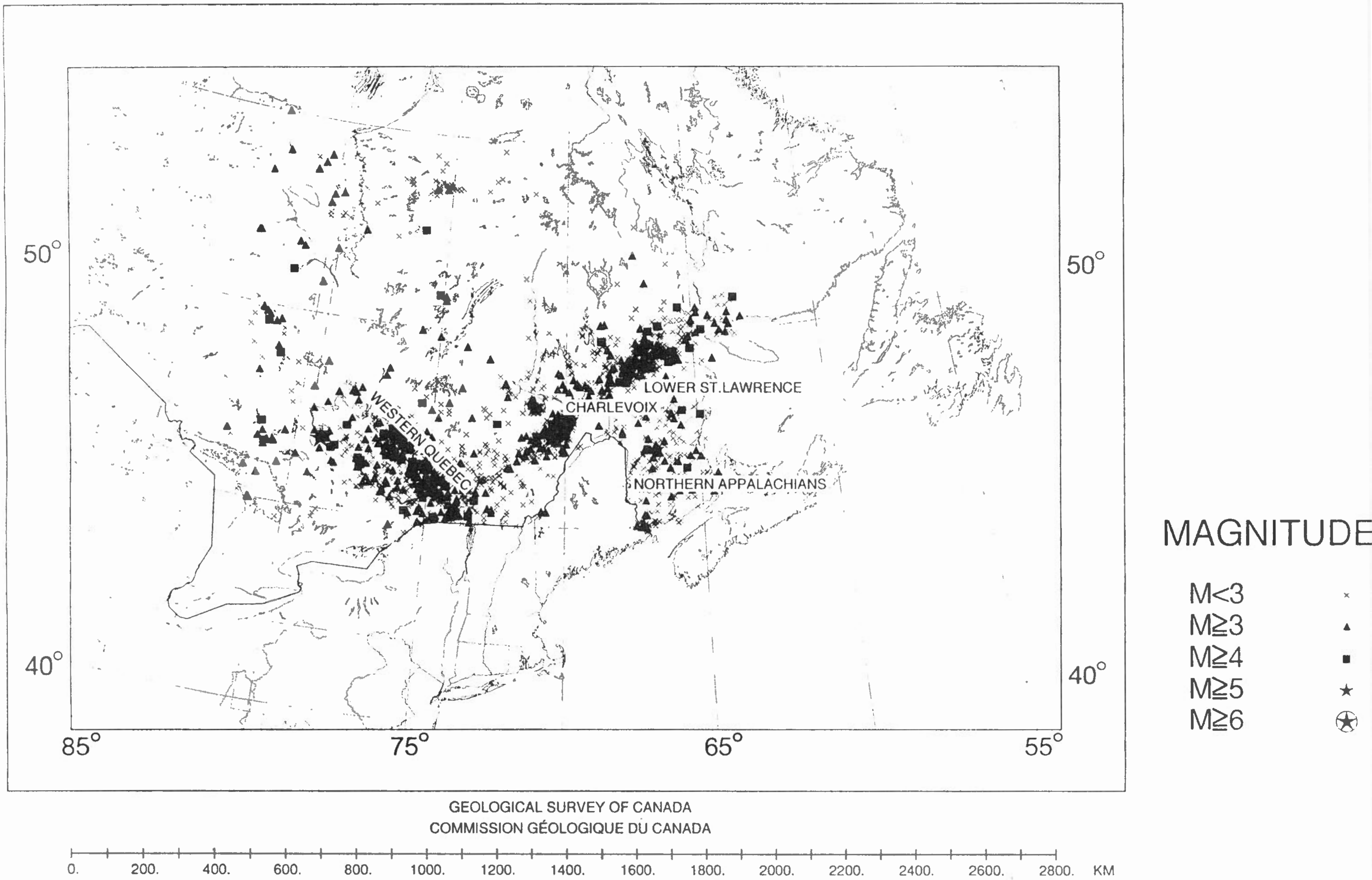


Figure 2. The cumulative number of all southeastern Canada earthquakes occurred from 1935 up to 1994 versus the magnitude value.

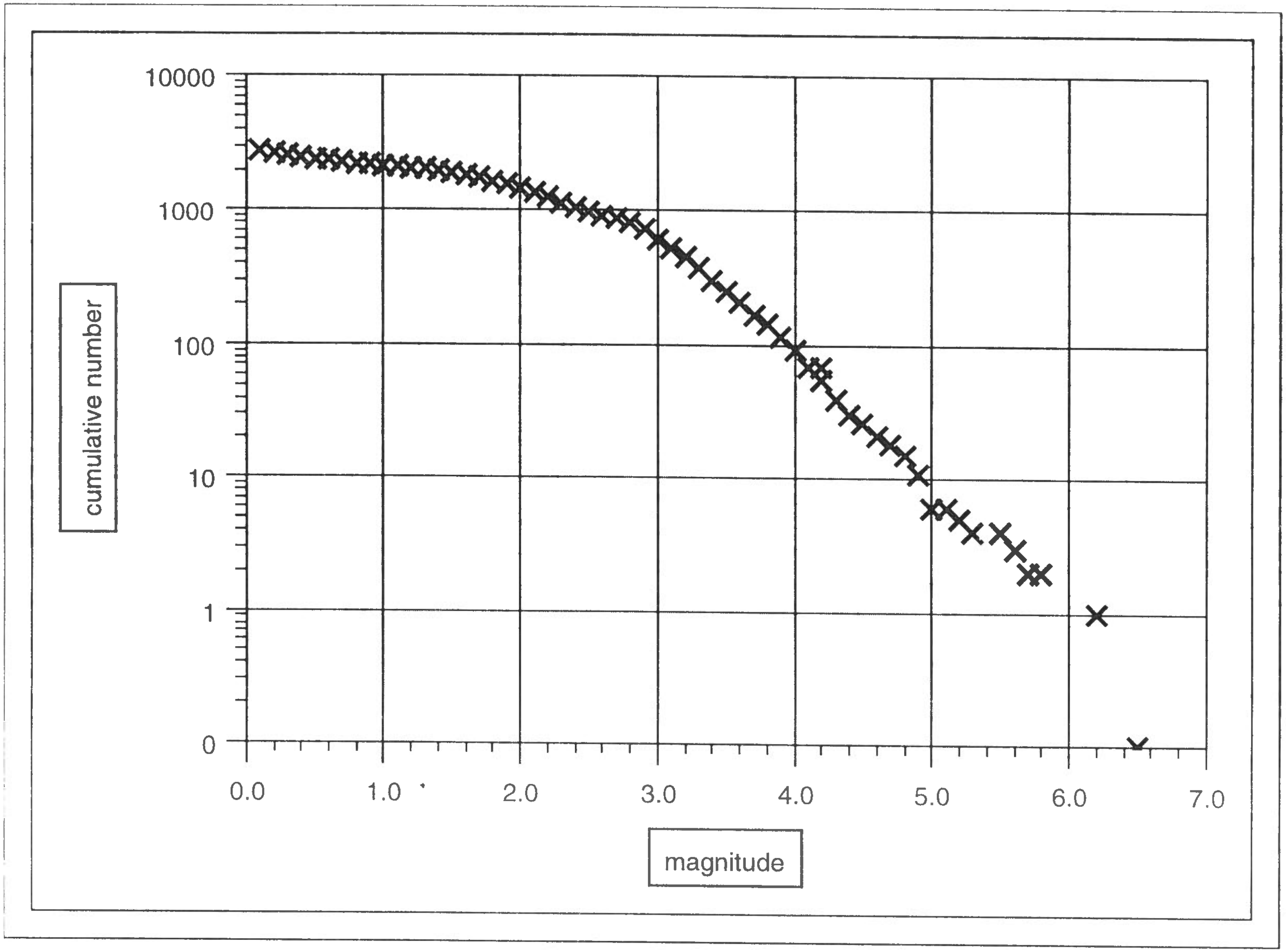


Figure 3. The cumulative number of mainshocks with different magnitude values.

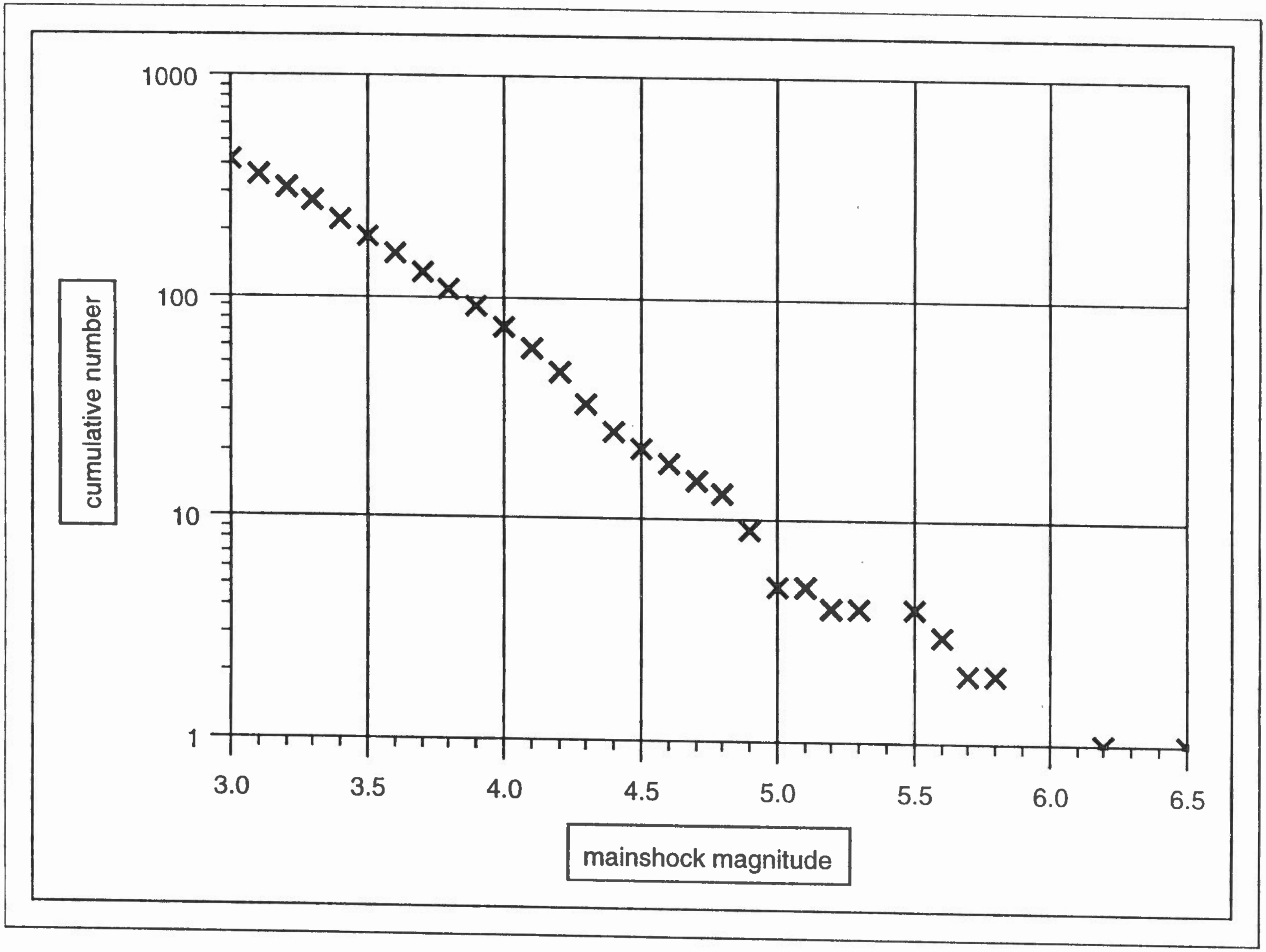
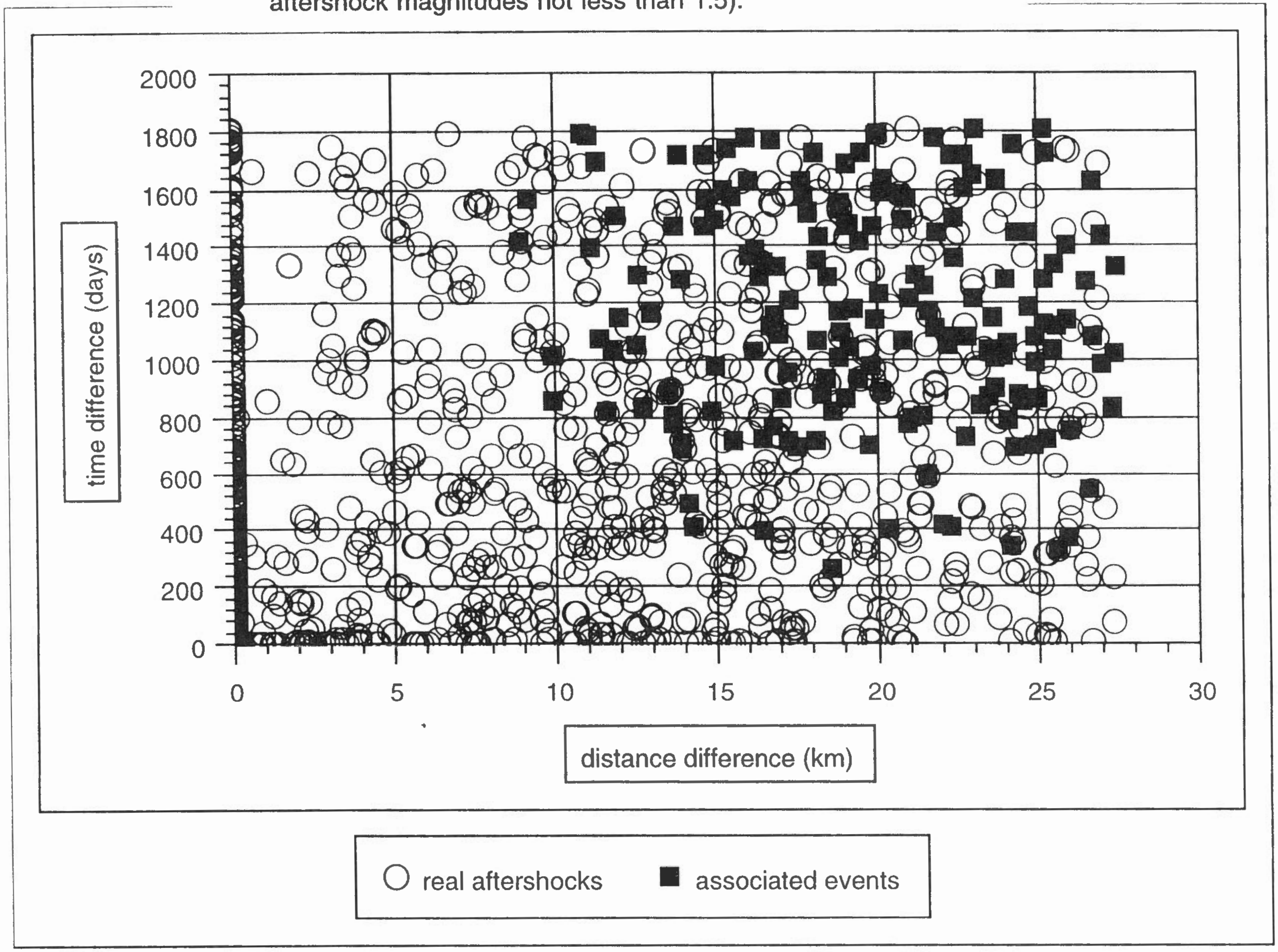
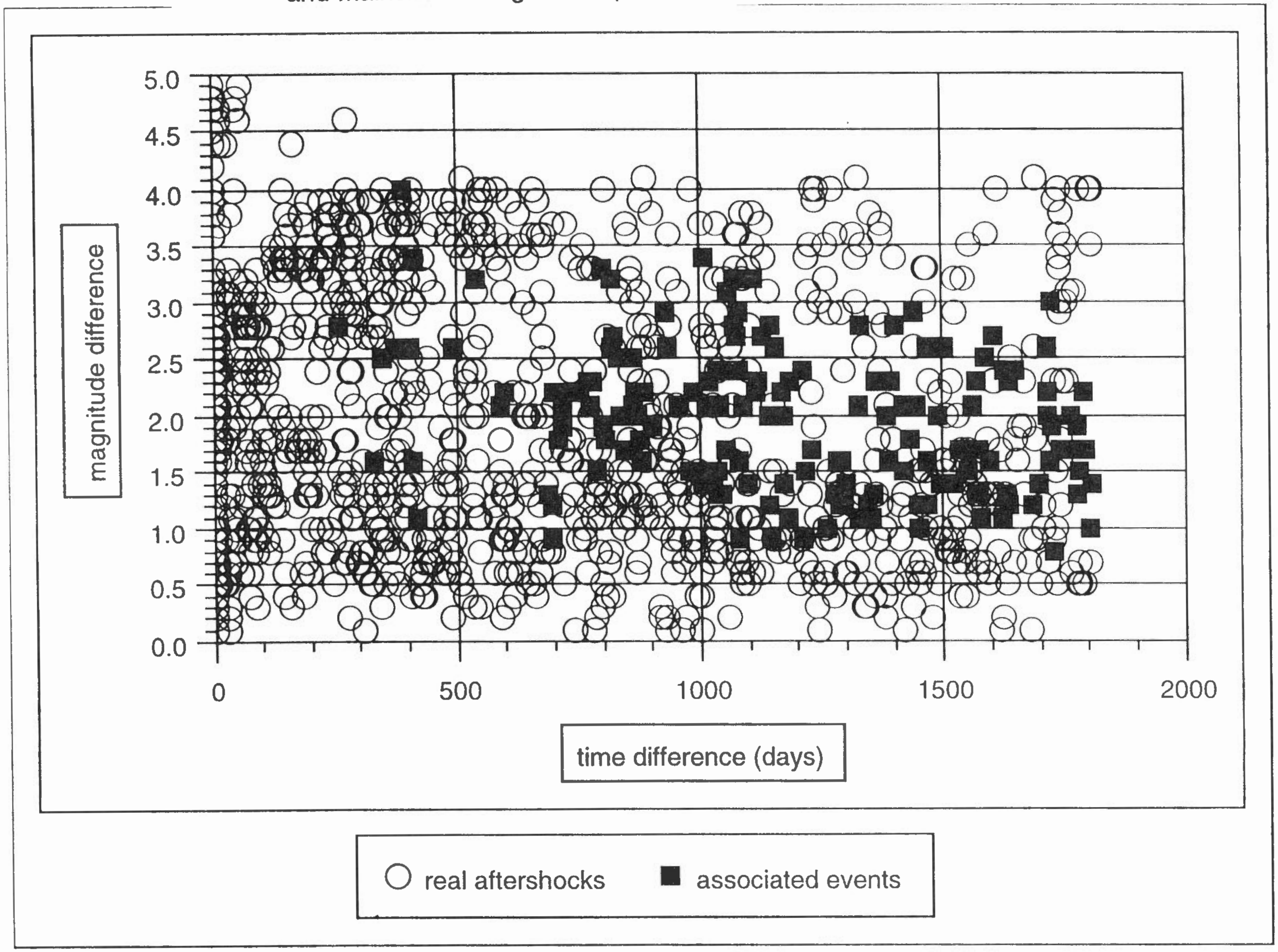


Figure 4. The difference between real aftershocks (circles) and mainshocks origin time versus the distance between real aftershock and mainshock epicentres (for aftershock magnitudes not less than 1.5).



Associated events are plotted as squares.

Figure 5. The difference between real aftershock (circles) and mainshock magnitude versus the difference between real aftershock (associated event) and mainshocks origin time (for aftershocks magnitudes not less than 1.5).



Associated events are plotted as squares.

The events in the top right corner of the plot are the aftershocks of the

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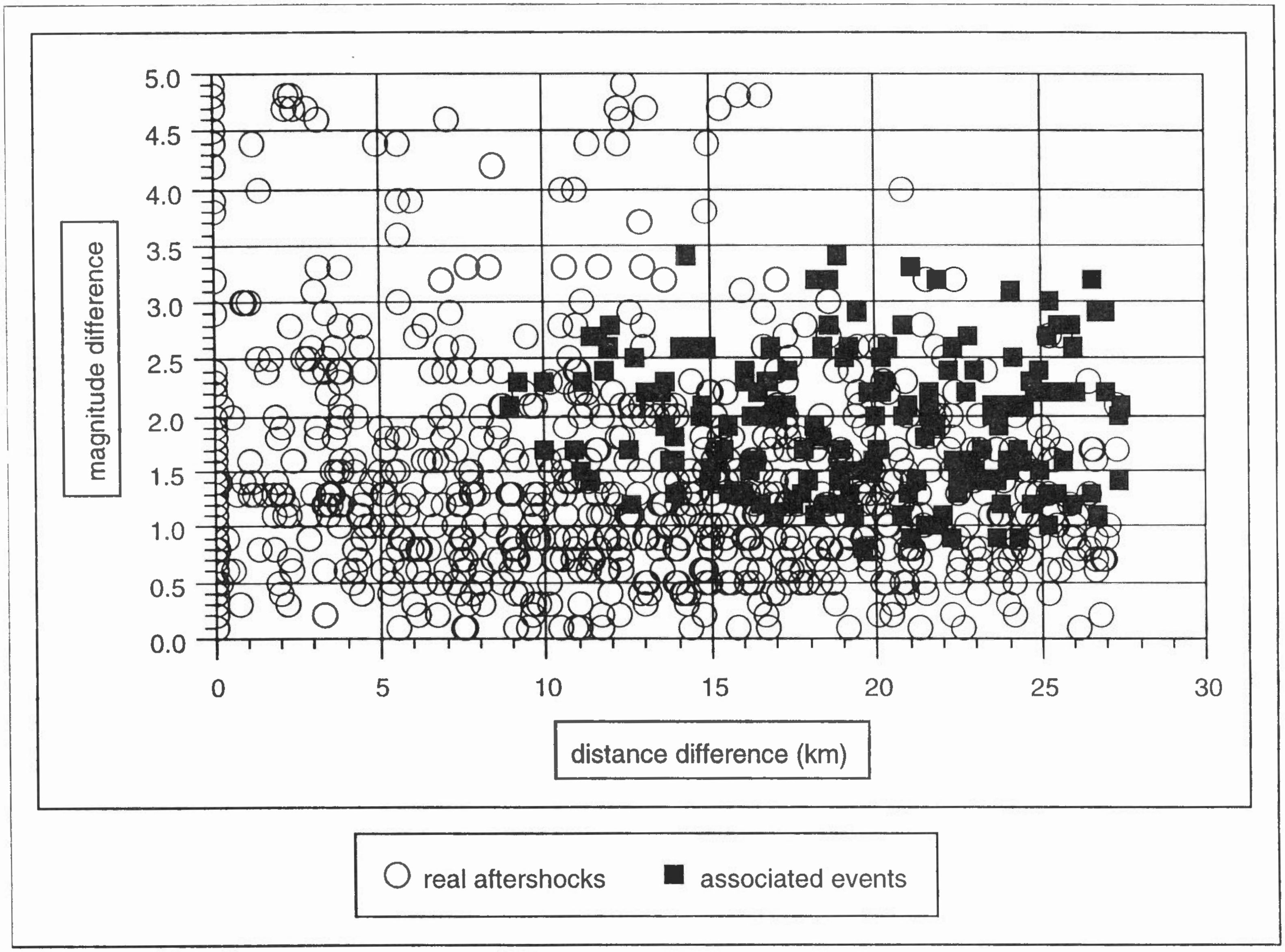


Associated events are plotted as squares.

Figure 7. The number of aftershocks for each mainshock.

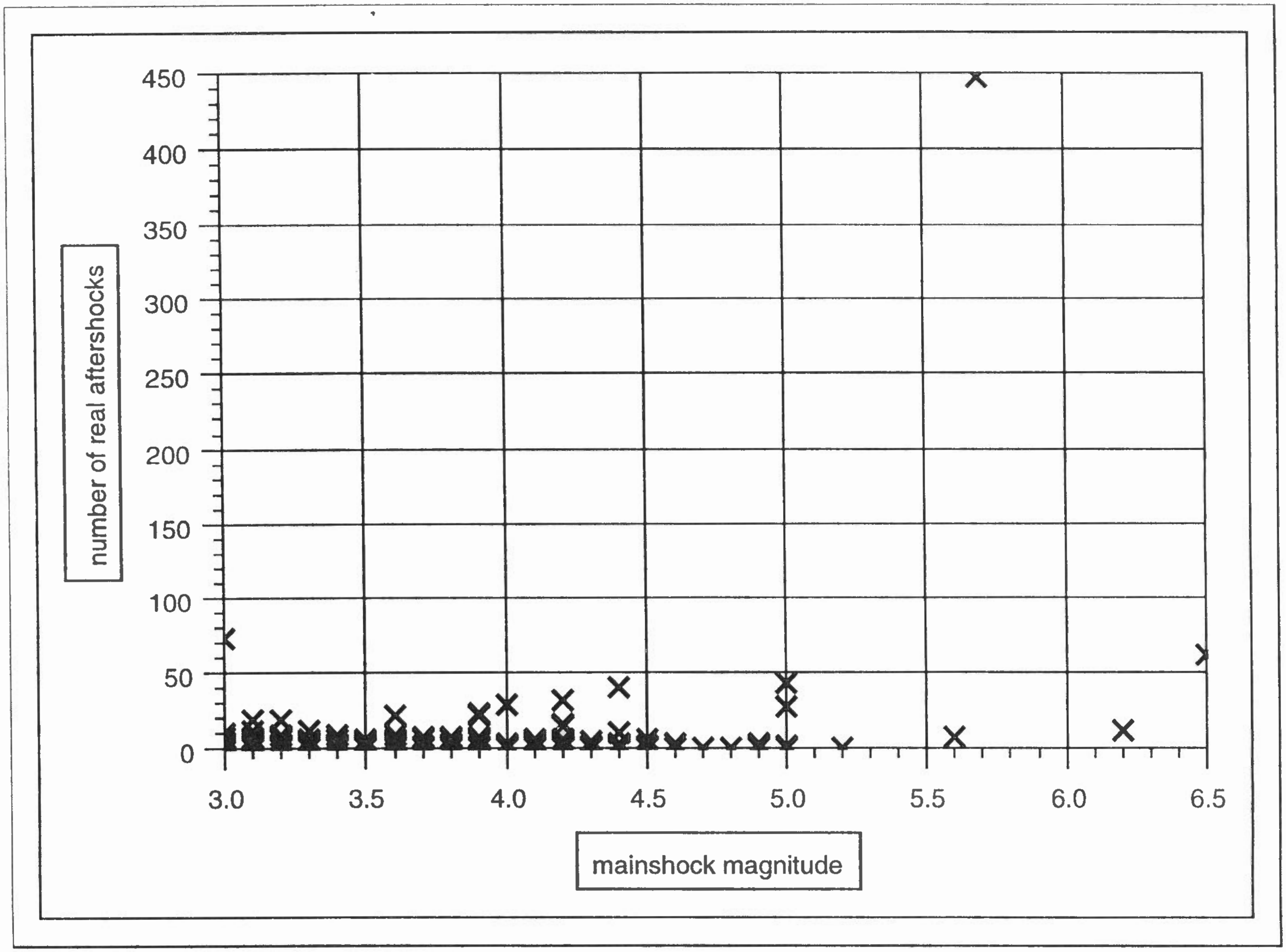


Figure 8. The magnitude of maximum aftershock for each mainshock.

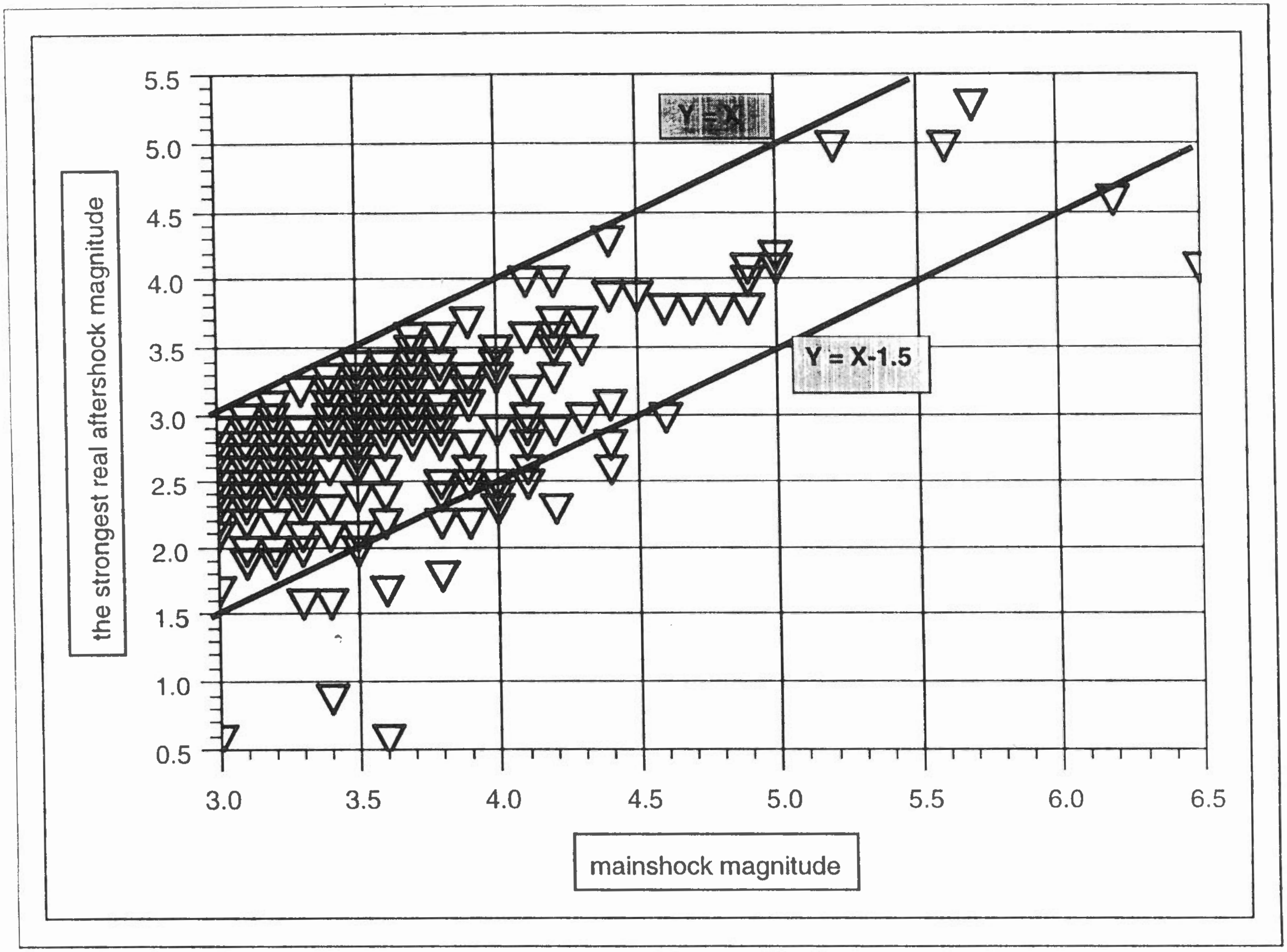


Figure 9. Percentage of earthquakes without aftershocks, with just one aftershock or with more than one aftershock.

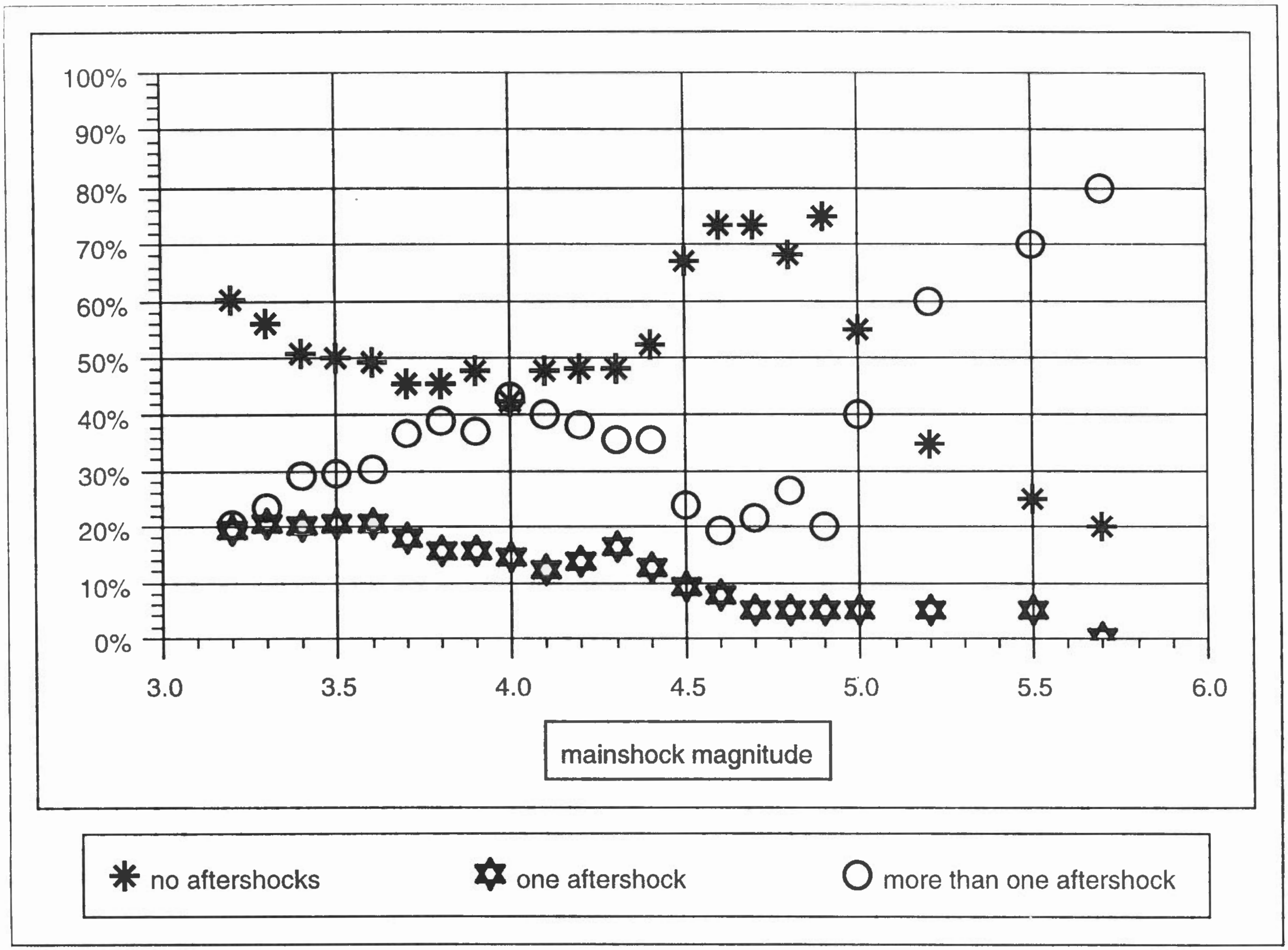


Figure 10. Magnitudes of mainshocks versus magnitudes of their strongest foreshocks.

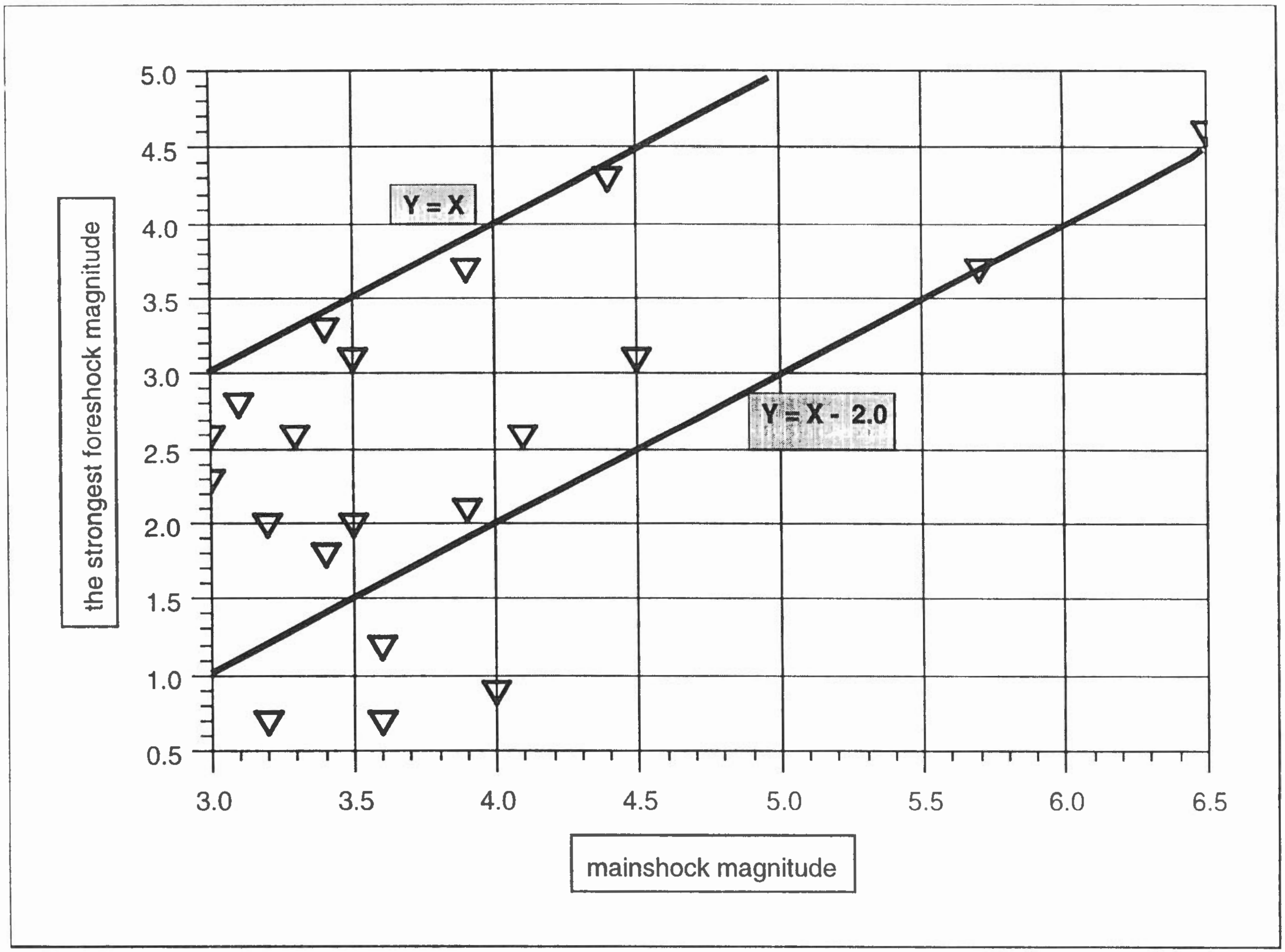


Figure 11. Percentage of earthquakes without foreshocks , with just one foreshock or with more than one foreshock.

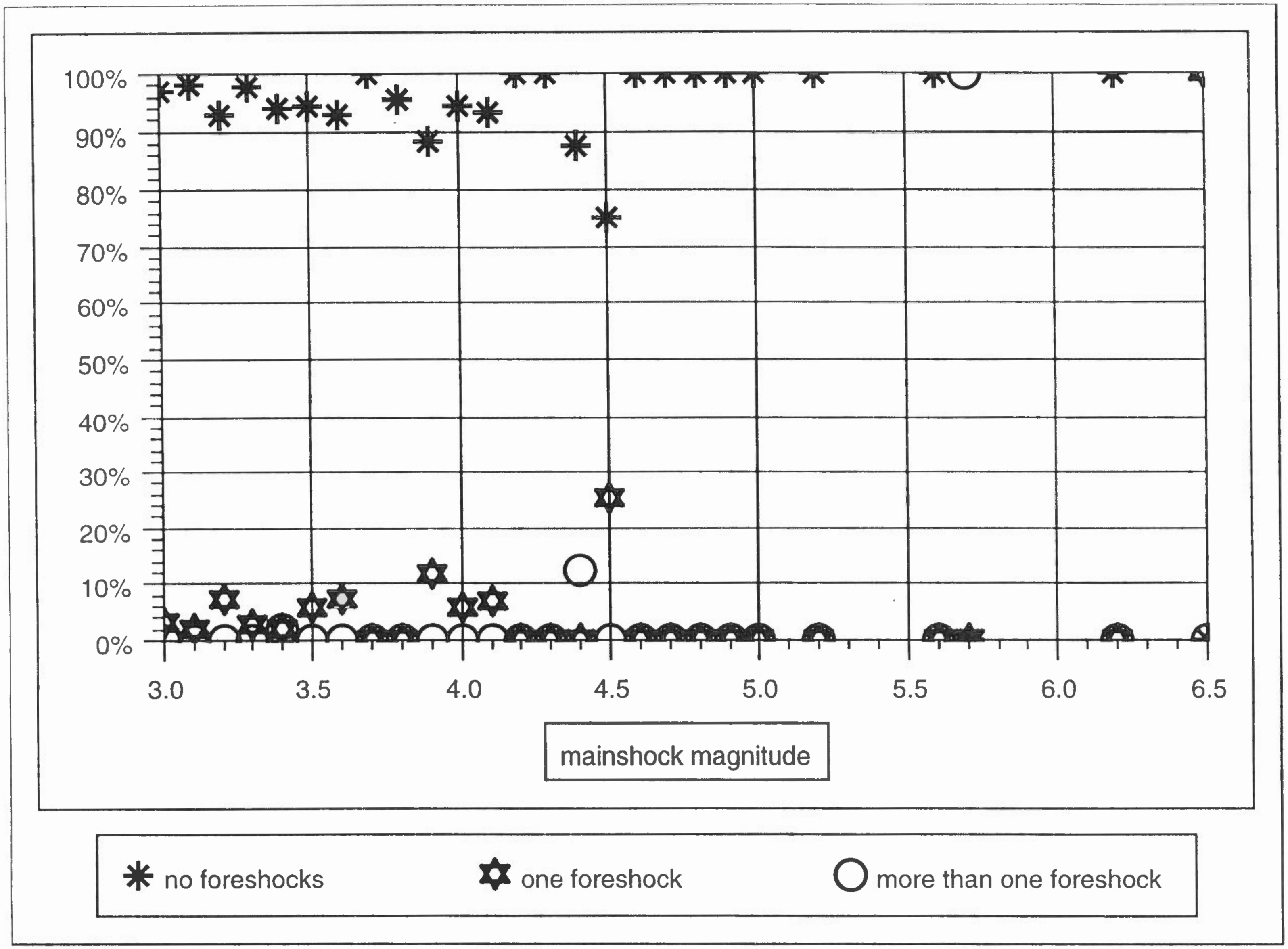


Figure 12. The time lag of foreshocks versus mainshock magnitude.

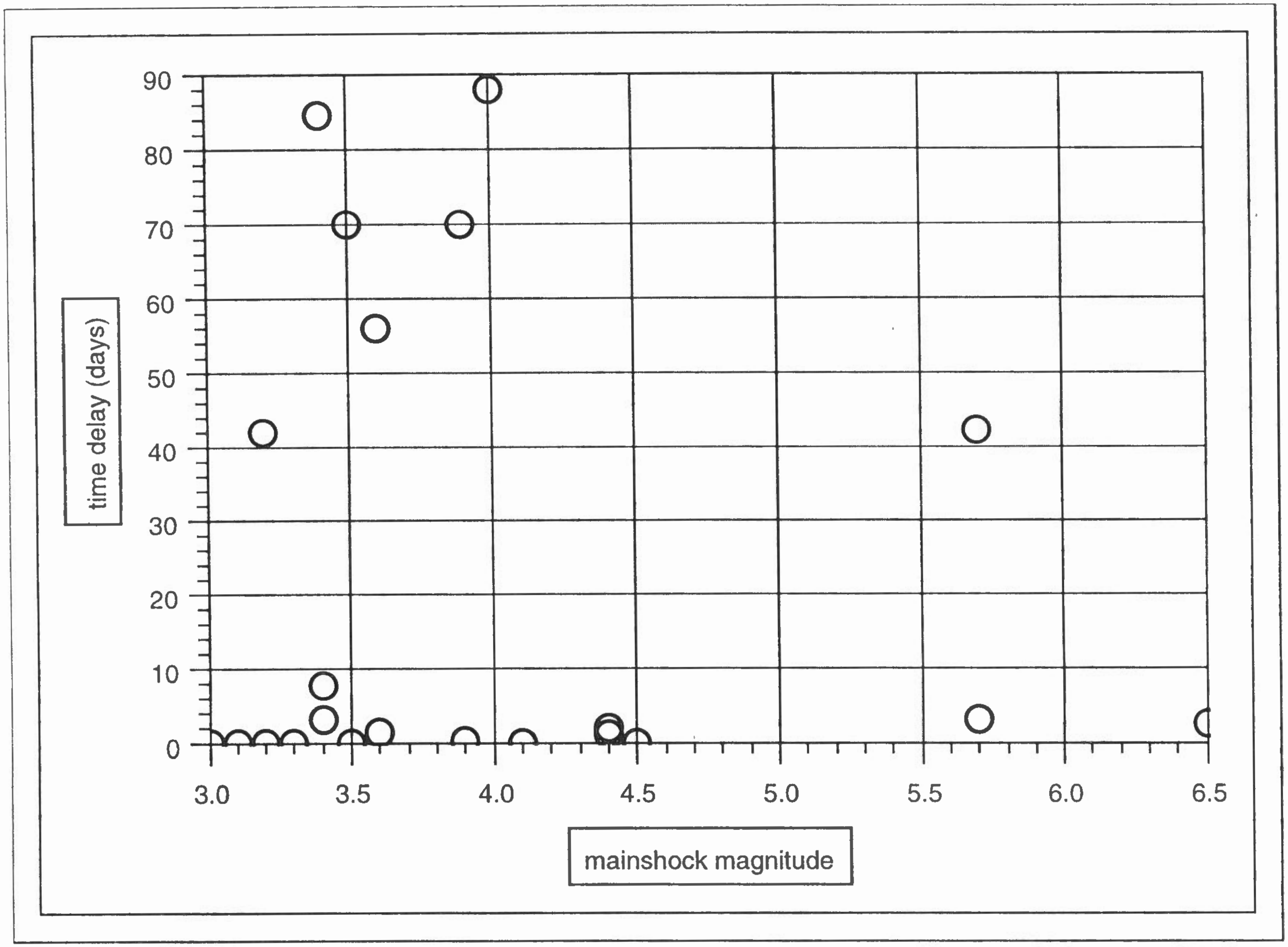


Figure 13. The time lag of all foreshocks versus foreshock magnitude.

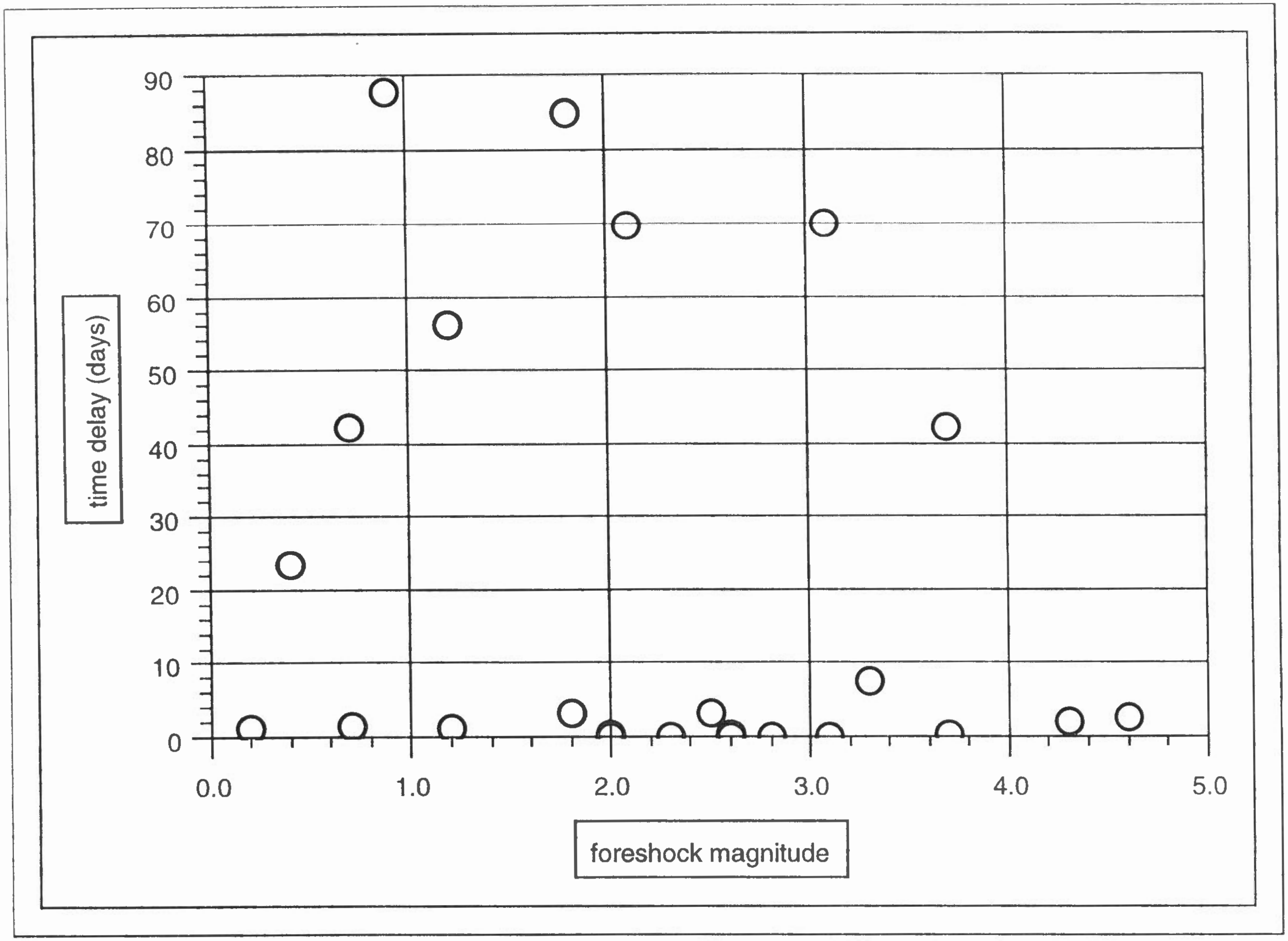


Figure 14a.Cumulative number of foreshocks versus their time lags.

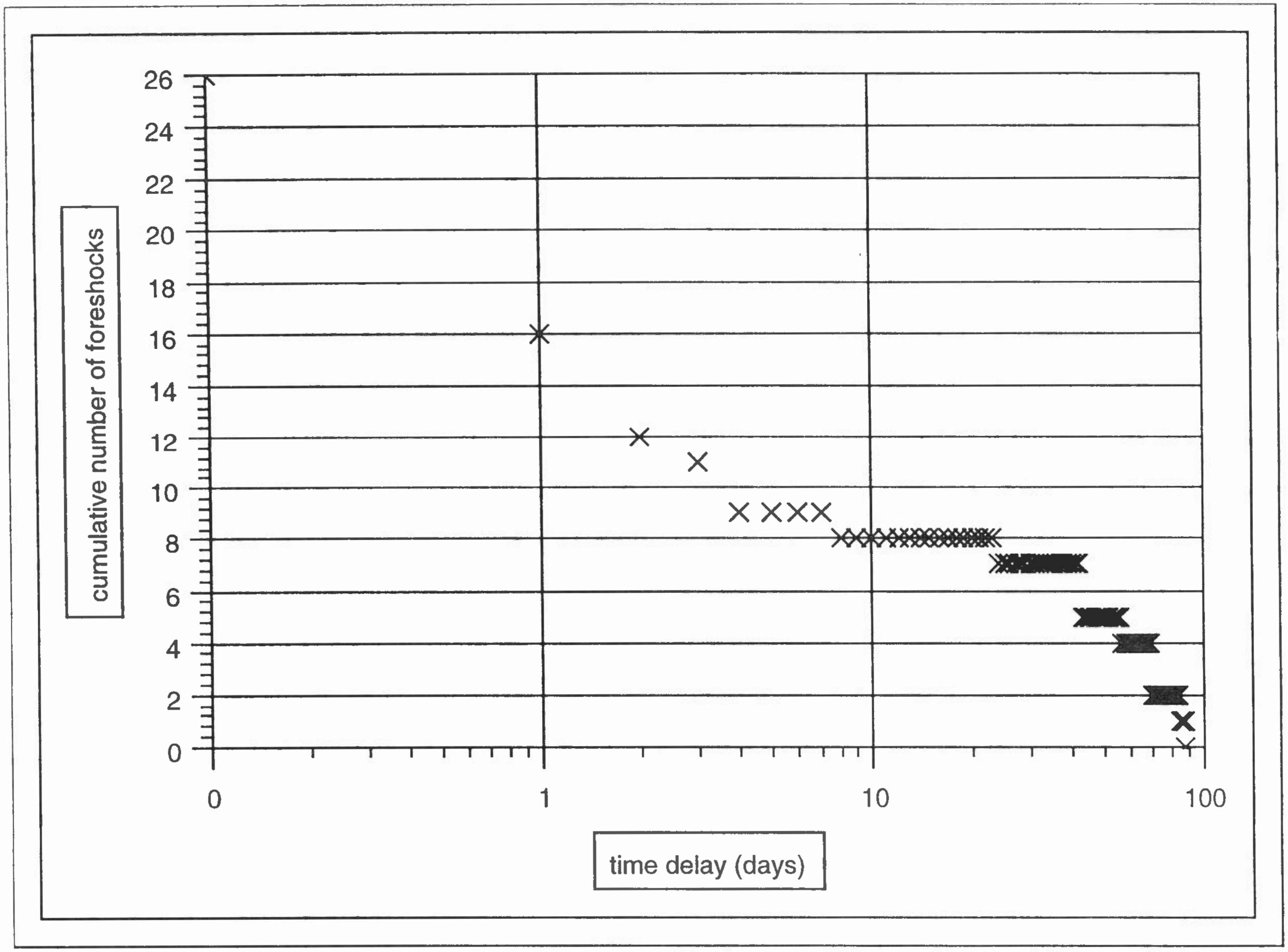


Figure 14b. Cumulative number of foreshocks versus their time lags.

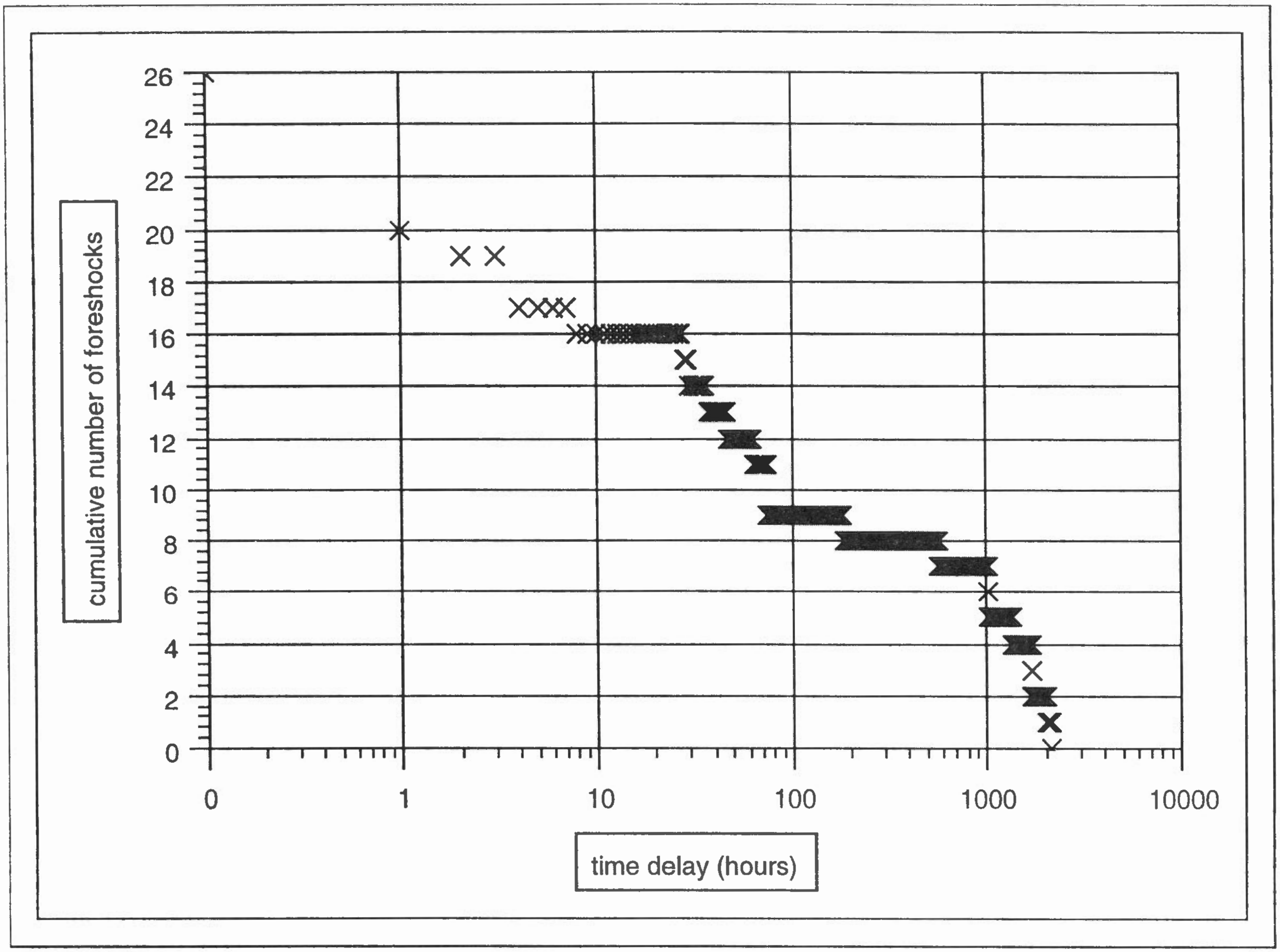


Figure 15. Saguenay earthquake (25-Nov-1988): foreshock, mainshock, aftershock magnitudes versus number of days from the first foreshock occurrence.

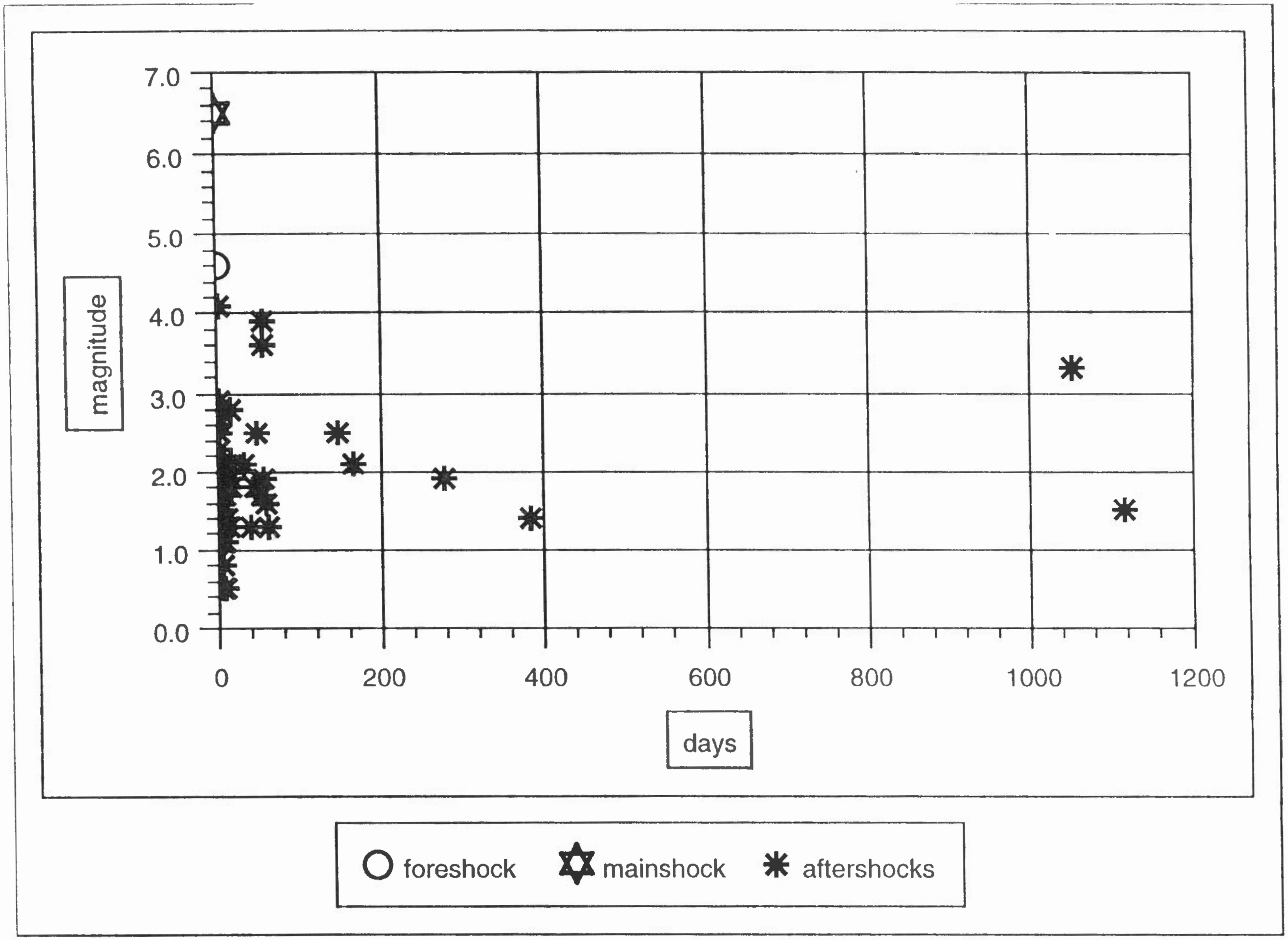


Figure 16. Saguenay earthquake (25-Nov-1988): the cumulative number of aftershocks for various differences between mainshock and aftershock magnitudes.

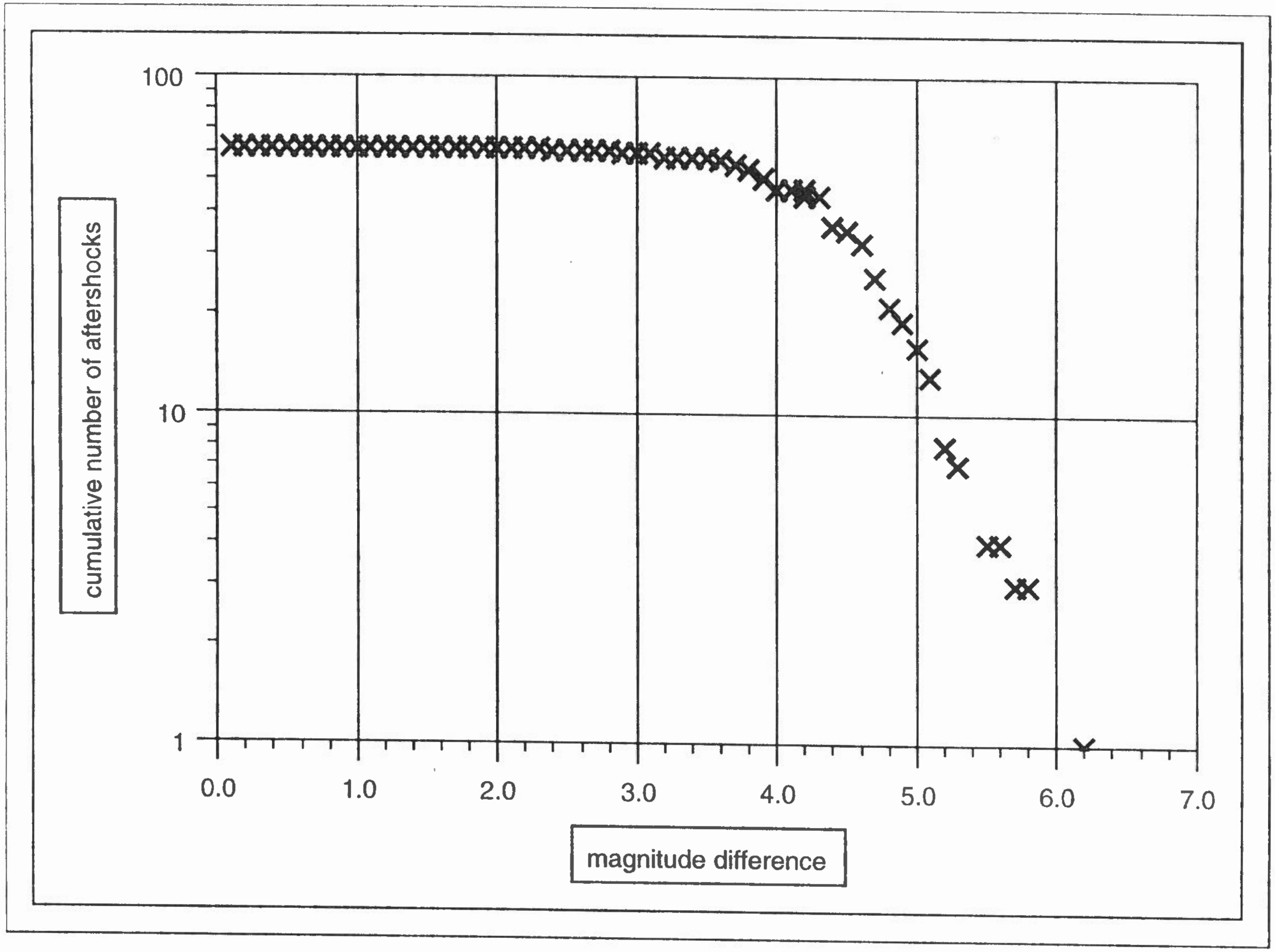


Figure 17. Miramichi earthquake (09-Jan-1982): foreshocks, mainshocks, aftershocks magnitudes versus number of days from the first foreshock occurrence.

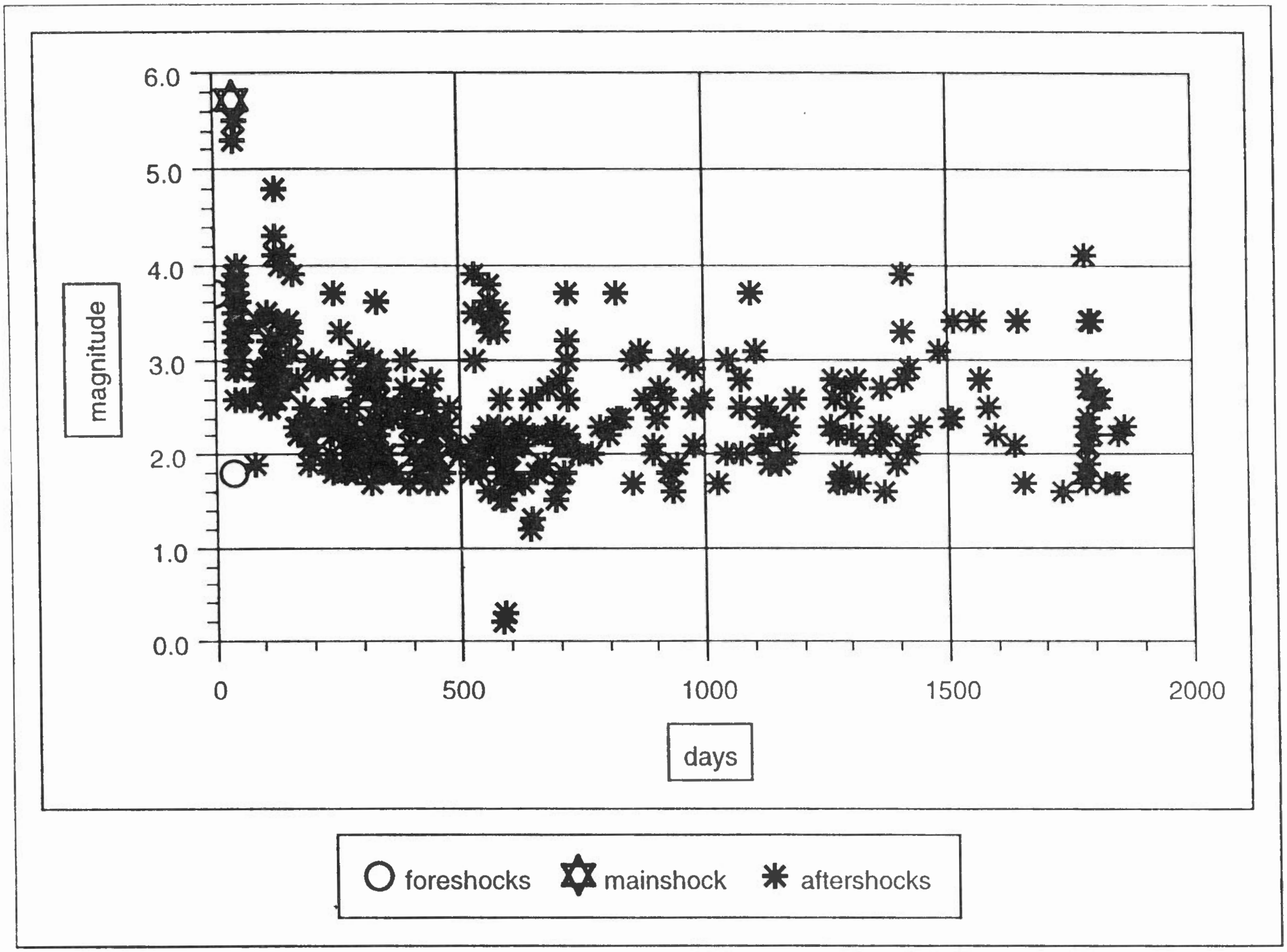


Figure 18. Miramichi earthquake (09-Jan-1982): the cumulative number of aftershocks for various differences between mainshock and aftershock magnitudes.

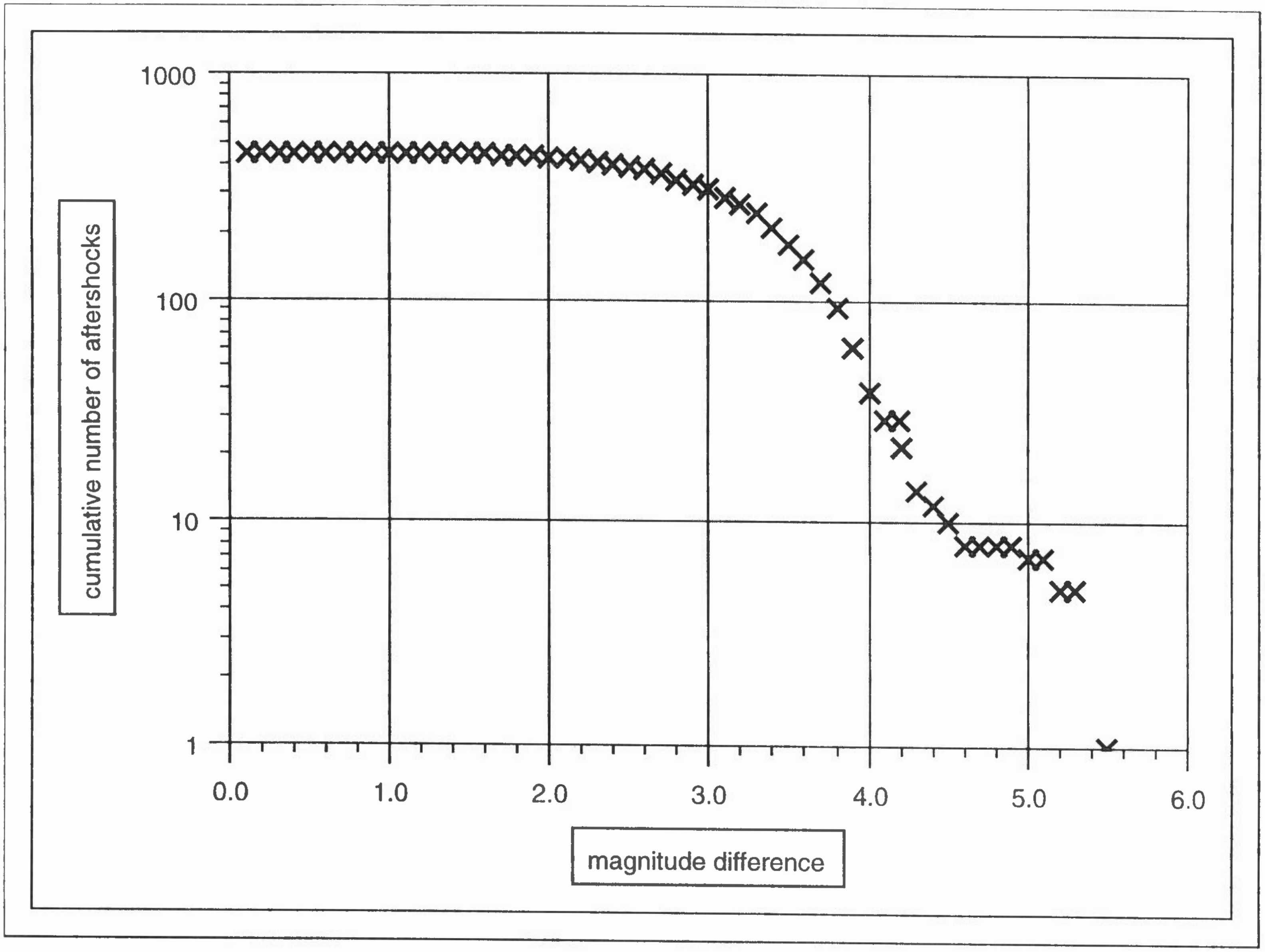
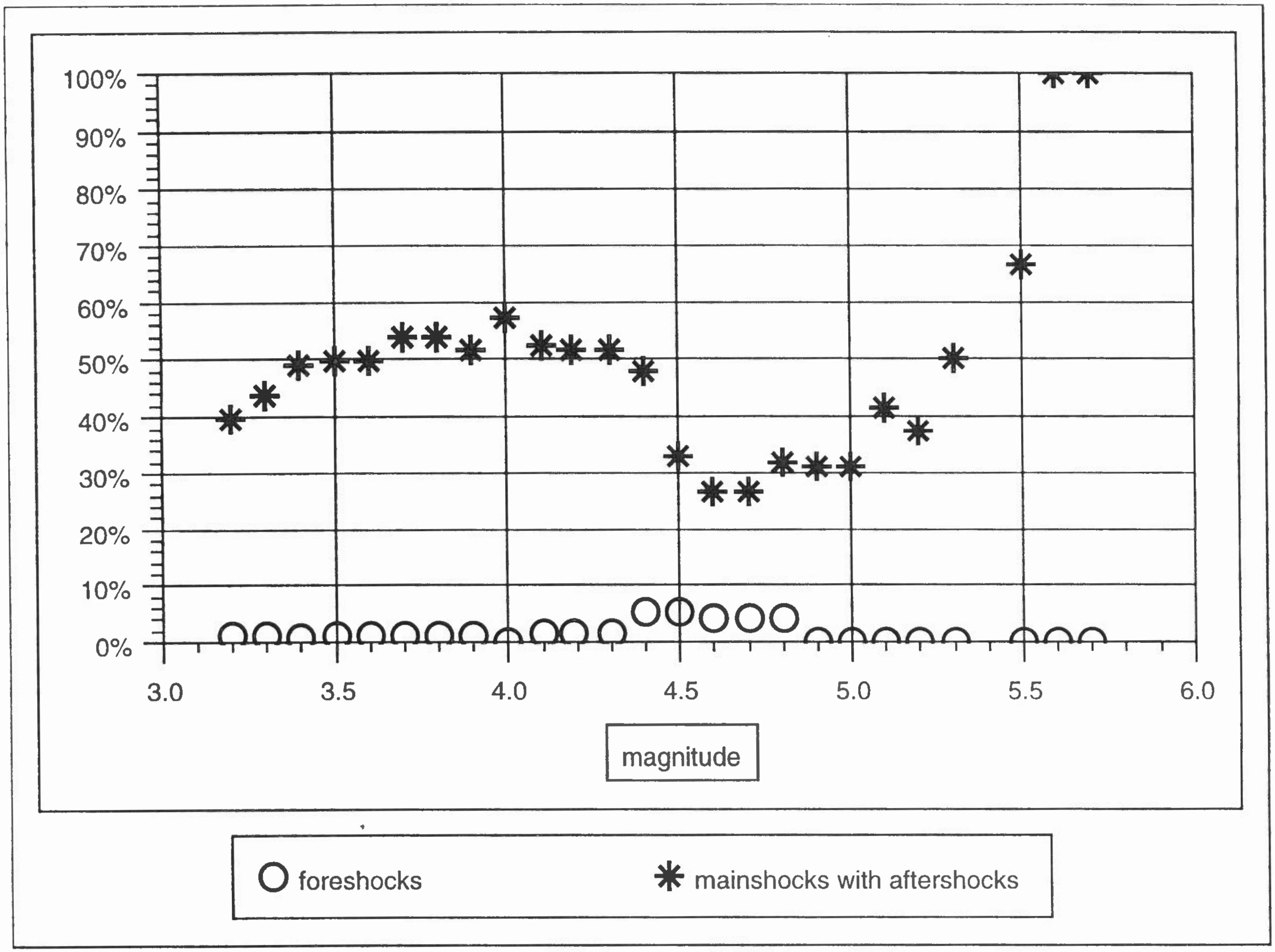


Figure 19. Probability that the event will be followed by a larger quake (circles), by smaller quake (by any aftershock) (stars) versus the event magnitude.



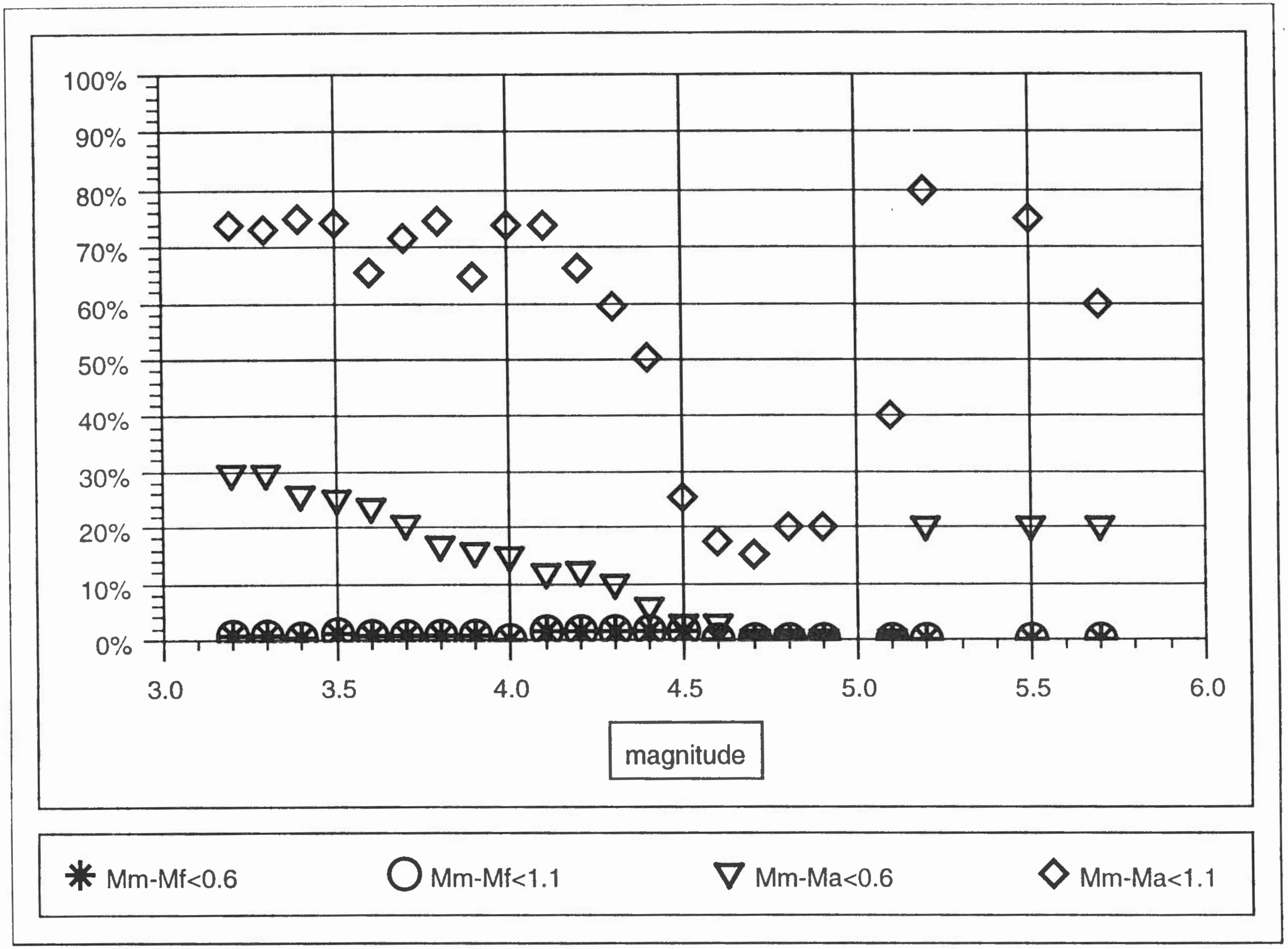


Figure 20. Probability that the event (foreshock) will be followed by a larger quake (mainshock) with magnitude more by minimum 0.5 (stars) or by minimum 1.0 (circles) that the initial event (foreshock) magnitude, and that the mainshock will be followed by an aftershock with magnitude within 0.5 (triangles) or 1.0 (diamonds) magnitude un its of mainshock.

APPENDIX

This appendix includes the texts of the most important programs which were used for this work.

```
      program GROUPS
C     This program devides the catalog into groups of foreshocks-
C     mainshock-aftershocks, using the criteria described in the
C     text of the Open File
      exec sql include sqlca
      exec sql begin declare section
      character*25 m_dat1, m_dat2
      real m_lat, m_lon, m_mag, m_mag0
      integer*4 n_grp
      exec sql end declare section
      n_grp=1
      exec sql connect eq
      exec sql update abr5
     1 set afm=' ', grp=0
      exec sql commit
 20   m_mag0=20.
      exec sql select max(magn)
     1 into :m_mag0
     2 from abr5
     3 where grp=0
      exec sql commit
      if(m_mag0.lt.3.) goto 12
      exec sql select tim1, tim2, lati, lon, magn
     5 into :m_dat1, :m_dat2, :m_lat, :m_lon,
     4 :m_mag
     6 from abr5
     7 where (magn=:m_mag0) and (grp=0)
      exec sql begin
      exec sql endselect
      exec sql end
      exec sql commit
      exec sql update abr5
     1 set grp=:n_grp, afm ='m'
     2 where (tim2=:m_dat2) and (tim1=:m_dat1)
     3 and (lati=:m_lat)
     4 and (lon=:m_lon) and (magn=:m_mag0)
      exec sql commit
      exec sql update abr5
     1 set afm='b', grp=:n_grp
     2 where sqrt((lati-:m_lat)**2+(lon-:m_lon)**2)<0.05
     6 and tim1>date(:m_dat1)-'3 months'
     8 and tim2<=:m_dat2
     9 and magn<:m_mag0
     7 and grp=0
      exec sql update abr5
```

```
    1    set afm=’p’, grp=:n_grp
    3    where sqrt((lati-:m_lat)**2+(lon-:m_lon)**2)< 0.25
    4    and tim2>:m_dat2
    5    and tim1<date(:m_dat1)+’60 months’
    7    and magn<:m_mag0
    6    and grp=0
         exec sql commit
         print *,n_grp, m_mag0
         n_grp=n_grp+1
         go to 20
12       exec sql disconnect
         stop
         end
```

```
       program ZONE
C     This is the program for determination of the seismic
C     zone for each earthquake
      character*30  zbfile
c variables for zone coordinates
      real xzon(100),yzon(100),slope(100),yinter(100)
       exec sql include sqlca
       exec sql whenever sqlerror stop;
       exec sql begin declare section
        real a_lon, a_lati
        character*6 a_zone
c        integer*4 a_grp
       exec sql end declare section
c open files

        write(*,*) ' Enter zone coordinates filename (*.zon)'
        read(*,5) zbfile
        open(unit=13, file=zbfile, status='unknown')
 5      format(a30)

c read in zone file. Same format as input to F.Anglin's mapping program
c (title, lat and lons, end line) Last line should be some form of:  99 99
        k=1
102         format(a80)
        read(13,102) lab1
35      read(13,*,end=40) yzon(k),xzon(k)
        if(yzon(k) .le. 90.) k=k+1
        if(yzon(k) .gt. 90.) nvert=k
        goto 35
40      continue
c calculate slopes and y intercepts for the sides of each zone
c set counter for number of events in each zone to zero
        inzon = 0
        xzon(nvert) = xzon(1)
        yzon(nvert) = yzon(1)
        rc2 = 1.e20
        rf2 = 0.
        do 50 is = 1, nvert-1
c slope and intercept
          isp1 = is + 1
          dx = xzon(is) - xzon(isp1)
          if (dx .ne. 0.) then
            slope(is) = (yzon(is) - yzon(isp1)) / dx
            yinter(is) = yzon(is) - (slope(is) * xzon(is))
c side is vertical; set slope and intercept to very large numbers
          else
            slope(is) = 1.e30
            yinter(is) = 1.e30
            end if
50          continue
c           print *, '50 passed'
c read data file (CEEF format), convert lat and lon to integers
         inzon = 0
c        ioutzon = 0
```

```
         exec sql connect eq
         exec sql declare cursor1 cursor for
     1    select lon, lati, zone
     2    from abr5
     4    where zone=' ' and grp>0
     3    for update of zone
          exec sql open cursor1
          do while (sqlcod.ne.100 .and. sqlcod .ge. 0)
          exec sql fetch cursor1
     1   into :a_lon, :a_lati, :a_zone
         print *, 'exec1', a_lati, a_lon
c         call f_ing_error('select')
         i=i+1
          print *, 'i'
c test to see if point falls within the bounds of the zone
         ins = inside(a_lon,a_lati,xzon,yzon,slope,yinter,nvert-1)
         print *, 'inside passed'
         if (ins .and. sqlcod .eq. 0) then
         print *, 'then passed'
c write to inside file
c c         write(14,10) record
          exec sql update abr5
     1    set zone='ebg'
     2    where current of cursor1
           print *, 'update passed'
           inzon = inzon + 1
c write to outside file
           end if
           end do
30         continue
           exec sql close cursor1
           exec sql commit
c30         continue
           exec sql disconnect
           stop
           end


      logical function inside(xp, yp, x, y, slope, yinter, n)
c
c determines whether point (xp,yp) lies inside a polygonal region
c defined by the coordinates of the vertices: (x(i),y(i)), i=1,n
c algorithm: if number of intersections with half-line x=xp; y>yp
c is odd, point lies inside, if even, point lies outside.
c
      dimension x(100),y(100),slope(100),yinter(100)
      icount = 0.
      do 1 i = 1, n
c no intersections if side I is vertical
        i1 = i + 1
c no intersections if both enpoints of side are to the right or
c to the left of XP
        if (slope(i) .gt. 1.e10) goto 1
c calculate Y value of intersection  of side with vertical line
```

```
        if (((x(i) .le. xp) .and. (x(i1) .le. xp)) .or.
     &  ((x(i) .gt. xp) .and. (x(i1) .gt. xp))) goto 1
        yy = yinter(i) + (slope(i) * xp)
c points on the boundary are considered to be outside
        if (yy .gt. yp) icount = icount + 1
c TEST IF ICOUNT IS EVEN
    1 continue
      inside = .true.
      if (mod(icount,2) .eq. 0) inside = .false.
      return
      end
```

```
            program ASEV
c   (the last version)
c   program for determination of the current event type (is it a
c     fore- aftershock or an associated event)
          real*8 Etime1, Etime0, tim_str2epoch
          external tim_str2epoch !$pragma C( tim_str2epoch )
          exec sql include sqlca
          exec sql whenever sqlerror stop
          exec sql begin declare section
          character*25 t_main, t_cur
c         integer*2 n_grp_ind
          integer*4 n_grp, m_grp, n_grp0
          real x_main, y_main, x_cur, y_cur
          real a_cur, a_res, b_res, d_DT, r_RAD, d_DT1, d_DT2
          exec sql end declare section
c        extraction of the mainshock parameters
c          n_grp=3
          exec sql connect eq
 10         n_grp=1
           exec sql select min(grp)
     1    into :n_grp0
     2    from abr5
     3    where grp>0 and zone='nap' and res!=-1.
     4    and afm='m'
     5    and (na>0 or nf>0)
           exec sql commit
          print *, 'GRP0', n_grp0
          print * , n_grp_ind, n_grp
          exec sql commit
          exec sql select   tim2 , lati, lon, grp, res
     2    into :t_main, :x_main, :y_main, :n_grp, :b_res
     3    from abr5
     4    where  (afm='m') and grp=:n_grp0
     5    and (zone='nap') and (res!=-1.)
     6    and (na!=0 or nf!=0)
          exec sql begin
          exec sql endselect
          exec sql end
          exec sql commit
          b_res=-1.
          exec sql update abr5
     1    set res=:b_res
     2    where afm='m' and grp=:n_grp0
     3    and zone='nap'
          exec sql commit
          Etime0 = tim_str2epoch(t_main)
          print *,'M', Etime0, t_main, x_main, y_main, n_grp
          exec sql declare cursor1 cursor for
     1    select tim2, lati, lon, magn, res, grp, rad, d_DT,
     2     DTday, DThour
     3     from abr5
     4     where (afm != 'm') and (zone='nap')
     6     and (grp=:n_grp0)
     5     for update of res, rad, d_DT, dtday, dthour
```

```
          exec sql open cursor1
          do while (sqlcod.ne.100 .and. sqlcod .ge. 0)
          exec sql fetch cursor1
     1    into :t_cur, :x_cur, :y_cur, :a_cur, :a_res, :m_grp,
     2    :r_RAD, :d_DT, :d_DT1, :d_DT2
c    calculation of the radius bw the mainshock and the fore-
c   aftershock epicentres
          Etime1 = tim_str2epoch(t_cur)
          print*,'P', Etime1, t_cur, x_cur, y_cur, m_grp
          d_DT=abs(Etime1 - Etime0)
          d_DT1=d_DT/(60*60*24)
          d_DT2=d_DT/(60*60)
          print *, 'DT', d_DT, d_DT1, d_DT2
          PI=3.141592653589
          r_RAD=sqrt((x_cur-x_main)**2 + ((y_cur-y_main)*
     1    cos((x_cur+x_main)/2))**2)*111.
          print *,'RAD', r_RAD .
c     calculation of the cumulative curve
          N0=638.
          Ax=6.0
          B=1.87
c    where N0-the number of all events, Ax-max magnitude,
c    b-exp degree
          CUM=N0*exp(-B*a_cur)*(1-exp(-B*(Ax-a_cur)))
          print *, 'CUM', CUM
c   multiplication of CUM and RAD, div. on the big area
c   square and on the 1 year (in sec)
          AREA=241000.
c   an area square in km**2
          YEAR=365*24*60*60
          a_res=(CUM*PI*(r_RAD**2)*d_DT)/(YEAR*AREA)
          print *, 'ARES', a_res
          if (sqlcod .eq. 0) then
          exec sql update abr5
     1   set  res = :a_res,
     3   rad=:r_RAD, d_DT=:d_DT, dtday=:d_DT1, dthour=:d_DT2
     2   where current of cursor1
         print *,'update passed'
         end if
         end do
         n_grp=n_grp+1
         if(n_grp.LE.482) goto 10
         exec sql close cursor1
         exec sql commit
         exec sql disconnect
         stop
         end
```