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Statistical Analysis of Damaging Earthquakes and Volcanic Eruptions in Iceland From 1550–1978

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Abstract. Records of all known eruptions and damaging earthquakes in Iceland since 1550 were produced containing 82 and 44 events, respectively. Neither record exhibits a significant trend. Analysis of the second order properties of the records reveals no indication of clustering or periodicity in either record. There is a significant relationship between the two kinds of events. Some of this may be due to triggering effects, but there is also a more long term relationship with eruptions leading the earthquakes. This relationship was examined further by classification of the events geographically and by types of the eruptions. The relationship seems to embody the whole area rather than local effects.

Key words: Iceland – Earthquake statistics – Volcanism – Seismicity – Poisson process.

Introduction

The idea that volcanic activity in Iceland is episodic or even periodic has been discussed from time to time. This was first suggested by Thoroddsen (1925). In recent years the idea has come up again, especially in view of the active period from 1961 onwards compared to the two or so decades before. Thorarinsson (1966) pointed out that this might apply to the entire Mid-Atlantic Ridge. Later expressions of this view include Björnsson et al. (1977) who suggest that rifting episodes occur in northern Iceland at 100–150 years intervals, Saemundsson (1978) who observed a simultaneity in the occurrence of eruptions and major earthquakes for the last few centuries and Tómasson (personal communication), who suggests that 25 years of volcanic quiescence alternate with 25 years of volcanic and tectonic unrest.

Earthquake sequences where one earthquake triggers off another in a neighbouring area or even a series within a short span of time is characteristic of the South Iceland seismic zone (Björnsson and Einarsson, 1974). A triggering effect between a volcanic eruption and an earthquake was suggested at the outset of the Krafla rifting episode in 1975/1976 (Björnsson et al., 1977). This has also been mentioned in case of the Laki eruption of 1783 followed by the large South Iceland earthquake sequence of 1784 which in turn was followed by rifting of the Hengill swarm still farther west in 1789.

There has been a great deal of research into the history of eruptions and earthquakes. We shall provide a resumé of this in the next section and a record of 82 eruptions and 44 major earthquakes since 1550.

An analysis has been presented so far only for eruptions of the central volcanoes Hekla and Katla in southern Iceland from 1100 up to the present time (Thorlaksson, 1967). The distribution of the intervals between eruptions differed from a purely random process in such a way that very short and very long intervals were less likely. There have also been studies of earthquakes in single seismic zones, e.g., in New Zealand by Vere-Jones (1970). These studies cover shorter time intervals than our records, but include much smaller earthquakes. There is highly significant clustering of the earthquakes within each zone, connected with fore- and aftershocks of the larger earthquakes.

The main purpose of the present work is to examine statistically possible relationships between eruptions and earthquakes in Iceland and regularity in the pattern of events. It is not difficult to find at least a qualitative explanation of a variety of hypothetical relationships within each record or between them. Apart from the triggered earthquake sequences we are, however, not aware that strong evidence exists for any such regularities except for what may be divined from the records themselves. It is then a useful precaution to start by testing the hypothesis that there is no relationship at all before using the data for a quantitative examination of such relationships as we think may exist. Failure to reject the hypothesis does not necessarily imply that the original idea was wrong. But it shows at least that the data contain little useful information about the relationship except that it cannot be very strong.

Records of Eruptions and Damaging Earthquakes

Written sources mention natural hazards from the earliest settlement of Iceland, but the records are very occasional up to the 16th century. From about 1550 the records seem to be sufficiently complete for our purpose. Eruptions and earthquakes occurring in this period are briefly mentioned in numerous annals and chronicles (Sigurdsson, 1868; Ann. Isl. 1400–1800, publ. 1922–1961). Letters and reports describing such events become more numerous in the 18th century. Magazines and newspapers bring such reports since the middle of the 19th century. Thorarinsson (1967, 1973, 1974, 1975) has evaluated the existing sources with respect to their reliability. Our listing of 82 eruptions (Table 1) is based mainly on his work. We have added a few more eruptions that are not quite definite (1661, 1896), or have been detected since (1697, 1706, 1720, 1739, 1768, 1854). The last six are from Steinthorsson (1978) who recorded representative tephra layers in an ice core from Vatnajökull. A few eruptions have been left out

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because they seem unlikely in view of later research. Thus an eruption in Vatnajökull in 1897 is refuted because the sources mention only a water flood but not definitely an eruption, also a representative tephra layer is not recorded in the ice core (Steinthorsson, 1978), although easterly winds were prevailing at the time of the presumed eruption. We have also refuted a 1823 eruption of Leirhafnarskörd (allotted with a question mark in Thorarinsson, 1974) on the basis of a recent description (Eliasson, 1977). Further we have moved the starting year of the Askja eruptive period of the nineteen-twenties back to 1919 (Steinthorsson, 1978). Regarding other eruptions lasting more than a year only the starting year is included in the table.

Table 1. List of volcanic eruptions since 1550

Date/year		Location	North Iceland	Vatna-jökull	South Iceland	Reykja-nes	Rift type	Central type
Spring	1554	SE of Hekla			×		×	
August 11,	1580	Katla			×			×
	1583	Eldeyjar				×	×	
January 3,	1597	Hekla			×			×
November 7,	1598	Grimsvötn		×				×
October 31,	1603	Vatnajökull		×				
October 21,	1612	Katla			×			×
July 29,	1619	Grimsvötn		×				×
September 2,	1625	Katla			×			×
	1629	Grimsvötn		×				×
May 8,	1636	Hekla			×			×
February	1638	Grimsvötn		×				×
Spring	1655	Kverkfjöll	×					×
	1659	Grimsvötn		×				×
November 3,	1660	Katla			×			×
December	1661	Grindavik				×	×	
April 10,	1681	Grimsvötn		×				×
November	1684	NW-Vatnajökull		×				
December	1684	Grimsvötn		×				×
February 13,	1693	Hekla			×			×
	1697	Vatnajökull?		×				
Winter	1702	Vatnajökull		×				
Autumn	1706	Grimsvötn		×				×
	1706	Vatnajökull		×				
Winter	1711	Kverkfjöll	×					×
October 6,	1716	Grimsvötn		×				×
August	1717	Kverkfjöll	×					×
	1720	Vatnajökull		×				
May 11,	1721	Katla			×			×
May 17,	1724	Krafla	×				×	
February	1725	Grimsvötn		×				×
April 2,	1725	S of Hekla			×		×	
	1726	NW-Vatnajökull		×				
August 8,	1727	Öræfajökull		×				×
	1729	Kverkfjöll	×					×
	1739	Vatnajökull		×				
July 10,	1746	Krafla	×				×	
Autumn	1753	SW-Vatnajökull		×				
October 17,	1755	Katla			×			×
April 5,	1766	Hekla			×			×
July	1766	Grimsvötn		×				×
	1768	Vatnajökull		×				
February	1774	NW-Vatnajökull		×			×	
May 1,	1783	Eldeyjar				×	×	
June 8,	1783	Laki/Grimsvötn		×			×	
Summer	1794	W-Vatnajökull		×				
	1797	N-Vatnajökull		×				
	1807	N-Vatnajökull		×				
December 19,	1821	Eyjafjallajökull			×			×

Table 1 (Continued)

Date/year		Location	North Iceland	Vatna-jökull	South Iceland	Reykja-nes	Rift type	Central type
February	1823	SW-Vatnajökull		×				
	1823	Katla			×			×
March 13,	1830	Eldeyjar				×	×	
	1838	Grimsvötn		×				×
September 2,	1845	Hekla			×			×
	1854	Grimsvötn		×				×
May 8,	1860	Katla			×			×
June 30,	1862	Tröllahraun		×			×	
December	1867	Mánáreyjar	×				×	
August 29,	1867	Grimsvötn		×				×
January 8,	1873	Grimsvötn		×				×
December	1874	Askja/Sveinagjá	×				×	
February 27,	1878	NE-Hekla			×		×	
May 30,	1879	Eldeyjar				×	×	
January 15,	1883	Grimsvötn		×				×
August	1887	SW-Vatnajökull		×				
March	1892	Grimsvötn		×				×
September	1896	Vestmannaeyjar			×			×
May 28,	1903	SW-Vatnajökull		×				×
June 18,	1910	W-Vatnajökull		×				
April 25,	1913	NE-Hekla			×		×	
October 12,	1918	Katla			×			×
	1919	Askja	×				×	
September	1922	Grimsvötn		×				×
June	1926	Eldeyjar				×	×	
	1933	NW-Vatnajökull		×			×	
March 30,	1934	Grimsvötn		×				×
March 29,	1947	Hekla			×			×
October 26,	1961	Askja	×				×	
November 14,	1963	Vestmannaeyjar			×			×
May 5,	1970	N+S-Hekla			×		×	
January 23,	1973	Vestmannaeyjar			×			×
December 20,	1975	Krafla	×				×	

Tryggvason et al. (1959) have evaluated the earthquake records and presented a list of all earthquakes or earthquake sequences that were strong enough to cause the collapse of houses. We have used this list in our analysis with two minor corrections only: A reference to an earthquake in South Iceland in 1828 stands actually for an earthquake in the year after (Björnsson, S., personal communication). An earthquake in 1876 is misspelled in Tryggvason et al. (1959). It should read 1879 (see Thoroddsen, 1925). We have added also an earthquake in North Iceland in 1624 with reference to Larusson (1951). The analyzed earthquake record is thus by necessity selective because for most of this period no earthquakes were mentioned except such that caused damage. In the twentieth century information about earthquake magnitude became available (Tryggvason 1973), at the same time as constructions became more rigid. For this period we have chosen to include most earthquakes reported by Tryggvason (1973) as magnitude 6 or larger. From earthquakes that have occurred in the seismic zone north of Iceland we have omitted the smallest one of magnitude 6; it would certainly not have been included in the annals. The high proportion of earthquakes on the eastern Reykjanes Peninsula during the 20th century raises doubts about the completeness of the records for this area also. Incompleteness could be due to the fact that the interior of the Reykjanes Peninsula is unpopulated. But also chronicles relating to this area are rather meagre.

From triggered earthquake sequences we have chosen to include in our analysis only the first shock if the earthquakes are clustered within a short spell of time (weeks or months). The two most dramatic examples of such sequences are the 1784 and 1896 earthquakes of the South Iceland seismic zone with earthquakes of magnitude 6–8 propagating generally from east to west across it.

No information is available about earthquake magnitudes for the period 1550–1700. But for earthquakes after 1700 Tryggvason (1973) has given an estimate for all 'major destructive earthquakes' which he found to be of magnitude $6–6^1/_2$ and larger. From a comparison with Tryggvason (1973) we expect that the magnitudes of earthquakes dealt with here are on the order of $5^1/_2–6$ up to $7^1/_2–8$. A graphical representation of all events included in our analysis is given in Fig. 1.

Table 2. List of damaging earthquakes since 1550

Date/year		North Iceland seismic zone	South Iceland seismic zone	Borgarfjördur seismic zone
May 30,	1581		×	
	1584	×		
Spring	1597		×	
	1614		×	
Autumn	1618	×		
November	1624		×	
	1624	×		
February 21,	1630		×	
Early	1633		×	
March 16,	1657		×	
	1663		× (R)[a]	
Summer	1671		×	
January 28,	1706		×	
August	1724		× (R)	
April 1,	1725		×	
Summer	1726		×	
September 7,	1732		×	
March 21,	1734		×	
	1749		×	
	1752		×	
September 11,	1755	×		
	1757		×	
September 9,	1766		×	
August 14,	1784		×	
June 10,	1789		× (R)	
February	1829		×	
June 11,	1838	×		
December 30,	1867	×		
April 17,	1872	×		
Late May	1879		× (R)	
January 25,	1885	×		
April 19,	1889		× (R)	
August 26,	1896		×	
January 22,	1910	×		
May 6,	1912		×	
August 23,	1921	×		
July 23,	1929		× (R)	
June 10,	1933		× (R)	
June 2,	1934	×		
October 9,	1935		× (R)	
March 28,	1963	×		
December 5,	1968		× (R)	
June 12,	1974			×
January 13,	1976	×		

[a] (R) = Reykjanes Peninsula

Regional Distribution of Eruptions and Earthquakes

Figure 2 shows the neovolcanic zones of Iceland and the zones of seismic hazard. The activity is far from evenly distributed with time. Since 1550 no volcanic activity has been recorded in the Snaefellsnes volcanic zone nor within the Langjökull and Hofsjökull volcanic complexes. Even the Reykjanes Peninsula has been quiescent apart from its submarine continuation, the Eldeyjar area, and one doubtful eruption (1661) on land. A rifting episode occurred on the Hengill swarm farther east (1789) which is likely to have been associated with magmatic movement similar to the present rifting episode of Krafla (Björnsson et al., 1977). Most of the volcanic activity has been confined to the eastern volcanic zone in this period of time.

We have divided the volcanic eruptions into four groups with regard to location. Two groups are obvious from tectonic implications. i.e., the Reykjanes and South Iceland volcanic zones. The latter includes stratovolcanoes that erupt alkalic to transitional rocks and rift structures are poorly developed (Saemundsson, 1978). The division between a Vatnajökull zone and a North Iceland zone is somewhat arbitrary being based primarily on a possible transverse structure connecting the volcanoes under the ice sheets of Central Iceland.

Among the eruptions we make a distinction in Table 1 between eruptions associated with rifting of the crust similar in nature to the recently described Krafla rifting episode (Björnsson et al., 1977) and eruptions of central volcanoes accompanied by no or minor rifting. Many of the latter appear to be triggered by processes within magma chambers beneath the volcanoes themselves rather than release of tensional stress accumulated as a result of spreading. For consistency we have grouped all eruptions occurring on the fissure swarms that pass through the volcanoes with the rift type, but all eruptions that were confined to the actual central volcano were classified as central type. Thus the eruptions of Hekla proper are classified as central type. This may be inappropriate in view of the pronounced rift that opens up along the volcanic axis of this volcano during eruptions. Indeed Thoroddsen (1925) and Tryggvason et al. (1959) have pointed out that damaging earthquakes have more than once occurred in the Ölfus district of South Iceland following shortly upon a Hekla eruption. For the period considered here this has happened twice. In this context we must also mention that two rifting episodes that were not accompanied by a volcanic eruption appear in Table 2 among the earthquakes (1618, 1789). In a separate examination we have, however, also added them to the rift type eruptions.

The seismic zones are clearly defined as transverse shear zones in the case of North and South Iceland. We have grouped earthquakes occurring in the eastern part of Reykjanes with the South Iceland earthquakes, although in the case of Reykjanes we are obviously dealing with an oblique rift zone and not a zone dominated by shear. The Borgarfjördur seismic zone bridges the gap between Langjökull and the Snaefellsnes volcanic zone. Only one earthquake (1974) from this zone is included here (Einarsson et al., 1977). The last earthquakes before that were reported in 1928 (Vedrattan, 1928). One of them was moderately strong but probably did not reach magnitude 6, so we have left it out. Apparently earthquakes in this zone are rare and they do not reach the same magnitude as in the other two areas.

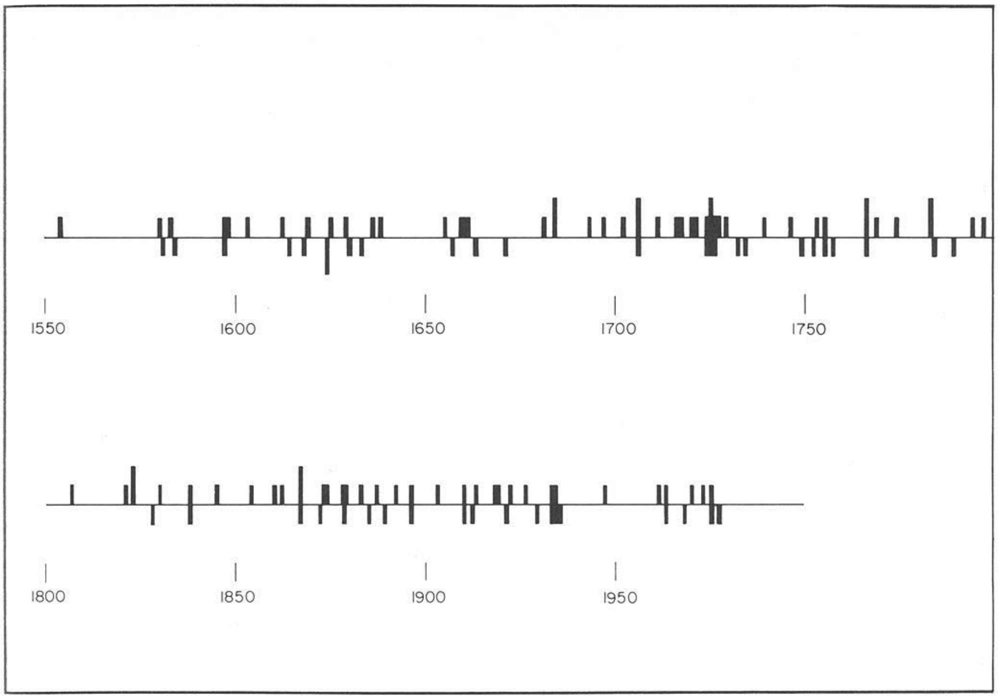

Fig. 1. Graphical representation of the records of eruptions and earthquakes

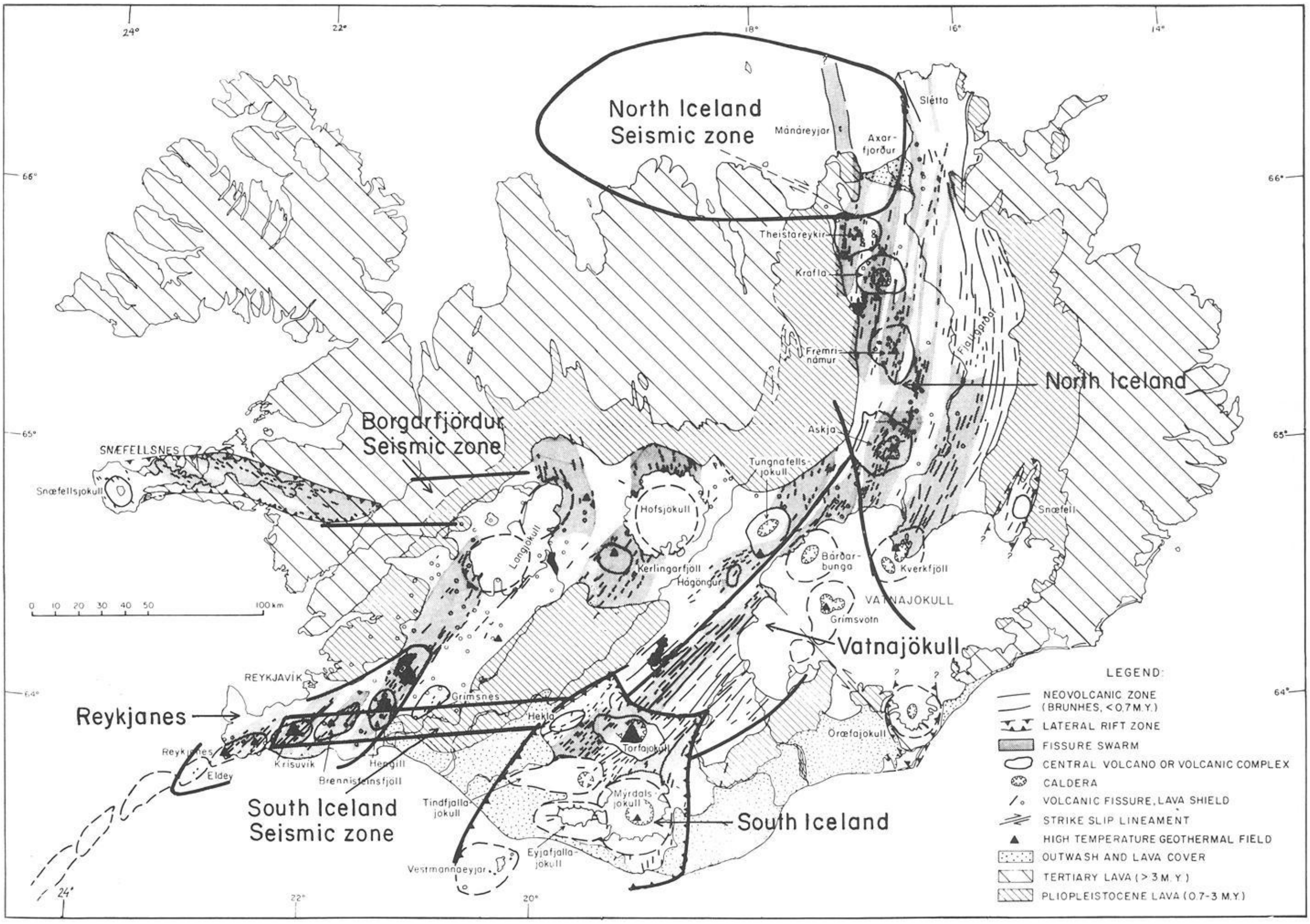

Fig. 2. Divisions of the neovolcanic zones of Iceland forming the basis for discussion in text. Seismic zones form connections between offset segments of the axial rift zones. The map is from Saemundsson (1978)

Analysis of the Total Records

Our records can be regarded as observations of stochastic point processes. There is a large mathematical literature on this subject, but less experience with the analysis of actual data than in the related field of time series analysis. We have analysed our data partly by a slightly modified version of a procedure described by Ripley (1976, 1977) and partly by turning them into time series.

A basic model in studies of this kind is the Poisson process with constant intensity (expected number of events/length of the record). In a Poisson process with intensity λ, the probability of an event in the interval from t to $t+\Delta t$ approaches $\lambda\Delta t$ when $\Delta t \rightarrow 0$, independent of the position of other events. A Poisson process is thus totally devoid of memory between events or any resemblance to periodicity.

An important characteristic of the Poisson process is that the duration of the intervals between events is exponentially distributed with the average value of λ^{-1}. According to this distribution the shortest intervals are always most likely, but the probability of obtaining relatively large intervals, say >3 standard deviations above the mean value which is 0.0014 for the normal distribution is about 0.018 for the exponential distribution. Even in small samples we can therefore expect the appearance of some intervals much longer than the mean or median value.

For many events only the year when they took place is known and we shall also only use this part of the information about all events. Much of the analysis will consist of comparing these data with hypothetical records of the number of events from a Poisson process in each year. We shall retain the name Poisson process for such records.

Considering the uncertainties in the recording of the events it would hardly be surprising to find that the intensity of events was not equal throughout the time interval. This applies in particular to the earthquakes. The possibilities of large earthquakes being unrecorded are probably greater in the earlier years, but systematic misjudging of the size of earthquakes might equally produce a negative as a positive trend.

A simple method for testing the hypothesis that an observed process is free of trend is described by Cox and Lewis (1966, p. 47). When the observations come from a Poisson process with a constant intensity the value of the test statistic is distributed as a normal random variable with zero mean and unit variance. The hypothesis is thus rejected with 95% confidence if the result lies outside ± 1.96. Our results were 1.1 for both the eruptions and for the earthquakes. Although these results provide no ground for assuming that the records are realizations from trend-free processes they suggest that eventual trends can be ignored, as the data are too few to distinguish them from such processes.

This test is only useful for detecting a monotonous change in the intensity. Deviations from the Poisson process resulting from various departures from the assumption of independent events would not be detected at all. A fairly general method of investigating interconnection between events is to count the number of events that take place in the same year as another event, one year after another event, 2 years etc. Let us call the number of events taking place less than or equal to n years after another event on the record $\phi(n)$. Observations of $\phi(n)$ contain all information in the records about the second order properties of the process, which is equivalent to the variances and correlation coefficient of two random variables.

Comparison of the two records is carried out by counting the number of eruptions preceding an earthquake by $\leq n$ years which we call $\theta(n)$. The number of earthquakes preceding an eruption by $\leq n$ years is then $\theta(-n)$. The expected value of $\theta(n)$ is only equal to $\theta(-n)$ if the two events are independent or related without any time lag.

It is easy to calculate the expected value of $\phi(n)$ or $\theta(n)$ when a given number of eruptions or earthquakes are distributed purely at random on 429 years. In an actual experiment we cannot expect to obtain exactly the theoretical values, but large discrepancies between observed and expected values would indicate that the events are not independent. How large the discrepancy needs to be for rejecting with confidence the hypothesis of a Poisson process depends upon the distribution of $\phi(n)$ or $\theta(n)$ which is rather complicated. But for low values of n the variance is approximately equal to the expected value.

The number of observations on our records is very small for the analysis of stochastic processes. Methods of analysis which use less of the information of the records than estimation of $\phi(n)$ and $\theta(n)$ are therefore not likely to produce worthwhile results. But because of the small number of observations we can, at moderate costs, investigate the relevant statistical properties of $\phi(n)$ and $\theta(n)$ empirically by simulation on a computer.

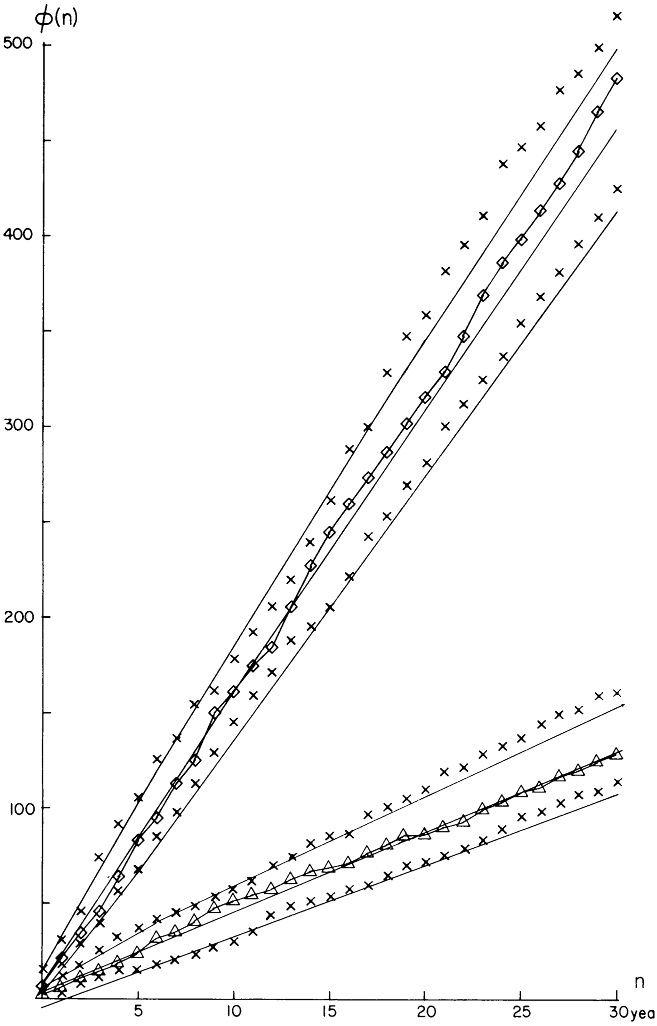

Fig. 3. Estimates of $\phi(n)$ from the records of all eruptions and all earthquakes. Also the extreme values of 20 simulations of Poisson processes corresponding to each record. Symbols are explained on Fig. 4

We estimated $\phi(n)$ and $\theta(n)$ for 20 pairs of independent Poisson processes with 82 and 44 events respectively, distributed at random on 429 years. The results are presented in Figs. 3 and 4. Figure 5 gives the result of the estimations of $\theta(n)$a nd $\theta(-n)$ from the 5 first simulations. We do not distinguish between the estimates of $\theta(n)$ and $\theta(-n)$ in the simulated values as their distribution is identical for independent processes. The largest and smallest values of $\phi(n)$ and $\theta(n)$ obtained in the simulations at each value of n are shown in Figs. 3–5. Lines two square roots above and below the expected values of ϕ and θ are shown on Figs. 3–8. We notice that the relative positions of these lines and the extreme values are very similar for all functions. (The extreme values of $\theta(n)$ were obtained from 40 estimates whereas the extreme values of $\phi(n)$ were only based on 20. It is therefore to be expected that the extreme values of θ lie relatively farther away from the expected value than those of ϕ although there is of course no certainty of observing this in a single experiment).

Turning now to our records we see that the estimates of $\phi(n)$ from the total records of eruptions and earthquakes presented in Fig. 3 do not differ much from the expected values for Poisson processes. Many of the simulated records produce larger deviations from the theoretical values. Interconnections of periodic or almost periodic kind may not produce very large differences from the expected values of ϕ (n) for Poisson processes if they only account for a small proportion of the total variation. The power spectrum contains the same information as $\phi(n)$, but is better suited for

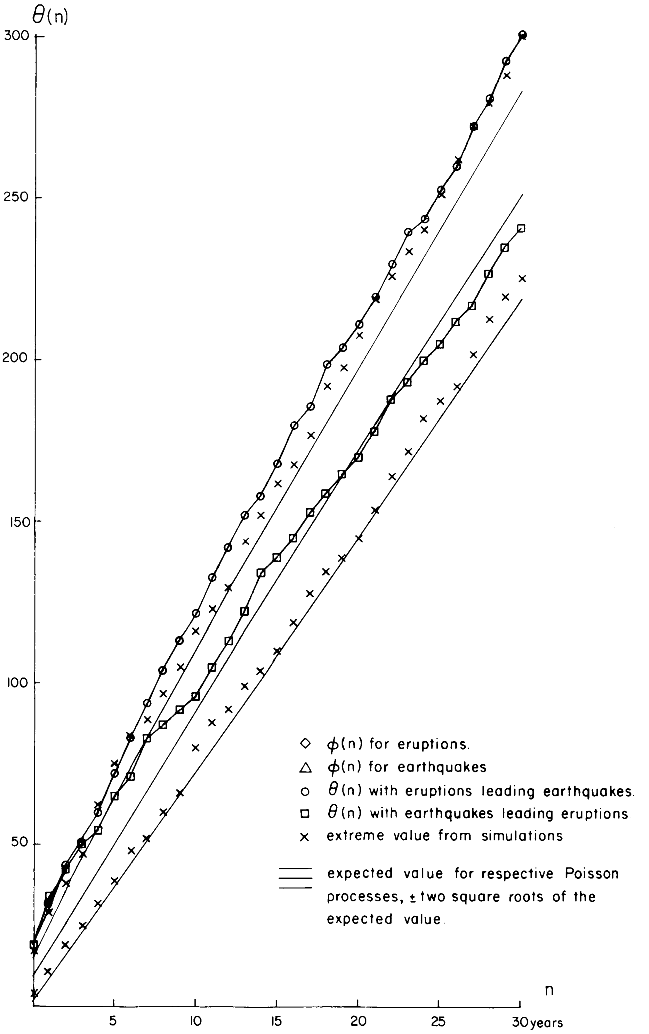

Fig. 4. Estimates of $\theta(n)$ from the records of all eruptions and all earthquakes. Also the extreme values of $\theta(n)$ from 20 pairs of independent Poisson processes

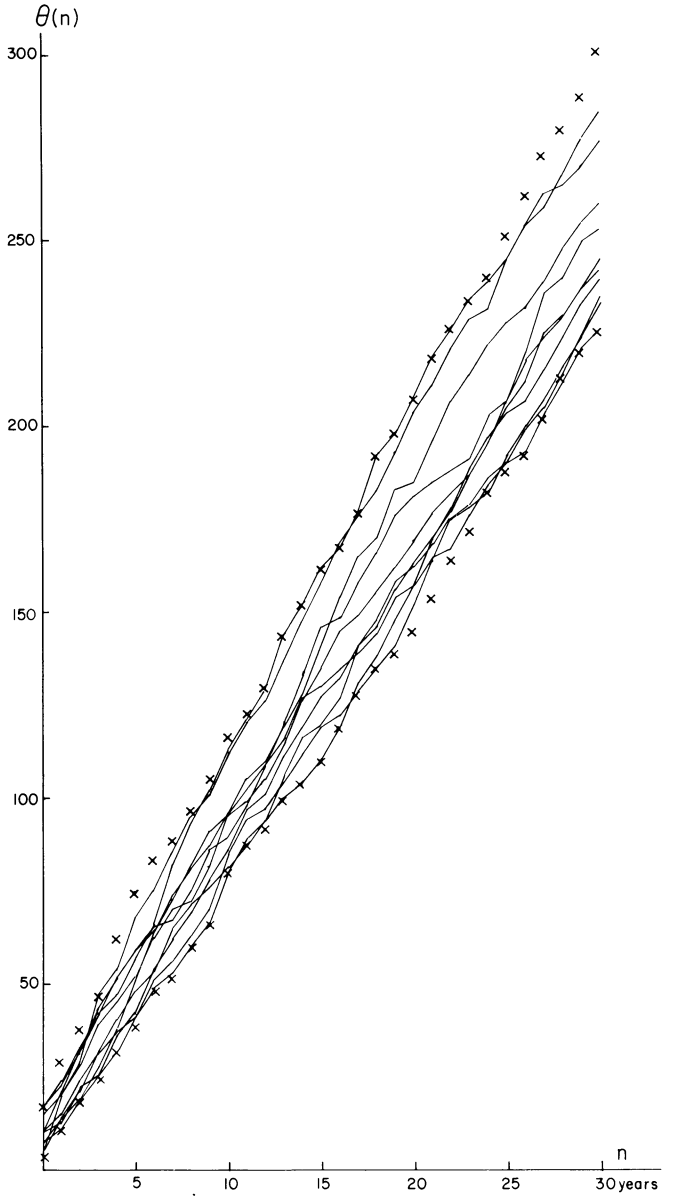

Fig. 5. Estimates of $\theta(n)$ from pairs of simulated independent Poisson processes. Also the extreme values of 20 simulations. Symbols are explained on Fig. 4

detecting periodicities. The statistical properties are not fully known here and the estimation of the power spectrum is a less straight-forward matter than the calculation of $\phi(n)$. We shall not enter the details here beyond mentioning that spectral analysis was carried out and produced no indication whatsoever of periodic effects.

The main result of the analysis described above is that neither record differs significantly from a Poisson process. This is different from results concerning single central volcanoes or seismic zones. But if the occurrence of eruptions in each volcano is independent of other volcanoes, the records are too short for detecting the small regularities associated with the events from one central volcano when it is included in the record of all eruptions. As only the largest earthquakes are included, clustering effects due to aftershocks (or triggered earthquake sequences) will not appear in these records. The clusters due to triggered earthquake sequences are eliminated from the record by regarding them as single events.

These conclusions differ from the common view that volcanic and seismic activity is periodic or episodic. One explanation of this may be that perfectly normal features of a purely random process have been misinterpreted as evidence for episodic characteristics. Thus although the average interval between eruptions is 5.2 years, neither the occurrence of 9 eruptions within a spell of 20 years nor of a period of that length without a single eruption is in any way remarkable in a record of this length.

Tomasson's suggestion (op. cit) of a periodicity with a 50 years cycle is based on slightly different data. On our records the evidence for this hypothesis, starting from the year 1579, would be that there are 54 eruptions in years ending on 10–34 and 60–84, and 27 in the remaining years. By moving the intervals 2 years forwards the corresponding numbers for earthquakes are 32 and 12. Even granted that these numbers were obtained by data-mining, the difference is high, 3 standard deviations from the mean in a binomial distribution with equal probabilities. It would be expected that a periodic effect with 1 cycle/50 years entails large correlations at short lags and at about 50 years lag, low correlations at 25 lags and a peak in the power spectrum at this frequency. The correlations would produce a maximum at $\phi(12)$ and a minimum at $\phi(37)$. In fact none of our estimates of these effects approaches any respectable level of significance. It thus appears that the mechanism controlling this phenomenon keeps account of the calender, but not of the past history of the events themselves. Considering the difficulties in producing a physical explanation of this kind of periodic effects, lacking the normal associated second order properties, little weight can be attached to the possibility of a 50-years period. But the records are not final, new evidence may appear, or, against the odds, a meaningful explanation of all the present results. There is, therefore, no reason to forget altogether about the curious numbers obtained by counting events in 25-years intervals.

Figure 4 shows the results of the calculation of $\theta(n)$ from the records of all eruptions and all earthquakes. The value of $\theta(o)$, which is the number of eruptions and earthquakes taking place during the same year, is large, and the values of $\theta(n)$ when eruptions are leading earthquakes is consistently larger than the simulated values for independent random processes. The difference between the observed value of $\theta(n)$ and the expected value increases with n. The values of θ where earthquakes lead eruptions are not different from what can be expected from random processes.

The relationship between two processes can also be studied by means of the cross-spectrum. A separate measure of the strength of the relationship, the coherence, is then obtained for each frequency band and an estimate of the phase difference or time lag. With a bandwidth of 0.045 cycle/year the average coherence in this frequency range is 0.28 and the phase difference lies between 16° and 37° The coherences are not high, but they are larger than in any of the simulation examples. The relationship seems to be mainly confined to frequencies below 0.1 cycle/year which is in accordance with the observation that the covariances seem to be positive up to long time-lags. As a result of the low coherences, estimates of the phase difference are very inaccurate, but the average time lag seems to be of the order of 3 years. Notice that this does not imply that it is most likely to observe an earthquake 3 years after an eruption. The relationship could rather be described so that following an eruption the probability of an earthquake is a little higher than normal for a fairly long time.

As the eruptions are leading the earthquakes we might be observing a causal relationship. A different explanation would be that both events are influenced by a common factor affecting the volcanic activity before the seismic activity.

The most obvious causal explanation of a relationship between those two kinds of activities is the triggering of latent events. This would produce an abnormally large number of short intervals, compensated by a reduction of longer intervals. But our records show no sign of such reduction. Triggering effect is therefore not a satisfactory single explanation of the results.

For many of the events more accurate timing is known than the year when they happened. Our analysis does not make use of this information. In principle there are no difficulties in designing methods of analysis which also take into account the known dates, e.g., by a modification of the method of Charnock (1977). But this would entail a substantial increase in the program writing and computing. Obviously it would make no difference to the geophysical interpretation if the number of eruptions leading an earthquake by 6 years was increased somewhat and the numbers corresponding to 5 and 7 years decreased accordingly. But considering the large number of earthquakes and eruptions in the same year, and 13 earthquakes leading an eruption by one year, a relationship where earthquakes trigger off eruptions must be considered a possibility, alongside the relationship where eruptions lead the earthquakes. But our analysis provides rather inaccurate information about this; an eruption in January and an earthquake in December the same year would be regarded as simultaneous whereas an earthquake in December and an eruption in January the following year appear as events with an interval of one year. In order to investigate this further we looked for all intervals shorter than one year between the two kinds of events. We found 11 cases where eruptions lead an earthquake by an interval of less than a year and 12 cases with the earthquakes leading. The expected value, taking into account the number of dated events, is about 5.

Another possible explanation of a causal relationship would be that the volcanic activity contributes directly to the strain that is subsequently released in the earthquakes. An eruption would then, presumably, be more likely to precede an earthquake in a neighbouring seismic zone than a more distant one. We could expect such effects to be most pronounced in South Iceland where both activities are confined within the same area.

We estimated separately the functions $\phi(n)$ for the 24 eruptions and 30 earthquakes in the Southern area. The results are given in Figs. 6 and 7. There is in fact no indication of a relationship between the two activities in these results. The distribution of the earthquakes is similar to the Poisson process, but $\phi(n)$ is rather low for the eruptions. This could be due to the fact that a large proportion of the eruptions is confined to the two central volcanoes where Thorlaksson's (1967) investigations showed that

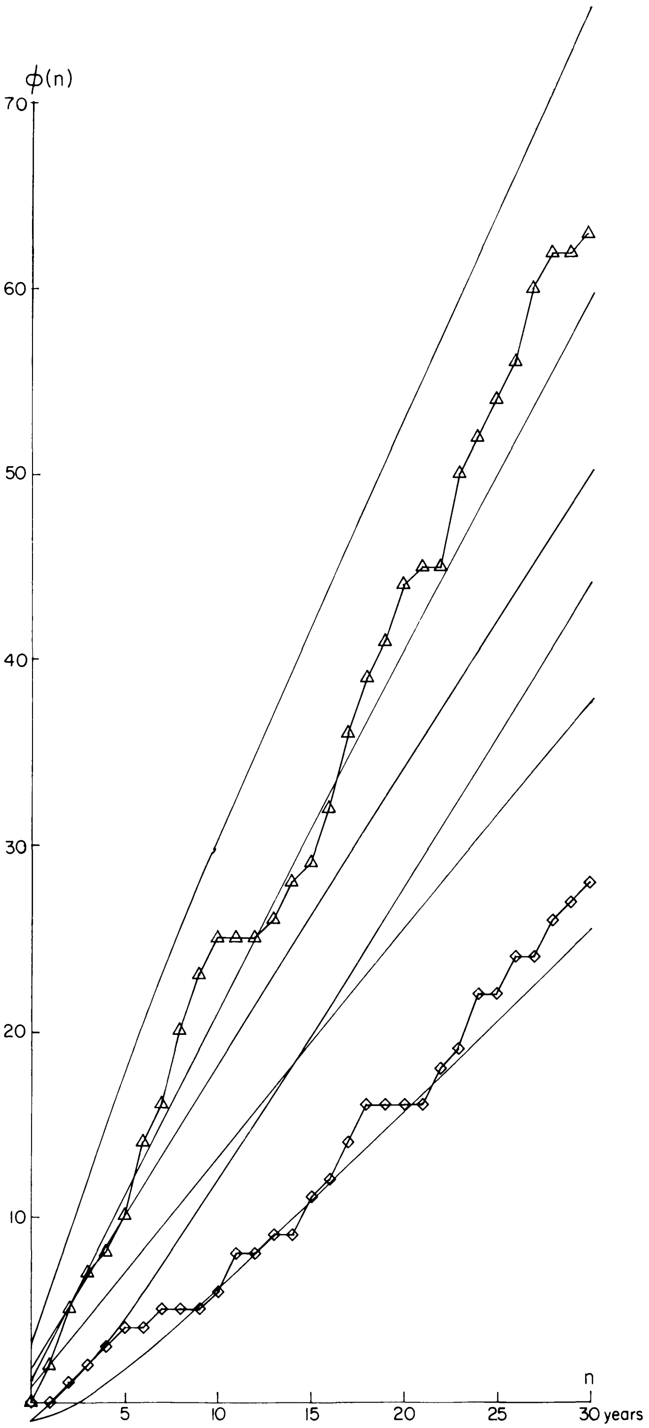

Fig. 6. Estimates of $\phi(n)$ from eruptions and earthquakes in South Iceland. Symbols are explained on Fig. 4

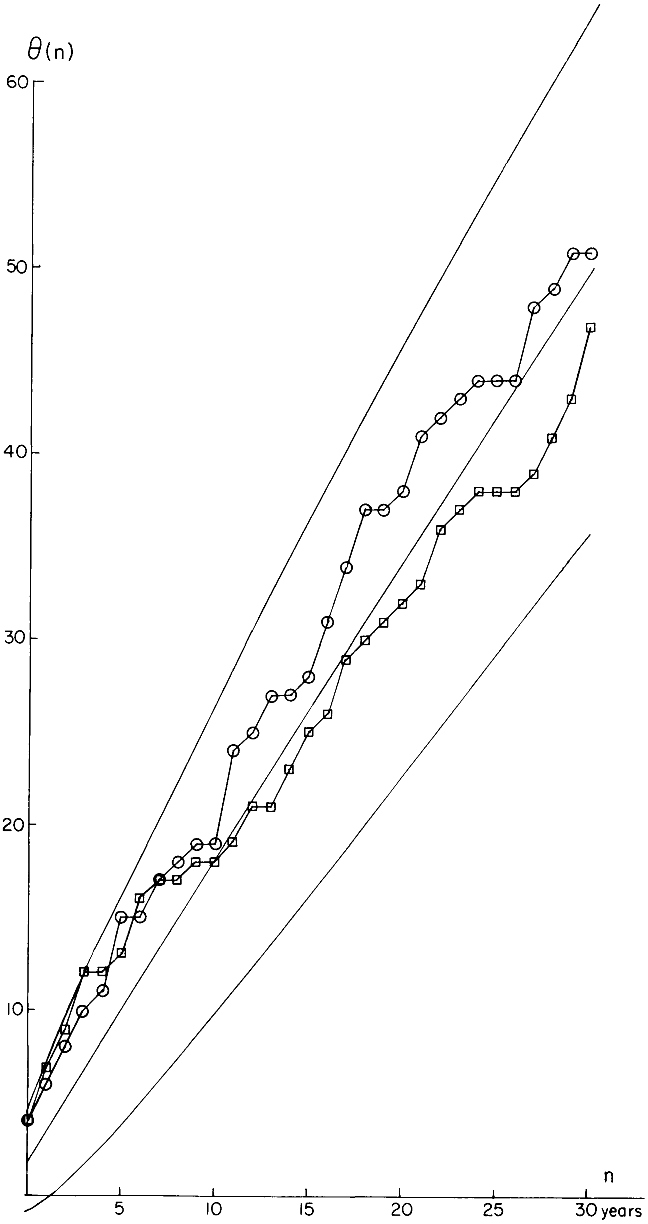

Fig. 7. Estimates of $\theta(n)$ from eruptions and earthquakes in South Iceland. Symbols are explained on Fig. 4

short intervals were less frequent than would be expected in a Poisson process.

The ratio between the released energies in the largest and smallest earthquakes on our records is about 10^3 The ratio between the largest and smallest masses of erupted material may be about 10^2 Little is, however, known about the size of many eruptions, especially those taking place under glaciers. Analysis of the dates of the events alone is therefore an inadequate method of investigating possible causal relationships between these activities.

Having failed to establish any causal link between eruptions and large earthquakes the possibility remains that the timing of both kinds of events is affected by a common factor. Plate movement is the obvious choice. Constructive plate boundaries consist of rift zones offset by transform faults. Plate accretion and volcanism are confined to the rift zones and large earthquakes to the transverse fault zones. The present activity at Krafla has clearly demonstrated a connection between volcanism and rift movements (Björnsson et al., 1977). The difference in the respective structures of rift- and fault zones, with frequent small earthquakes on rift zones as compared to the concentration around a few large earthquakes along the transverse fault zone, indicate larger friction in the fault zones than the rift zones. The average time-lag between movements on the two types of plate boundaries would therefore be with the rift movement leading. But the kind of relationship envisaged here does not exclude the possibility that an earthquake, related to an eruption through plate movement, could occasionally precede it. The large number of occurrences of both events within one year could therefore all be the consequence of the connection with plate movements without any separate triggering effect.

It might be expected that eruptions associated with rifting of the crust would be more closely associated with earthquakes on the transverse fault zones than the eruptions of central volcanoes. We have therefore compared the two kinds of eruptions separately with all earthquakes, including the rifting episodes in 1618 and 1789 with the rift-type eruptions. The estimates of $\theta(n)$ are given in Fig. 8.

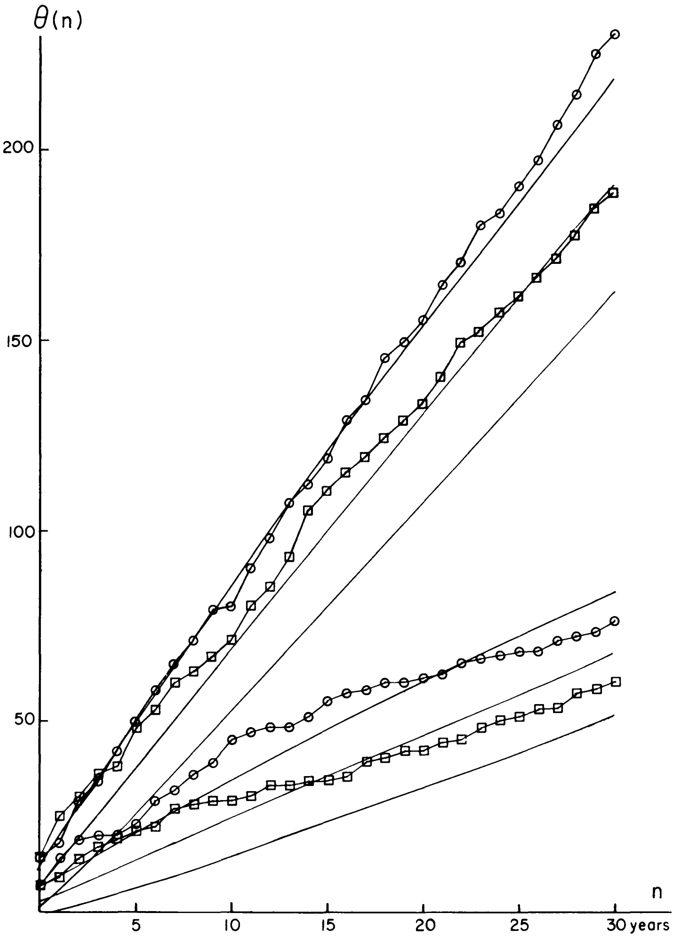

Fig. 8. Estimates of $\theta(n)$ from the record of all earthquakes and records of rift type- and central eruptions respectively. The larger values belong to the central eruptions. Symbols are explained on Fig. 4

For the rift type eruptions $\theta(n)$ is highly significant at the lower values of n, but returns to normal values for independent Poisson processes at $n>20$. The values of $\theta(n)$ calculated from the central type eruptions lie consistently about two square roots above the expected value. This behaviour, which is also present in $\theta(n)$ from the record of all eruptions, implies that correlations remain positive up to very large values of n. It is more difficult to find a plausible explanation for this than for zero or even negative correlations after positive correlations at short lags as with the rift type eruptions. (Negative correlations could originate from repose periods following strain release). It should be kept in mind that persistent non-zero correlation at long lags can easily arise from systematic time-dependent errors in the records. These results provide no occasion for rejecting the idea that the relationship between eruptions and earthquakes, apart from possible triggering effects, is confined to the rift type eruptions. But they do not provide strong support for it either.

Conclusions

Rather against our expectation the analysis of second order properties revealed no indication of clustering or other regularities within the records of eruptions or earthquakes, respectively. This should not be regarded as evidence for the total absence of such phenomena. Regarding the earthquakes we are in fact fairly sure that the result is merely a consequence of leaving out all but the largest events and the treatment of triggered sequences. But it shows that the data provide an inadequate basis for any quantative conclusion about relationships within respective records. In prediction the only relevant information on each record about its own future is the intensity of events. Thus the best prediction of the number of events during the next n years is the product of n and the intensity. And the best prediction of the interval until the next eruption takes place is the inverse value of the intensity. Knowledge of the dates of past events is irrelevant. (This does not of course apply to individual central volcanoes or seismic zones.)

A rather weak, but apparently significant, relationship exists between eruptions and earthquakes with the eruptions leading. Triggering may be present too, but it is not the main factor in the relationship which embodies the whole area rather than local effects. We prefer to explain this by plate movement affecting both kinds of events rather than any causal link from eruptions to large earthquakes. This relationship is too weak to contribute much to the prediction of earthquakes.

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