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Map of probable locations of future earthquakes for The Iberian Peninsula, the Balearics and Canaries

NATURAL RISKS

Earthquakes do not occur randomly in space; they tend to recur close to previous earthquake sites. This paper draws up a forecast map, based on this fact, for the Iberian Peninsula, the Balearic Islands and the Canary Islands. First of all an analysis is made of the comprehensiveness of the figures to hand on earthquakes in these areas, to weed out the untrustworthy data. A description is then given of a groundbreaking method for calculating the likely distance of the next earthquake from previous ones. A backdated check then shows that this procedure would have efficiently predicted the location of 90% of the earthquakes occurring between January 1985 and April 2009. Lastly, the forecast map for earthquakes after this date is presented.

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The distribution of earthquakes in space is very complex but not random: they tend to cluster in some regions while other regions never have any (figure 1). This holds true at all levels, from the world as a whole down to small regions (1). This distribution is relatively constant in time: over timescales of decades and centuries earthquakes tend to recur systematically in the same sites. This is because earthquakes happen only where there are faults capable of generating them and specifically where these faults build up the highest tensions (2).

It is not possible at the moment to ascertain exactly where the next earthquake will occur, since their generation is a very complex process and impossible to observe directly. All proposed forecasting methods have chalked up a fair amount of failures in the past, as in weather forecasting. To ascertain the real effectiveness of the procedure it has to be tested not against one particular earthquake but many (3). Forthright claims that one particular earthquake was successfully predicted therefore need to be taken with a pinch of salt.

Only in recent years has a start been made on a thoroughgoing investigation into how far the location of future earthquakes can be predicted simply on the basis of where they have previously occurred (4-6). This simple hypothesis has been shown to be capable of forecasting future earthquake locations as well or better than many more complicated forecasting methods used hitherto (3,7).

The assessment of any region's seismic risk is always more or less based on the working assumption that future earthquakes will tend to occur in or close to previous earthquake sites. In general, however, the exact places where these earthquakes occurred have not been taken into account. On the contrary, the usual procedure is to map out the earthquake-prone areas according to the criterion of each researcher or group of researchers (8-9).

The seismic risk map in Spain (10) and similar maps of many comparable countries (11) are based on demarcating such zones (figure 2). The method works from the assumption that no significant earthquake can occur outside them, while, within them, earthquakes may be generated in any site. This simplification skates over the fine detail of the distribution of earthquakes in space. As a result, the risk is in general overestimated, since some areas within a seismic zone do not generate earthquakes even if we assume the contrary (12). Conversely, the earthquake risk may be underestimated in some one-off areas where earthquakes have occurred, since the risk is averaged out with the lower risk of inactive areas roundabout. In general the distribution of earthquakes (figure 1) is more complex than these zones may suggest (figure 2), and many do not occur within them.

This article draws up a map showing where future earthquakes are most likely to occur on the Iberian Peninsula, the Balearic Islands and the Canary Islands. This involves the use of a groundbreaking forecasting method (13), which estimates how far future earthquakes are likely to occur from previous ones. First of all an analysis is made of the quality of the figures to hand, selecting only the most complete and trustworthy data. An explanation is then given of the forecasting method and it is tested on a backdated basis against earthquakes that occurred between January 1985 and April 2009. It is found that most of them did indeed occur in regions demarcated by previous earthquakes, and it would have been possible to forecast a pre-fixed percentage of them, namely 90%. In view of the success of the backdated test, a forecast map is drawn up showing the regions where most (ideally about 90%) earthquakes are expected to occur as from May 2009.

> *The distribution of earthquakes in space is very complex but not random; they tend to recur close to previous earthquake sites*

Data Quality Analysis

A description is now given of the figures used in this article and their quality is analysed, in the interests of selecting only the most trustworthy data. The map drawn up here is based exclusively on the location of past earthquakes. The region's most complete earthquake list will be used, as drawn up by the *Instituto Geográfico Nacional* (IGN). This information is published and made freely available on the internet (14).

Only some of the region's earthquakes can be detected. There is a bias towards the biggest quakes and those that occurred near working seismographs. Many of the small or distant earthquakes are not detected. This fact can be gauged by means of the dimension called the "magnitude of completeness". This marks the watershed of complete detection in any given area, all earthquakes with an equal or greater magnitude being detected but not all of the earthquakes below the magnitude of completeness.

This factor has to be taken into account when making any statistical analysis of earthquakes (1), to ensure that our forecasts and the assessment of them are correct (15). If we fail to bear in mind data quality, for example, we might be misled into thinking that earthquakes occurred a long way from each other in a given region, when it might in fact be the case that only a minority of the earthquakes occurring in that region were detected. This would distort our measurements of the inter-earthquake distances. Likewise, the actual percentage of forecast earthquakes can be calculated only if it is reasonably sure that all earthquakes in that region within the considered magnitude frame were detected. It is therefore necessary to consider only earthquakes with a magnitude equal to or greater than the magnitude of completeness. Smaller magnitude quakes also input information, but they should not be included in the final analysis.

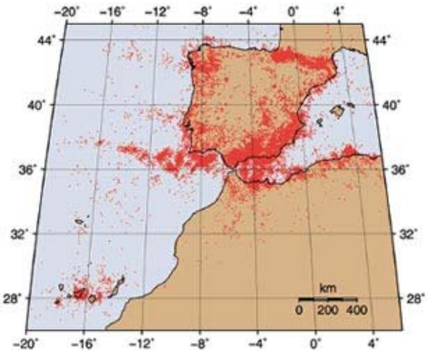

Figure 1. Map of 43,539 earthquake epicentres located from January 1985 to April 2009 by the National Geographic Institute (Instituto Geográfico Nacional) on the Iberian Peninsula, Balearic Islands, Canary Islands and neighbouring areas. For ease of discernment all earthquakes are represented as circles of equal diameter whatever their size.

It is not yet possible to ascertain exactly where the next earthquake will occur, since their generation is a very complex process and impossible to observe directly

The IGN-run National Seismic Network (*Red Sísmica Nacional*) comprises a set of stations fitted with seismographs distributed throughout the whole of Spain. This network's figures are the IGN's main source of information for pinpointing the earthquakes and drawing up the list used herein. This network has been regularly upgraded over time (16-18). The period of highest data quality began in 1985, by which time there were many seismic stations enabling earthquakes to be located in real time. As from 1991 data began to be used from a very sensitive device, made up by a group of seismographs set up around Sonseca, Toledo (18-19). In 2000 wideband digital seismographs began to be installed, allowing more sensitive recording of soil movements (18). On 2 June 2003 the IGN began to use an improved method for calculating earthquake magnitudes (20). Due to this improvement the magnitudes of events occurring before and after this date are not strictly comparable.

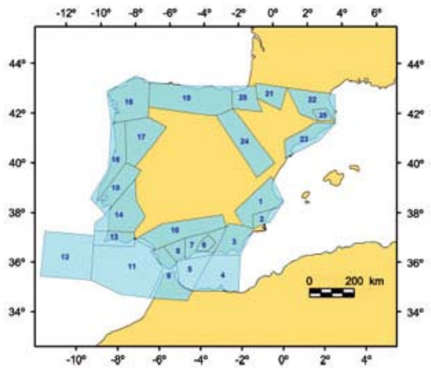

Figure 2. Zones considered for calculating the official seismic risk on mainland Spain, the Balearics, Ceuta and Melilla (10). According to these estimates no damage-causing earthquake should occur outside these twenty five polygons. Figure courtesy of Julián García Mayordomo.

This article draws up a map showing where future earthquakes are most likely to occur on the Iberian Peninsula, the Balearic Islands and the Canary Islands.

A measurement has been made of the IGN database's magnitude of completeness for four different periods, marked off by the abovementioned developments in the *Red Sísmica Nacional*. This magnitude has been mapped by means of the «entire magnitude range» method (21). There follow some technical details for specialist readers. The mesh used had sampling points at every 0.1° of longitude and latitude. A calculation of the magnitude of completeness is made for each point using the 60 earthquakes closest thereto, providing that the furthest is at most 100 kilometres away. The result is an average of 200 re-samplings (*bootstraps*) per point and calculations are made using the ZMAP computer programme (22).

Figure 3 shows the magnitude-of-completeness maps, illustrating how this magnitude has steadily come down over time. Progressive improvements in the *Red Sísmica Nacional* have made the figures increasingly comprehensive. The sharp drop in the final period could be partly an effect of the new method used to calculate the magnitudes. The lowest figures are recorded on the Iberian Peninsula and the Canary Islands. In the Atlantic and the north coast of Africa only earthquakes of a fairly high magnitude are detected. These results tally with independent estimates made by other methods for the years 1993 (16) and 2002 (18).

It has been decided to consider only the earthquakes occurring within the two polygons taking in the regions with the most complete figures. In these regions, moreover, the earthquakes should be located with greater precision
(23). One polygon includes the Iberian Peninsula, Balearics and neighbouring maritime areas. The other does likewise with the Canary Isles. Table 1 lists the coordinates of the polygon vertices to facilitate future comparisons of the results. Table 2 shows the minimum values used as from the specified dates, so that the data are reasonably complete within each polygon.

Description of the Forecasting Method

The method used herein has been recently proposed and tested against figures from around the world and from several regions of California (13). It serves for forecasting in which regions most earthquakes will occur without giving information on the exact site, the exact time or the magnitude they will have. As in other related methods (4-6), it involves drawing circles around the epicentres of previous earthquakes and assuming that future earthquakes will tend to occur within them. The new feature of the method used here (13) is the choice of this radius on the basis of inter-earthquake distances, thus giving this radius a physical significance. The basic hypothesis is that the distribution of distances separating previous earthquakes can be extrapolated to ascertain the distance therefrom that the next earthquake is most likely to occur. The main practical improvements of this method as compared with earlier procedures (4-6) are twofold: firstly it forecasts a pre-fixed percentage of earthquakes and secondly the maps produced are fine tuned over time (13).

The map involves drawing circles around the epicentres of previous earthquakes and assuming that future earthquakes will tend to occur within them

This forecast is binary in type: the next earthquake is expected to occur in marked zones of the map and is not expected outside them. There is no grey area between these two extremes. If the next earthquake occurs within the marked zones the forecast is considered to have been right, and wrong otherwise. The aim is to predict the greatest number of earthquakes marking the smallest possible area within the region under study. Binary forecasts are frequently used in weather forecasting with statements such as: «tomorrow it will rain (or will not rain) in this city». The sheer simplicity of this utterance means that a thoroughgoing statistical assessment can be made (3, 24).
The method can be explained in detail without needing to use any formula, with the following instructions (13):

- A study region is chosen together with a forecasting start date. Only the earthquakes occurring in this region will be considered, as from this date, with a magnitude equal to or greater than the magnitude of completeness at each moment.
- The percentage of earthquakes to be predicted is fixed beforehand. The higher this percentage, the larger must be

On 29 January 2005 an earthquake with a magnitude of 4.6 on the Richter Scale was recorded, with epicentre in the parishes of Zarzilla de Ramos and La Paca in the Murcia municipality of Lorca.

the areas marked on the map. The percentage 90% has been chosen for this article.

- Initially no data is to hand on where the next earthquakes will occur, so the whole region is marked. The first two earthquakes will thus be speculatively «forecast».
- When two or more earthquakes have occurred, the following is done just after each one:
    - Check whether the earthquake occurred where expected and calculate the percentage of earthquakes forecast.
    - Measure the distance from each epicentre to its nearest «neighbour».
    - Choose the 90 percentile from among these distances: the distance such that 90% of all of them will be less than or equal thereto.
    - Draw a circle around each one of the epicentres of the earthquakes that have already occurred, taking the above-calculated distance as the radius. On a precaution principle, if less than 90% of the earthquakes have been forecast, the new radius is not allowed to be less than the former.

The resulting map is hence tested against each earthquake and modified afterwards: a new circle is added around its epicentre and generally the radii of all circles are changed. The more earthquakes that have occurred in any region, the denser will be their distribution. The distances between them therefore fall and the same usually goes for the selected radius. As a result, as shown in the following section, the areas marked tend to become smaller: the map, therefore, is fine tuned automatically and naturally.

On 2 February 1999 two earthquakes were recorded in the Murcia locality of Puebla de Mula, with magnitudes of 3.5 and 5.2 on the Richter Scale.

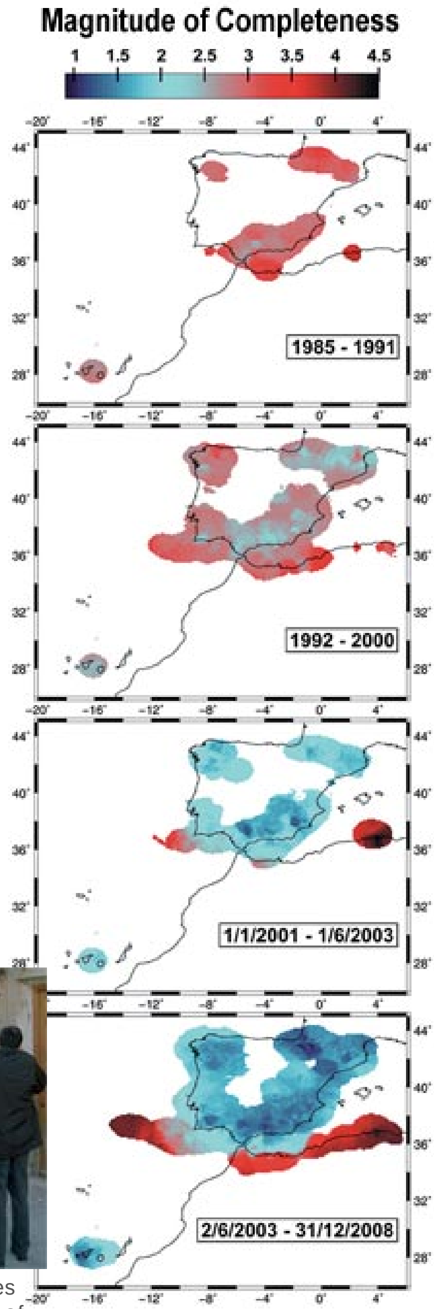

Figure 3. Average magnitude of completeness of the earthquakes located by the Instituto Geográfico Nacional in the indicated periods. The figures in a given site are complete for the earthquakes of a magnitude equal to or greater than this magnitude of completeness. In the white areas there were not enough earthquakes for making the analysis

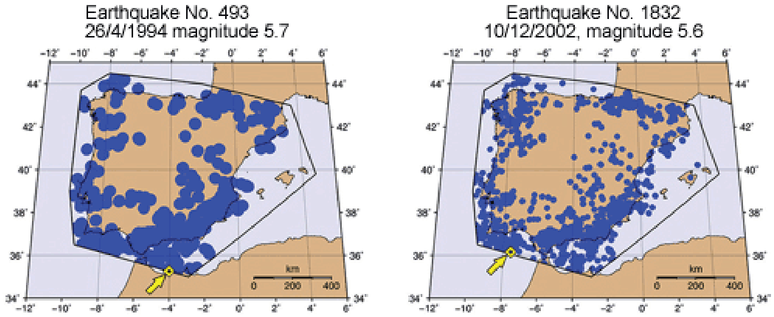

Figure 4. Aspect the forecast maps would have shown if drawn up just before the two higher magnitude earthquakes recorded in the period under study. The blue circles are drawn around previous epicentres, showing the regions where the next earthquake was expected to occur with 90% probability. Both events would have occurred within these regions, very close to the southern border of the study polygon.

The evolution of the forecast over time is shown in figure 5. The lefthand table shows the area marked by the circles. Initially this is high and seesawing but soon begins to settle down and shrink. The percentage of forecast earthquakes (regardless of their magnitude) is shown in the righthand table. After the initial oscillations it holds perfectly steady at the target 90%, thus bearing out the method's working hypothesis. The result also implies that the method optimises the area marked at each moment, automatically fine tuning it to forecast the target percentage of all the earthquakes. The success percentage is considerably higher than that of the marked area, statistically bearing out the procedure's predictive capacity. Furthermore, with continued forecasting of the same earthquake percentage but marking an ever smaller area, the map's performance progressively improves.

Figure 6 shows the magnitude-related percentage of forecast earthquakes. The method forecasts about 90% of the earthquakes, regardless of their magnitude. The slight difference for earthquakes of magnitude five or higher is not statistically significant, since there are only thirteen events (eleven of which, 84.6%, would have been predicted).

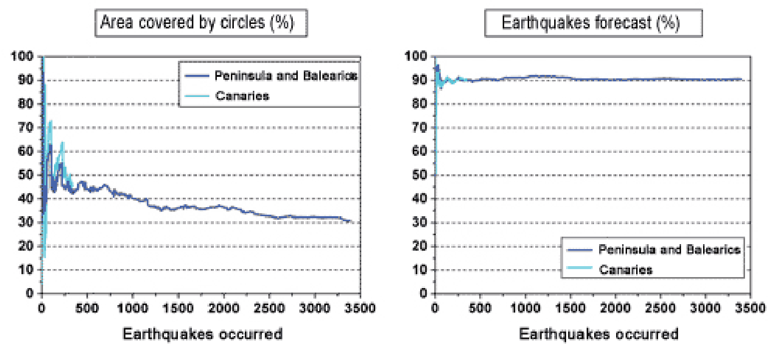

Figure 5. Results of the backdated forecast, from January 1985 to April 2009. Lefthand table: area occupied by circles on the forecast maps. As more earthquakes occur, more circles are added to the map, while their radius tends to shrink. With time the marked regions tend to take up a smaller area, so the map becomes increasingly fine tuned. Righthand table: percentage of earthquakes forecast. The target 90% is actually borne out on the graph.

The final map, updated as at 30 April 2009, is shown in figure 7. In the Iberian region the circles have a 10.9 kilometre radius, taking up 30.9% of the polygon area. In the Canary region they have a 13.7 kilometre radius and take up 45.5% of the polygon area. Adding together the areas of the two polygons, we come up with a total area occupied by the circles, which comes out as

32.4%.

Conclusions

This article shows that it is possible to forecast where future earthquakes will break out on the Iberian Peninsula, Balearic Isles and Canary Isles simply on the basis of where previous earthquakes have occurred. This study, as in other regions where the same method has been used (13), shows that, by marking a relatively small area in the region under study, a forecast can be made of a pre-fixed percentage of quakes (figure 5), regardless of their size (figure 6).

The resulting map is more complex and detailed (figure 7) than that of the officially considered seismic zones (figure 2). It also shows that, outside these zones, there are many sites proven here to be capable of generating future earthquakes. This research suggests that, to estimate the seismic risk, it might well be worthwhile to consider in more detail exactly where previous quakes have occurred, calculating the higher risk for these particular areas. At least one work along these lines has been published for the Iberian Peninsula (25).

With time the marked regions tend to take up a smaller area, so the map becomes increasingly fine tuned

These results also bear out the importance of detecting and pinpointing as many lower-magnitude earthquakes as possible (26). This would allow us to fine tune future forecast maps. Inside the Iberian Peninsula and on the Canary Islands the figures are complete down to small magnitudes (figure 3). This is not the case in the outlying parts of the peninsula, precisely where large magnitude quakes are most frequent, e.g., the two biggest events of all those studied herein (figure 4) or the great Lisbon earthquake of 1755, which began in the southwest of the Iberian Peninsula and caused grave damage in Portugal and Spain (27). It would therefore be worthwhile to make further investments in improving and extending the seismic networks to be able to pinpoint more earthquakes with greater precision.

The main limitation of the map as drawn up herein (figure 7) is that it will not be updated with new earthquakes after it has been published on 15 May 2009. This differs from the trial carried out with figures ranging from 1 January 1985 to 30 April 2009, in which the map was updated after each new event. To ensure that the map remains effective as future earthquakes occur, the percentage of earthquakes occurring within the marked regions (ideally about 90%) should be considerably greater than the percentage area that these regions occupy (32.4%). This will have to be tested later as it is always possible that big quakes might occur in sites with few previous events (28). Only time will tell, therefore, whether the map published here continues to show the same effectiveness as the living version of the backdated trial.

Iberian Peninsula and Balearics		Canaries	
Longitude	Latitude	Longitude	Latitude
3.6	43.0	-17.0	29.5
4.8	39.8	-13.0	29.5
-2.9	35.0	-13.5	28.0
-9.5	36.5	-17.0	27.0
-10.0	39.0	-18.5	27.5
-9.8	43.7	-18.5	29.0
-8.0	44.5		
-2.0	44.0		

Table 1. Coordinates of the polygon vertices used for demarcating the study regions

Start date	Minimum Magnitude	
day/month/year	Iberian Peninsula and Balearics	Canaries
1/1/1985	3.4	2.9
1/1/1992	3.2	2.8
1/1/2001	2.5	2.3
2/6/2003	2.5	2.2

Table 2. Minimum earthquake magnitudes used in each region, as from the stipulated date.

On 15 June 1964 a medium intensity earthquake hit the province of Granada, causing damage to housing in several localities.

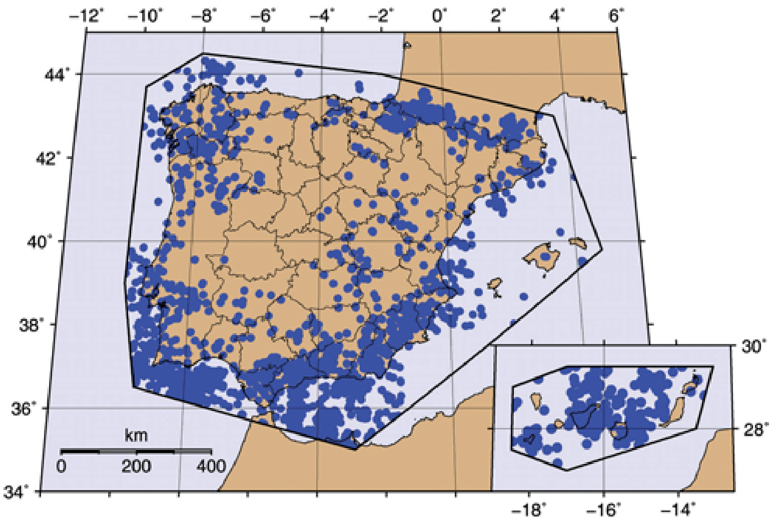

Figure 7. Location forecast map of future earthquakes in the Iberian Peninsula, the Balearic Islands and Canary Islands. The borders of the Spanish provinces have been sketched in as reference. Ideally, about 90% of the epicentres of earthquakes occurring from May 2009 onwards (with a magnitude equal to or greater than 2.5 in the Iberian polygon and 2.2 in the Canaries) should fall within the areas marked in dark blue.

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By way of a glossary

Epicentre. Point of the earth's surface under which, at a certain depth, an earthquake commenced.

Fault. An irregular fracture caused by the movement of one block of rock against another. It might be microscopic in size but can then grow in time until becoming kilometres long in extreme cases. Fault movements tend to be episodic rather than continuous. The blocks slowly warp without movement until building up sufficient tension to overcome mutual friction. The relative movement is then sudden, unleashing an earthquake. This process is usually repeated cyclically. The bigger the fault, the bigger the resulting earthquake is likely to be.

Magnitude. A measurement of the energy released by an earthquake. Each magnitude increment entails a 32-fold increase in energy. The biggest magnitude ever recorded was 9.5 in the Great Chilean Earthquake of 1960. In Spain damage is usually produced in vulnerable buildings by earthquakes with a magnitude of 4 or 5 or greater. Ceteris paribus, an earthquake's effects are directly proportional to its depth of origin.

Seismometer. An instrument that measures and records soil movements, such as earthquake vibrations. Analysis of these movements in several seismometers enables any earthquake's origin and magnitude to be determined.

Earthquake. Land vibration usually caused by the sudden movement of one block of rock against another along the surface of a fault. This movement, which may last for several minutes, starts in a specific point of the fault, over which the earthquake epicentre lies.

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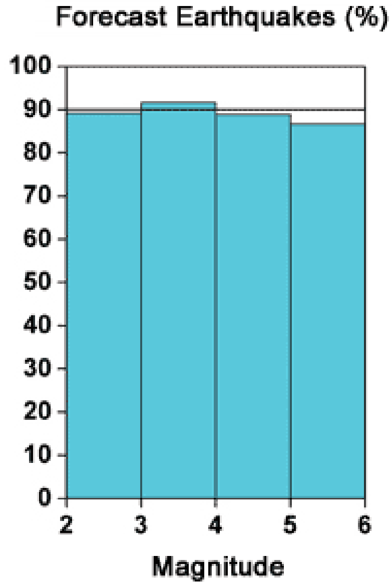

Figure 6. Percentage of earthquakes forecast in the backdated trial for different magnitudes. The results of the study zones (Mainland and Balearics, and Canaries) have been jointly considered. The method would have forecast about 90% of the earthquakes, regardless of their magnitude.