Text Classification of the Precursory Accelerating Seismicity Corpus: Inference on some Theoretical Trends in Earthquake Predictability Research from 1988 to 2018

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Abstract: Text analytics based on supervised machine learning classifiers has shown great promise in a multitude of domains, but has yet to be applied to Seismology. We test various standard models (Naïve Bayes, k-Nearest Neighbors, Support Vector Machines, and Random Forests) on a seismological corpus of a hundred articles related to the topic of precursory accelerating seismicity, spanning from 1988 to 2010. This corpus was labelled in a previous study [Mignan, Tectonophysics, 2011] with the precursor whether explained by critical processes (i.e., cascade triggering) or by other processes (such as signature of main fault loading). We investigate rather the classification process can be automatized to help analyze larger corpora in order to better understand trends in earthquake predictability research. We find that the Naïve Bayes model performs best, in agreement with the machine learning literature for the case of small datasets, with cross-validation accuracies of 86% for binary classification. For a refined multiclass classification ('non-critical process' < 'agnostic' < 'critical process assumed' < 'critical process demonstrated'), we obtain up to 78% accuracy. Prediction on a dozen of articles published since 2011 shows however a weak generalization with a F1-score of 60%, only slightly better than a random classifier, which can be explained by a change of authorship and use of different terminologies. Yet, the model shows F1-scores greater than 80% for the two multiclass extremes ('non-critical process' versus 'critical process demonstrated') while it falls to random classifier results (around 25%) for papers labelled 'agnostic' or 'critical process assumed'. Those results are encouraging in view of the small size of the corpus and of the high degree of abstraction of the labelling, and demonstrate the potential of supervised learning to reveal textual patterns. Domain knowledge engineering
remains essential but can be made transparent by an investigation of Naïve Bayes keyword posterior probabilities.

1. Introduction

Text analytics (or text mining) uses tools from information retrieval, natural language processing (NLP), and machine learning, to autonomously extract information from corpora (Sebastiani, 2002; Aggarwal, 2018). Prominent in Web data classification (Sebastiani, 2002; Tsytsarau and Palpanas, 2012; Kharde and Sonawane, 2016), text analytics is also commonly used in science, such as social sciences (Grimmer and Stewart, 2013) or biomedical sciences (Ng and Wong, 1999). The present article is the first to investigate the potential of text analytics in Seismology.

Analysis of corpora from the seismological literature remain rare, and are so far based on domain knowledge with no use of text analytics (Mignan, 2011; 2014). These early investigations, with manual extraction of information and categorization (so-called knowledge engineering), remain somewhat non-transparent and/or difficult to scale to larger corpora. Those types of meta-analyses however provide useful conclusions regarding the scientific process, including status-quo biases, paradigm shifts, and other patterns (Kuhn, 1970), which can then be used as input to improve the scientific debate. For instance, Mignan (2011) used the precursory accelerating seismicity corpus (86 articles) to identify a scientific cycle composed of three phases: early works, criticality paradigm, and divergent directions (Fig. 1). This meta-analysis also showed the implications of different theoretical trends on the stated predictability of large earthquakes and that this scientific process was dynamic, with current research being at a "crisis" stage (see Hough (2010) for a novelized review of earthquake prediction research cycles). Despite the present "earthquake prediction winter", a better understanding of the history of earthquake predictability remains crucial for the next research phase.

Here we will reinvestigate the precursory accelerating seismicity corpus already labelled by Mignan (2011) and we will extend it by including the articles published since then, yielding a corpus of 101 articles for the past 30-year period (1988-2018). We will test various machine learning algorithms for supervised learning (Naïve Bayes, k-Nearest Neighbors, Support Vector Machines, and Random Forests) and apply them to the text domain (Sebastiani, 2002; Aggarwal, 2018). We will discuss the specificities of text classification (sparse high-dimensional non-negative data) and of our corpus (small and slightly unbalanced dataset) to be considered for both feature and classifier selection. Our aim is threefold: (1) to illustrate, for
the first time, text classification procedures in Seismology, (2) to improve the meta-analysis initiated by Mignan (2011), by making information extraction (i.e., theoretical trends) more transparent and scalable with autonomous learning, and (3) to engage the Seismological community in debating scientific issues using the concept of metascience (Pearce and Rantala, 1983).

2. Methods & Data

2.1. Corpus Definition & Text Analytics Prerequisites

Our corpus is composed of \( n_{all} = 101 \) articles that explore the phenomenon of accelerating seismicity observed prior to large earthquakes. The training set is composed of \( n_{train} = 86 \) articles published between 1988 and 2010, and which have been labelled by Mignan (2011). The test set is composed of \( n_{test} = 15 \) articles, corresponding to the articles published since 2011. Following the same approach as in Mignan (2011), works not considered here are the ones where precursory accelerating seismicity is not the main topic, the term is used to mean short-term foreshocks (events occurring in the near-field during the nucleation phase; see review by Mignan, 2014), or where tectonic earthquakes are not the target (e.g., volcanic precursors, laboratory acoustic emissions, etc.).

The corpus is treated as a bag-of-words, from which we define an \( n \times d \) document-term matrix (DTM), which is a sparse high-dimensional non-negative matrix \( D = \{ \mathbf{x}_1, ..., \mathbf{x}_n \} \) with \( \mathbf{x}_i \) a \( d \)-dimensional vector, following Aggarwal (2018)'s notation. Each possible word from the corpus lexicon corresponds to one dimension, or to one feature. We extract text from our corpus following two different approaches, one considering the full articles (from PDF files) and another the meta-data only, consisting of the title, publication year, author list, abstract and keywords (which can be extracted from each PDF, or from website queries). While the first approach yields a larger set of tokens (or total number of words), the second approach gives a subset of the full texts that condenses the authors' vision while avoiding journal paywalls. Using the meta-data instead of the PDF provides a natural approach to feature reduction and can take advantage of web scraping tools to automatize the corpus creation (Glez-Peña et al., 2013).

We use the unigram model, which is equivalent to the bag-of-words, and yields a lexicon of \( d = 21,017 \) terms (or dimensions) for the full texts and of \( d = 1,891 \) terms for the meta-data, with only terms composed of at least 3 characters considered in the full text corpus. The tokens are subsequently cleaned by removing stop-words (common English words, such
as articles, pronouns, etc.) and punctuation, by converting upper cases into lower cases, and by consolidating related words which have the same root into a single term (i.e. process of stemming, e.g., 'accel' = {'accelerating', 'accelerated', 'acceleration'}). All of those preliminary text mining steps are done with the quanteda R package (Benoit, 2018).

We test as feature-value weighting scheme both the term frequency and the term frequency-inverse document frequency (tf-idf) model, in which the inverse document frequency log(n/ni) is multiplied with the term frequency, with ni the number of documents in which the ith term occurs (Salton and McGill, 1983). Normalization by document length is only done when it increases cross-validation accuracy.

2.2. Class definition and labelling

We first define the following binary class: 1 = 'critical process assumed or demonstrated' versus 0 = 'else'. We then refine the labelling with an ordered multi-class categorization of the theoretical trends with: 0 (='non-criticality assumed or demonstrated') < 1 (='theoretically agnostic') < 2 (='criticality assumed') < 3 (='criticality demonstrated').

Let us now explain the rationale behind categorizing the precursory seismicity literature around the concept of Criticality (Sornette, 2000). Criticality is a generic term encompassing Self-Organized Criticality (SOC; Bak and Tang, 1989) and the Critical Point theory (Sammis and Sornette, 2002). It is related to Complexity theory, which can be summed up as dynamic processes controlled by bottom-up triggering leading to emergent phenomena at the system level (i.e., holistic system). In contrast to criticality would be non-criticality, where processes may be static and are controlled by top-down triggering (often referred to as loading, e.g., from a main fault). In that case, the system can be reductionist. The debate of criticality versus non-criticality is important since the two diametrically opposed views offer different conclusions as to the precursory seismicity phenomenology and to the predictability of earthquakes (Mignan, 2011; 2014). It is also a fundamental question, as most earthquake theories, if not all, can be related to one or the other view.

On top of the obvious reason for using the precursory accelerating seismicity corpus, which is the availability of an already defined and labelled dataset (Mignan, 2011), another one is the relatively simple debate illustrated by this precursory pattern, which is defined by a power-law time-to-failure equation (Bufe and Varnes, 1993). Power-laws are often described as the signature of a critical process (Bak and Tang, 1989) although they can also be explained by geometric top-down processes (King, 1983; Mignan et al., 2007; Mignan, 2012). Then, whether the process is truly critical or non-critical has tremendous implications for earthquake
predictability. If the system is controlled by SOC, then earthquakes would be unpredictable (Geller, 1997) and accelerating seismicity patterns would only represent random fluctuations of the natural clustering behavior of seismicity (Hardebeck et al., 2008), which is commonly described by the Epidemic-Type Aftershock Sequence (ETAS) model (Ogata, 1988; Seif et al., 2017 and references therein). If the system is a variant of SOC however, the system-level event (i.e., mainshock) could show some degree of predictability with accelerating seismicity representing some cascading triggering towards the critical point (Sammis and Sornette, 2002).

In a non-critical model, accelerating seismicity would be the signature of loading on the fault that will host the mainshock (Mignan, 2012). While the critical point and top-down loading expect some degree of predictability, the accelerating seismicity phenomenology differs. Also, in criticality, patterns are expected to emerge on average by timeseries stacking while in non-criticality, patterns may change from timeseries to timeseries with stacking having for effect to smooth out the precursory pattern. Theoretical choices have therefore a clear impact on the outcome, as proven also for the prognostic value of short-term foreshocks (Mignan, 2014).

Figure 1 shows the number of articles per class as a function of publication year. The Kuhnian cycle already described by Mignan (2011) is visible and composed of three successive phases: early works, criticality paradigm, and divergent directions. For the training set, the binary labelling follows the one of Mignan (2011) with 1 ('critical process assumed or demonstrated') = 'x', '+', and 0 ('else') = '−', '' (see their Table 1). Mignan (2011) labelled as 'unclear' ('~') 6 articles. Here we decided whether they correspond to 0 or 1 (see the supplementary material for the full list of labels). The multiclass labelling also tries to follow Mignan (2011) with 0 ('non-criticality assumed or demonstrated') = '−', 2 ('criticality assumed') = 'x' and 3 ('criticality demonstrated') = '+'. For their empty class ' ', most were related to our class 1 ('theoretically agnostic') but the articles where non-criticality was assumed were moved to our class 0. As previously mentioned, the knowledge engineering approach that led to this labelling was not explicit in Mignan (2011). It is also not simple to describe, as illustrated in Table 1 for the test document set. Obviously, the meta-analysis would become more transparent and objective if one could autonomously classify the articles per theoretical trend. More generally, this would have important implications if the process could be scaled to larger corpora, for example to the complete literature on earthquake predictability research.
Fig. 1. The two categorizations defined to represent the precursory accelerating seismicity 1988-2018 corpus: (a) Binary classes 'critical process' or 'else', based on the results of the meta-analysis by Mignan (2011), updated for the period 2011-2018; (b) Multiple ordered classes 'non-criticality demonstrated or assumed' < 'agnostic' < 'criticality assumed' < 'criticality demonstrated' - Labels were determined using domain knowledge (see e.g., Table 1).

2.3. Supervised Learning for Text Classification

The DTMs defined in section 2.1 are used as input to test different machine learning classifiers. We consider some of the most common methods: Naïve Bayes (Domingos and Pazzani, 1997), k-Nearest Neighbors (Cover and Hart, 1967), Support Vector Machines (Cortes
and Vapnik, 1995), and Random Forests (Breiman, 2001). The $k$-Nearest Neighbor, Support Vector Machines, and Random Forest are sketched in Figure 2. Deep learning approaches such as artificial neural networks (Rumelhart et al., 1986) are not considered since our corpus is too small, nor are boosting techniques (Freund and Schapire, 1999) used to improve any of the above classifiers. We also do not experiment with the ensembling of different classifiers (Rokach, 2010). Hyperparameter tuning based on cross-validation results will be described in section 3.1.

The Naïve Bayes classifier is based on Bayesian probability theory with the term 'naïve' referring to the assumption that all features are independent. Although this is rarely true, naïve Bayes models perform relatively well in many problems (Domingos and Pazzani, 1997). Bayes' theorem defines the posterior probability as

$$P(c|\vec{X}) = \frac{P(c)P(\vec{X}|c)}{P(\vec{X})}$$ (1)

with $P(\vec{X}|c)$ the likelihood, $P(c)$ the prior probability and $P(\vec{X})$ the marginal likelihood, with $\vec{X}$ the feature vector of the document and $c$ the class. For $d$ features, we get

$$P(c|\vec{X} = \{x_1, \ldots, x_i, \ldots, x_d\}) \propto P(c) \prod_{i=1}^{d} P(i|c)^{x_i}$$ (2)

which is the multinomial Naïve Bayes classifier of a given document, with $x_i$ the weighted frequency of term $i$. Note that the marginal is constant and thus only acts as scaling factor. We test two different priors $P(c)$, the uniform distribution and the document frequency of $c$. Note that the corpus is unbalanced in opposite directions for the training set (58% in class 1) and test set (20% in class 1) for the binary case. We use the Naïve Bayes classifier textmodel_nb of the quanteda R package (Benoit, 2018) with Laplace smoothing of 1 to avoid null probabilities.

The $k$-Nearest Neighbors ($k$NN) classifier (Fig. 2a) is a simple non-parametric method where documents are classified to the majority class in the cluster composed of the $k$ closest instances in the feature space (Cover and Hart, 1967). We use Euclidean distance combined to a cosine (similarity) kernel function to reduce weights on orthogonal documents (Hechenbichler and Schliep, 2004). The value of the parameter $k$, which thus specifies the number of neighbor observations that contribute to the predictions, is optimized via cross-validation. We did not test other Minkowski distances (i.e., other than Euclidean). We use the $k$NN classifier of the KernelKnn R package (Mouselimis, 2018).

A Support Vector Machine (SVM) divides the $d$-dimensional space into partitions of similar classes, by searching for the Maximum Margin Hyperplane (MMH) that creates the greatest separation between two classes. The so-called support vectors are the points from each class which are the closest to the MMH (Fig. 2b). When the data are non-linear, kernels are
used to map the data into a linear problem in a higher dimensional space. We here test the following kernels: linear, polynomial and radial basic function networks (Joachims, 1998). Regularization is used to avoid overfitting, allowing instances to fall off the MMH but subject to the 'slack penalty' $C = 1/\lambda$ (here = 1), with $\lambda$ the regularization parameter. We refer the reader, who wants to learn more about the mathematics of SVMs, to Cortes and Vapnik (1995); Bennett and Campbell (2000); Steinwart and Christmann (2008). We use the \texttt{ksvm} classifier of the \texttt{kernlab} R package that uses Euclidean distance (Karatzoglou et al., 2004).

![Sketches illustrating three classic machine learning classifiers: (a) k-Nearest Neighbor kNN; (b) Support Vector Machine SVM; and (c) Decision tree (one instance of a Random Forest). The squares and circles represent two different classes characterized by the two features $x_1$ and $x_2$.](image)

\textbf{Fig. 2.} Sketches illustrating three classic machine learning classifiers: (a) $k$-Nearest Neighbor kNN; (b) Support Vector Machine SVM; and (c) Decision tree (one instance of a Random Forest). The squares and circles represent two different classes characterized by the two features $x_1$ and $x_2$.

A decision tree (Fig. 2c) makes a hierarchical partitioning of the data space, in which the partitioning is done recursively, top-down, using split conditions on the features (Breiman
et al., 1984). For text, the split condition corresponds to constraints on the frequency of one term (Aggarwal, 2018). At each step, two new branches are created, corresponding to the presence or absence of a term. The final nodes (leaf nodes) are labelled, meaning that a test document will be checked for the presence or not of each term of the tree, following the matching branches down to the label given by the leaf node. To avoid overfitting, pruning is generally done (by holding out part of the training data). Another option, used here, is the Random Forest classifier, which bootstraps decision trees grown to full height (Breiman, 2001). The main parameters are the number of features $n_{try}$ randomly selected at each node and the number of trees $m_{tree}$ from which an average is made (i.e., bagging approach). We use the randomForest R package (Liaw and Wiener, 2018) in which the split condition is based on a variant of the Gini index (Breiman et al., 1984).

3. Results

3.1. Cross-Validation & Model Selection (Binary Class only)

We select the feature weights and machine learning hyperparameters based on a leave-one-out (i.e., $n$-fold) cross-validation, which consists in training on all the data except for one document on which the prediction is made (Kohavi, 1995). The classifier is then evaluated by averaging the $n$ results. This is computationally non-intensive since we have only $n_{train} = 86$ training documents. Results are shown in Table 2 in terms of accuracy, F1-score, precision and recall. The accuracy is defined as the fraction of test instances in which the predicted class value matches the label. The F1-score is the harmonic mean of precision and recall. Precision is defined as the proportion of positive instances (i.e., true positives + false positives) that are truly positive and recall is defined as the number of true positives over the total number of positives (i.e., true positives + false negatives).

A random classifier would yield a 50% accuracy, but since our binary classes are 1 ('critical process assumed or demonstrated') and 0 ('else'), we must benchmark our machine learning classifiers against the obvious search of the keyword 'critic*'. This is a simple rule-based classifier that predicts 1 if the term 'critic*' is present and 0 if absent from the document. As we notice from Table 2, the accuracy of a classifier should be higher than 80% for the meta-data (composed of the list of authors, title, abstract, and keywords) and 63% for full texts (F1-score > 75% and 82%, respectively). The difference in accuracy of this baseline classifier is due to the fact that studies assuming or demonstrating criticality are more likely to use that term in the title and/or abstract than other studies, while any study may refer to criticality within the main text, for example when discussing the background literature.
Fig. 3. Naive Bayes results (including confusion matrices) for leave-one-out cross-validation on training document set (1988-2010) and for test document set prediction (2011-2018) - both cases for full texts: (a) Binary class; (b) Multiclass. See Figure 1 for comparison with the original labels and for the class color scheme.

The best results of the five machine learning classifiers, as listed in Table 2, were obtained as follows: for all cases, better results were obtained for full texts if the number of features was reduced by removing all terms with a frequency of occurrence lower than 5. We also found that using the term frequency gave similar or better results than the tf-idf model (Forman, 2008), which suggests that some frequent words that tf-idf possibly penalizes too strongly are important for classification. Further document length normalization only improved
results for $k$NN and was automatically done by `textmodel_nb` for Naïve Bayes. Specific hyperparameter tuning was as follows: we used a document frequency prior for Naïve Bayes, $k = 3$ for $k$NN, a linear kernel for the SVM, and $n_{tree} = 500$ and $n_{try}$ the square root of the total number of features for the Random Forest. All classifiers perform better than the keyword search for full texts with an accuracy equal to or greater than 78% (F1-score $\geq 81$%). For metadata however, only the Naïve Bayes classifier performs better than a simple keyword search with an accuracy of 84% and F1-score of 86%. Those scores are reasonable compared to, for instance, sentiment classification on the Web (Tsytsarau and Palpanas, 2012; Kharde and Sonawane, 2016). Overall, the Naïve Bayes classifier performs better than all other classifiers, although the differences range from 10% to as low as 1%. Note that using different strategies (e.g., different hyperparameter tuning, use of boosting) may also yield better accuracies. Results of Table 2 are however consistent with the bias-variance tradeoff that states that models with a high bias (such as Naïve Bayes) perform better on rather small training sets (Ng and Jordan, 2001). For the rest of this work, we will only consider the multinomial Naïve Bayes model with document frequency prior. This model has also the advantage to be computationally cheap and transparent.

### 3.2. Interpreting Naïve Bayes Results

Let us now investigate the Naïve Bayes results for the binary class in more detail. Figure 3a shows the results in time series form, as well as the confusion matrix (the test set results will be discussed in section 3.3). Of 86 training documents, 6 were wrongly categorized as 0 and 6 as 1. A ranking of posterior probabilities $P(c|i)$ (Eq. 1; Table 3) shows that terms $i$ best representative of class 1 (= 'critical process assumed or demonstrated') include (in stem form): 'powerlaw', 'automat', 'fibre-bundl', 'lattic', 'renormalizationgroup', etc., which are clearly related to the concept of critical phenomenon (Sornette, 2000). On the other side of the probability distribution, we find: 'backslip', 'prestress' or 'coulomb' suggestive of studies more focused on seismotectonic aspects than fundamental physics. However, we also find other terms correlated to one or the other class, which are intrinsically independent of the physical process, such as authors, methods or region names, showing that authors often follow one theoretical view, may favor some methods (e.g., 'lurr', acronym for Load/Unload Response Ratio, or 'ellipt' for use of elliptical areas, see Table 3) and only work on one specific region. Such sampling bias is expected to not generalize well. For example, let's consider the study made by Papadopoulos (1988), labelled 0 and misclassified 1. We can find the reason in the
fact that the terms used in many Greek works labelled 1 from the Papazachos group (e.g., Papazachos et al., 2007 and references therein) are also used by Papadopoulos (1988), such as 'hellen' for Hellenic \( P(c = 1| \text{hellen}) = 0.77 \) or 'peloponnesus' \( P(c = 1| \text{peloponnesus}) = 0.69 \), references to 'papazacho' \( P(c = 1| \text{papazacho}) = 0.81 \), use of 'ellipt', etc.. Only a larger corpus is likely to reduce the weight of such associations.

For the multiclass categorization, a random classifier would yield a 25% accuracy. The Naïve Bayes model yields, in leave-one-out cross-validation, 78% accuracy and \{80%, 72%, 78%, 84\} F1-score for classes 0, 1, 2 and 3, respectively, on the full texts, and 66% accuracy and \{74%, 50%, 68%, 73\} F1-score on meta-data only (Table 4). This result is encouraging since the intermediary classes are closely related, with similar lexicons. It means for example that 'criticality assumed' (class 2) and 'criticality demonstrated' (class 3) can be distinguished to some degree from a simple bag-of-words. Results are shown in Figure 3b with the confusion matrix showing how errors are distributed. Note that no document of class 0 is misclassified in class 4 nor vice versa. This verifies the proposed ordering of classes 0 (= 'non-criticality assumed or demonstrated') < 1 (= 'theoretically agnostic') < 2 (= 'criticality assumed') < 3 (= 'criticality demonstrated'). Table 5 shows some of the terms leading to high posterior probabilities \( P(c|i) \) for each class \( c \), which can easily be related to domain knowledge engineering. For class 0, seismotectonic terms dominate; for class 1, terms related to different regions and statistical tests dominate; for class 3, common methods used in criticality studies dominate; finally, for class 4, fundamental physics terms dominate.

3.3. Test Data Prediction with the Naïve Bayes Model

Figure 3 shows the test data results for the 2011-2018 part of the corpus (Table 1) for both binary and multiclass. The Naïve Bayes model built from the training document set yields for the test set 73% accuracy (for both full texts and meta-data). However, the F1-score provides a better metric with 50% and 60%, respectively (Table 6). It means that the model is only slightly better than a random classifier for the binary class. Note also that the search of the term 'critic' is worse than a random classifier for full texts. Results are better for the multiclass prediction (Table 7) with an accuracy between 47 and 53% (25% for a random classifier). F1-scores show that the extreme classes 0 (= 'non-criticality assumed or demonstrated') << 3 (= 'criticality demonstrated') are best predicted with F1-score = 80% and 100%, respectively, for full texts (67 and 100% for the meta-data). For full texts, the Naïve Bayes model predicts the intermediary classes 1 (= 'theoretically agnostic') and 2 (= 'criticality
assumed') at the level of a random classifier (with F1-score = 20 and 25%, respectively). The result is slightly better for the meta-data (with F1-score = 40 and 44%, respectively).

These results prove that the model does not generalize well, which was expected from some of the correlations observed during cross-validation. The results are however encouraging in view of the many difficulties associated with the present data set: (1) the training set is only composed of 86 documents; (2) the class distribution of the training set does not match the target distribution, being unbalanced in different directions with 58% of the training documents in class 1 and only 20% of the test set in class 1 (in binary class); (3) the test set has a rather small statistical overlap with the training set since both sets represent two independent time periods. Although some term weights remain valid, as proven by the results better than random ones, changes in terminology due to different authorships can in part explain the drastic decrease in accuracy.

4. Conclusions

We presented the first study that applies machine learning to Seismological text classification, which, we hope, will encourage its use by the community. We showed that the Naïve Bayes model is the best performing classifier, which is likely due to the small size of the corpus considered. While other classifiers (kNN, SVM, Random Forest, etc.) may work better on larger training document sets, Naïve Bayes combines two advantages, fast computation and transparency. We showed for example that this model allows making the knowledge engineering process more transparent.

Was manual labelling required in the first place? Applying k-means to the document-term matrix (DTM) leads to clusters of authors, suggesting a natural clustering of paper by writing style. This is further confirmed by applying Latent Dirichlet Allocation (LDA; Blei et al., 2003) to the DTM with no obvious topic emerging. This suggests that no data-driven guidance is provided in this corpus to define highly abstract classes relating to physical trends. Domain knowledge engineering is therefore still required.

One aim of text classification for earthquake predictability research could be to update theoretical trends online, any time a new research article is published. This would in principle clarify the current state of research in the field. We showed that the Naïve Bayes classifier generalizes poorly on a different time period, meaning that the possibility of new trends, with different term statistics, could be missed. Only training on a larger corpus is likely to improve
the text classification. This could be done by applying knowledge engineering on the full earthquake prediction literature.

Data and Resources: All the corpus articles are available on journal websites. The corpus metadata and labelling are provided in the supplementary material to this article.

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| Reference              | B / M | Rationale behind the labelling                                                                                                                                                                                                                                                                                                                                 |
|------------------------|-------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Jiang and Wu (2012)    | 0 / 1 | Empirical study. Criticality mentioned in the introduction but not assumed nor demonstrated: "(AMR) model [...] once related to the critical-point-like behavior of earthquake preparation"                                                                                                                                  |
| Lagios et al. (2012)   | 0 / 1 | Empirical study. Many mentions of "critical area" and "critical time" (in both abstract and main text) but in a generic manner, without any theoretical assertion                                                                                                                                                                |
| Mignan (2012)          | 0 / 0 | Explicit "Non-Critical Precursory Accelerating Seismicity Theory"                                                                                                                                                                                                                                                                                           |
| Pliakis et al. (2012)  | 1 / 3 | Critical-point model with no mention of criticality in the abstract nor title. In the main text, however, "a mounting body of evidence indicates that the earthquake generation process can be viewed as a critical phenomenon that culminates in a large event that corresponds to some critical point"                                                                 |
| Bouchon et al. (2013)  | 0 / 0 | Empirical study assuming non-criticality: "Such models [(where foreshocks trigger one another)] are contradicted by investigations of well-recorded foreshock sequences" and "one possible mechanism would be the slow slip of a patch of the subducting plate before the earthquake". No mention of criticality |
| Guilhem et al. (2013)  | 0 / 0 | Statistical test of the precursory accelerating seismicity hypothesis, assuming non-criticality ("models of stress accumulation"). Note some mentions of criticality within the text and the use of "criticized" in the abstract (part of the feature "critic*")                                                                                                                                 |
| Jiang and Wu (2013)    | 0 / 0 | Test of the critical point hypothesis, with the following non-critical conclusion: "potential spatial correlation [...] which might be an evidence for that the observed acceleration may have a geometrical or mechanical
rather than statistical origin". Note the use of "critical point" in both abstract and keywords

Karakaisis et al. (2013) 1 / 2 Empirical study assuming criticality: "The generation of accelerating preshocks is considered as a critical phenomenon"

De Santis et al. (2015) 0 / 1 Empirical study, theoretically agnostic, often using the term "criticism"

Felzer et al. (2015) 1 / 2 Comment to Bouchon et al. (2013) with simulation based on epidemic-type triggering, implicitly related to criticality (bottom-up cascading): "Acceleration of seismicity [... has been explained by the cascade model]. Note that the term "critical" is absent throughout the comment

Bouchon et al. (2015) 0 / 0 Rebuttal to Felzer et al. (2015) reemphasizing the non-criticality of the process: "Because these foreshocks cluster in time but do not cluster in space, as the ETAS model implicitly assumes, the ETAS model cannot provide a correct description of them"

Christou et al. (2016) 0 / 1 Empirical study, theoretically agnostic, often using the expression "critical region"

Adamaki and Roberts (2017) 0 / 1 Empirical study, theoretically agnostic. Only one mention of the term "near-critical"

Kazemian and Hatami (2017) 0 / 1 Empirical study, theoretically agnostic

Huang and Meng (2018) 0 / 0 Empirical study with non-critical conclusion: "We interpret [the accelerating rate of repeaters] as the large-scale slow unlocking process"

† the metadata and labelling of the full corpus can be found in the supplementary material.

* See text and Figure 1 for class numbering definition.

Table 2. One-leave-out cross-validation results for the binary classification.

| Algorithm † | Corpus     | Accuracy | F1 score | Precision | Recall  |
|------------|------------|----------|----------|-----------|---------|
|            | Full text  | 0.63     | 0.75     | 0.61      | 0.98    |
| 'critic*' keyword search | Meta-data* | 0.80 | 0.82 | 0.88 | 0.76 |
|--------------------------|------------|------|------|------|------|
| Naïve Bayes             | Full text  | 0.86 | 0.88 | 0.88 | 0.88 |
|                          | Meta-data  | 0.84 | 0.86 | 0.86 | 0.86 |
| kNN                     | Full text  | 0.85 | 0.88 | 0.82 | 0.94 |
|                          | Meta-data  | 0.77 | 0.81 | 0.76 | 0.88 |
| SVM                     | Full text  | 0.78 | 0.81 | 0.82 | 0.80 |
|                          | Meta-data  | 0.77 | 0.80 | 0.79 | 0.82 |
| Random Forest           | Full text  | 0.81 | 0.85 | 0.80 | 0.90 |
|                          | Meta-data  | 0.74 | 0.81 | 0.72 | 0.92 |

† Results in italics, based on a dictionary, are shown for machine learning benchmarking.
* Meta-data defined as the combination of title + authors + abstract + keywords.

**Table 3.** Ranked posterior probabilities of binary classes $c$ conditional on selected terms $i$ in the Naïve Bayes model.

| Term $i$           | $P(c = 1|i) > 0.9$ | Term $i$           | $P(c = 1|i) < 0.1$ |
|--------------------|--------------------|--------------------|--------------------|
| 'lurr'             | 0.993              | 'backslip'         | 0.027              |
| 'powerlaw'         | 0.987              | 'sumatra-java'     | 0.027              |
| 'automat'          | 0.984              | 'prestress'        | 0.031              |
| 'fibre-bundl'      | 0.984              | 'dip-slip'         | 0.032              |
| 'lattic'           | 0.976              | 'false-posit'      | 0.032              |
| 'renormalizationgroup' | 0.975          | 'non-crit'         | 0.032              |
| 'acoustic-emis'    | 0.972              | 'wenchuan'         | 0.336              |
| 'spinod'           | 0.972              | 'dmowska'          | 0.036              |
| 'ellipt'           | 0.971              | 'cff'              | 0.039              |
| 'rank-ord'         | 0.970              | 'rtl'              | 0.041              |

**Table 4.** One-leave-out cross-validation results for the multiclass classification.

| Algorithm      | Corpus  | Accuracy | F1 score | 0 | 1 | 2 | 3 |
|----------------|---------|----------|----------|---|---|---|---|
| Naïve Bayes    | Full text | 0.78     | 0.80     | 0.72 | 0.78 | 0.84 |   |
|                | Meta-data | 0.66     | 0.74     | 0.50 | 0.68 | 0.73 |   |
### Table 5. Selected terms \(i\) from the 40 highest posterior probabilities \(P(c|i)\) for multi-class \(c\).

| Class 0 | Class 1 | Class 2 | Class 3 |
|---------|---------|---------|---------|
| 'pas'   | 'kunlun' | 'ellipt' | 'fibre-bundle' |
| 'cff'   | 'wenchuan' | 'lurr' | 'cell' |
| 'e-valu' | 'palermo' | 'ellips' | 'spin' |
| 'pre-stress' | 'chi-sqaur' | 't'aquila' | 'accoustic-emiss' |
| 'non-crit' | 'false-posit' | 'aegane' | 'timestep' |
| 'lobe' | 'subcycl' | 'pre-shock' | 'singular' |
| 'sumatra-java' | 'quiescence-lik' | 'chaotic' | 'temperatur' |
| 'backslip' | 'subregion' | 'powerlaw' | 'finite-tim' |
| 'coulomb' | 'log10' | 'syntheticsequ' | 'dissip' |
| 'scenario' | 'bic' | 'cumulativebenioff' | 'quasi-period' |

### Table 6. Model prediction of the test data for binary classification.

| Algorithm† | Corpus  | Accuracy | F1 score | Precision | Recall |
|------------|---------|----------|----------|-----------|--------|
| 'critic** keyword search' | Full text | 0.27 | 0.27 | 0.17 | 0.67 |
|               | Meta-data | 0.53 | - | - | - |
| Naïve Bayes | Full text | 0.73 | 0.50 | 0.40 | 0.67 |
|               | Meta-data | 0.73 | 0.60 | 0.43 | 1.00 |

† Results in italics, based on a dictionary, are shown for machine learning benchmarking.

### Table 7. Model prediction of the test data for multiclass classification.

| Algorithm | Corpus  | Accuracy | F1 score |
|-----------|---------|----------|----------|
|           | 0  | 1  | 2  | 3   |
| Naïve Bayes | Full text | 0.47 | 0.80 | 0.20 | 0.25 | 1.00 |
|           | Meta-data | 0.53 | 0.67 | 0.40 | 0.44 | 1.00 |
Supplementary Material: 1988-2018 precursory accelerating seismicity corpus metadata with matching binary and multiclass labels.

Table S1 [page 22]. Corpus metadata in JSON format, with the following attributes: "refID", "title", "authors", "abstract", "keywords", "refs" for reference list (kept null for the present study), "journal", "year" and "doi".

Table S2 [page 90]. List of binary labels in JSON format with same "refID" as in Table S1.

Table S3 [page 98]. List of multiclass labels in JSON format with same "refID" as in Table S1.

Table S1.

[
  {
    "refID": "1988-1_Papadopoulos-GA_Tectonophys",
    "title": "Long-term accelerating foreshock activity may indicate the occurrence time of a strong shock in the Western Hellenic Arc",
    "authors": ["Papadopoulos-GA"],
    "abstract": "In the decades prior to the occurrence of the 1899 (M, = 6.6) and 1947 (MS = 7.0) main shocks in the Western Hellenic Arc (WHA) the rate of occurrence of foreshocks (M, 2 5.2) within a radius of 100 km around the epicenters can generally be said to have accelerated. After a long period of very low foreshock activity (stage I), the process culminates in a final rapid acceleration of foreshocks some months before the main shocks (stage II), while the last two months are quiescent (stage III). These three stages are in good correspondence with the three stages of crustal deformation and several precursors to the main shock as predicted by the dilatancy model. The data fit very well power law equations similar to those found for short-term foreshocks of ordinary earthquakes and those associated with the creation of artificial lakes. The position of the rupture zones of past WHA strong shocks implies that the eastern part of the segment is the most probable location for the next strong shock in the arc. A process of accelerating seismic activity, similar to that which preceded the 1899 and 1947 shocks, has been under way since 1966 around this part of the segment. A comparison between changes in the power law curves for the earlier earthquakes and the one now expected, indicates that the latter is now 3-8 months “overdue”. Assuming that the long-term accelerating foreshock activity is a seismotectonic peculiarity of the WHA segment, I suggest that the preparation of the next rupture in the WHA has entered a highly mature stage, and that there will very probably be an earthquake in this area within the next few months.",
    "keywords": null,
  }
]
Activity in moderate-size earthquakes accelerated in the several decades before the large California earthquakes of 1989, 1906 and 1868. This type of precursor seems to require the presence of several major faults in close enough proximity to one another that moderate-size shocks are selectively triggered on surrounding faults during the latter stages of the cycle of strain buildup to large earthquakes. It may be possible to use quantitative aspects of similar seismic precursors to make predictions of large earthquakes on timescales of a few years to one decade.

The moment release rate in the Kodiak Island (KI) segment increased prior to the great 1964 Prince William Sound earthquake (MW = 9.2). Starting in 1983 the moment release rate in the Shumagin Island (SI) segment shows a similar increase. In July 1990, an outer-rise reverse earthquake showed arc-normal compression at a depth of 42 km seaward of the Alaska Peninsula (AP) segment. Because accelerating moment release and arc-normal compression have both been proposed as precursors to large and great earthquakes, we suggest this is evidence that the SI-AP region is nearing the end of the seismic cycle between large thrust earthquakes.

The moment release rate in the Kodiak Island (KI) segment increased prior to the great 1964 Prince William Sound earthquake (MW = 9.2). Starting in 1983 the moment release rate in the Shumagin Island (SI) segment shows a similar increase. In July 1990, an outer-rise reverse earthquake showed arc-normal compression at a depth of 42 km seaward of the Alaska Peninsula (AP) segment. Because accelerating moment release and arc-normal compression have both been proposed as precursors to large and great earthquakes, we suggest this is evidence that the SI-AP region is nearing the end of the seismic cycle between large thrust earthquakes.
"title": "Predictive Modeling of the Seismic Cycle of the Greater San Francisco Bay Region",
"authors": ["Bufe-CG", "Varnes-DJ"],
"abstract": "The seismic cycle for the San Francisco Bay region is synthesized by a model combining the pre-and post-1906 seismic histories. The long-term acceleration of seismic release (seismic moment, Benioff strain release, or event count) in the seismic cycle and the shorter-term accelerations preceding the larger earthquakes within that cycle are modeled using an empirical predictive technique, called time-to-failure analysis, in which rate of seismic release is proportional to an inverse power of the remaining time to failure. The exponent of time to failure in the accelerating sequences appears to be scale invariant, and the length of the full cycle is estimated at 269 ± 50 years. The 1989 Loma Prieta earthquake, which is the culmination of the first subcycle in the present long-term seismic cycle, should have been predictable with an uncertainty of 2 years in time and 0.5 in magnitude, although the specific location (at Loma Prieta) was not predictable by this technique. If our model is correct and if the Loma Prieta earthquake is the culmination of a subcycle, the San Francisco Bay region should be entering a relatively long (20–50 years) period of seismic quiescence above magnitude 6. A great earthquake, such as the 1906 San Francisco event, would appear to be more than a century in the future."

"keywords": null,
"refs": null,
"journal": "Journal of Geophysical Research",
"year": 1993,
"doi": "10.1029/93JB00357"
},

"refID": "1994-1_Bufe-CG_PAGEOPH",
"title": "Seismicity Trends and Potential for Large Earthquakes in the Alaska-Aleutian Region",
"authors": ["Bufe-CG", "Nishenko-SP", "Varnes-DJ"],
"abstract": "The high likelihood of a gap-filling thrust earthquake in the Alaska subduction zone within this decade is indicated by two independent methods: analysis of historic earthquake recurrence data and time-to-failure analysis applied to recent decades of instrumental data. Recent (May 1993) earthquake activity in the Shumagin Islands gap is consistent with previous projections of increases in seismic release, indicating that this segment, along with the Alaska Peninsula segment, is approaching failure. Based on this pattern of accelerating seismic release, we project the occurrence of one or more M≥7.3 earthquakes in the Shumagin-Alaska Peninsula region during 1994–1996. Different segments of the Alaska-Aleutian seismic zone behave differently in the decade or two preceding great earthquakes, some showing acceleration of seismic release (type “A” zones), while others show deceleration (type “D” zones). The largest Alaska-Aleutian earthquakes—In 1957, 1964,
and 1965—originated in zones that exhibit type D behavior. Type A zones currently showing accelerating release are the Shumagin, Alaska Peninsula, Delarof, and Kommandorski segments. Time-to-failure analysis suggests that the large earthquakes could occur in these latter zones within the next few years."

"keywords": ["Alaska-Aleutian seismic zone", "Shumagin seismic gap", "accelerating moment release", "time-to-failure"],

"refs": null,

"journal": "Pure and Applied Geophysics",

"year": 1994,

"doi": null
}

{

"refID": "1995-1_Newman-WI_PRE",

"title": "Log-periodic behavior of a hierarchical failure model with applications to precursory seismic activation",

"authors": ["Newman-WI", "Turcotte-DL", "Gabrielov-AM"],

"abstract": "Seismic activation has been recognized to occur before many major earthquakes including the San Francisco Bay area, prior to the 1906 earthquake. There is a serious concern that the recent series of earthquakes in Southern California is seismic activation prior to a great Southern California earthquake. The seismic activation prior to the Loma Prieta earthquake has been quantified in terms of a power-law increase in the regional Benioff strain release prior to this event and there is an excellent fit to a log-periodic increase in the Benioff strain release. In order to better understand activation a hierarchical seismic failure model has been studied. An array of stress-carrying elements is considered (formally, a cellular automaton or lattice gas, but analogous to the strands of an ideal, frictionless cable). Each element has a time to failure that is dependent on the stress the element carries and has a statistical distribution of values. When an element fails, the stress on the element is transferred to a neighboring element; if two adjacent elements fail, stress is transferred to two neighboring elements; if four elements fail, stress is transferred to four adjacent elements, and so forth. When stress is transferred to an element its time to failure is reduced. The intermediate size failure events prior to total failure each have a sequence of precursory failures, and these precursory failures each have an embedded precursory sequence of smaller failures. The total failure of the array appears to be a critical point. There is a sequence of partial failures leading up to the total failure that resembles a log-periodic sequence."

"keywords": null,

"refs": null,

"journal": "Physical Review E",

"year": 1995,

"doi": "10.1103/PhysRevE.52.4827"
Several authors have proposed discrete renormalization group models of earthquakes, viewing them as a kind of dynamical critical phenomena. Here, we propose that the assumed discrete scale invariance stems from the irreversible and intermittent nature of rupture which ensures a breakdown of translational invariance. As a consequence, we show that the renormalization group entails complex critical exponents, describing log-periodic corrections to the leading scaling behavior. We use the mathematical form of this solution to fit the time to failure dependence of the Benioff strain on the approach of large earthquakes. This might provide a new technique for earthquake prediction for which we present preliminary tests on the 1989 Loma Prieta earthquake in northern California and on a recent build-up of seismic activity on a segment of the Aleutian-Island seismic zone. The earthquake phenomenology of precursory phenomena such as the causal sequence of quiescence and foreshocks is captured by the general structure of the mathematical solution of the renormalization group.

The rate of seismic activity of moderate-size (M > 5.5) earthquakes in the San Francisco Bay region has varied considerably during the past 150 years. As measured by the rate of seismic moment release, seismic activity in the SFB region is observed to accelerate prior to M > 7.0 earthquakes in 1868, 1906, and 1989, and then to decelerate following them. We examine these seismicity changes in the context of the evolution of the stress field in the SFB region as a result of strain accumulation and release using a model of dislocations in an elastic halfspace. We use a Coulomb failure function (CFF) to take into account changes in both shear and normal stresses on potential failure planes of varying strike and dip in the SFB region. We find that the occurrence of a large or great earthquake creates a “stress shadow”: a region where the stress driving earthquake deformation is decreased. Interseismic strain
accumulation acts to reverse this process, gradually bringing
faults in the SFB region out of the stress shadow of a previous
large or great earthquake and back into a state where earthquake
failure is possible. As the stress shadow generated by a large
or great earthquake disappears, it migrates inward toward the
fault associated with that large or great event. The observed
changes in the rate of occurrence of moderate earthquakes in the
SFB region are broadly consistent with this model. In detail,
the decrease in seismicity throughout most of the SFB region and
a localized increase in the Monterey Bay region following the
great 1906 earthquake is consistent with our predicted stress
changes. The timing and location of moderate-size earthquakes
when the rate of seismicity increases again in the 1950s is
consistent with areas in which the 1906 stress shadow had been
eliminated by strain accumulation in the SFB region. Those
earthquakes that are most inconsistent with our stress evolution
model, including the 1911 earthquake southeast of San Jose, are
found to occur in regions where dip-slip faulting is common in
addition to strike-slip. The 1906 earthquake brought that zone
of dip-slip faulting closer to failure, suggesting that the 1911
event may have been a reverse faulting earthquake rather than a
strike-slip one similar to the 1984 Morgan Hill earthquake. The
occurrence of activity on faults very close to the San Andreas,
such as the Lake Elsman earthquakes of 1988 and 1989, appear to
be associated with the last disappearance of the stress shadow
on the Loma Prieta segment of the San Andreas fault. Thus events
of that type may represent an intermediate-term precursor to a
large earthquake, such as the 1989 Loma Prieta event. Much of
the moderate-size earthquake activity in the SFB region appears
to be modulated in time by the buildup and release of stress in
large and great earthquakes. A tensorial approach to earthquake
prediction, i.e., taking into account changes in the components
of the stress tensor, has several advantages over examining
scalar changes such as those in seismic activity and moment
release rates. This tensorial approach allows for both
activation and quiescence (but in different subregions) prior
to as well as after large earthquakes."
large earthquake singularity. Discrete scale invariance is first illustrated on a geometrical fractal, the Sierpinsky gasket, which is shown to be fully described by a complex fractal dimension whose imaginary part is a simple function (inverse of the logarithm) of the discrete scaling factor. Then, a set of simple physical systems (spins and percolation) on hierarchical lattices is analyzed to exemplify the origin of the different terms in the discrete renormalization group formalism introduced to tackle this problem. As a more specific example of rupture relevant for earthquakes, we propose a solution of the hierarchical time-dependent fiber bundle of Newman et al. [1994] which exhibits explicitly a discrete renormalization group from which log-periodic corrections follow. We end by pointing out that discrete scale invariance does not necessarily require an underlying geometrical hierarchical structure. A hierarchy may appear "spontaneously" from the physics and/or the dynamics in a Euclidean (nonhierarchical) heterogeneous system. We briefly discuss a simple dynamical model of such mechanism, in terms of a random walk (or diffusion) of the seismic energy in a random heterogeneous system."
relatively high or relatively low rates of seismic activity, including period halving and doubling. The set of 666 time intervals between all possible pairs of the 37 recorded events appears to be a fractal; the set of time points that define the intervals has a finite, non-integer correlation dimension of 0.70. In contrast, the average correlation dimension of 50 random sequences of 37 events is significantly higher, close to 1.0. In a similar analysis, the set of distances between pairs of epicentres has a fractal correlation dimension of 1.52. Well-defined cycles, numerous precise ratios among time intervals, and a non-random temporal fractal dimension suggest that the seismic series is not a random process, but rather the product of a deterministic dynamic system.”;

Intermediate-Term Earthquake Prediction Using Precursory Events in the New Madrid Seismic Zone

The time-to-failure method described by Varnes (1989) and Bufe and Varnes (1990) uses precursory events (foreshocks) to define an accelerated energy release curve. By fitting an equation to the data, a predicted time of failure and magnitude can be calculated. Until recently, this method has been used in only a few studies in tectonically active areas, and for moderate- to large-magnitude mainshock events. Using the microearthquake network data set from the New Madrid Seismic Zone (NMSZ), which is reasonably complete for earthquakes of magnitude $\geq 1.5$ in the area of interest, the method has yielded predicted values of past events as small as mb = 3.5. The network data set used in this evaluation covers the time interval from 29 June 1974 to 20 July 1995 for the NMSZ. There have been 36 earthquakes of magnitude $\geq 3.5$ over the 21-yr period in which the network has been operating. Because precursory events are required for the application of the time-to-failure method, mainshocks that occurred before 1980 do not have enough data to adequately define the accelerated energy release curve. Therefore, we utilized the 26 earthquakes that occurred after 1980 and that had a magnitude $\geq 3.5$. Sixteen of the 26 mainshock events were modeled. In most cases, the precursory sequences yielded predicted times of failure and magnitudes that were reasonably close to the actual mainshock values. The remaining mainshocks, including those occurring before 1980, could not be modeled due to either (1) not enough events to adequately define the precursory sequence or (2) interfering events that disrupt the accelerated energy release curve. In addition, two events were modeled from the Nuttli catalog (Nuttli, 1979) along with one that used a combination of both catalogs. Nineteen earthquakes with magnitudes $\geq 3.5$ were evaluated using the time-to-failure method. The first calculation using the time-to-failure method gave predicted results with large error bounds, essentially no upper bound on the predicted magnitude. An empirical relationship between parameters has helped to constrain the range of the predicted magnitude and, to a lesser extent, the estimated time of failure. This relationship modifies the time-to-failure equation and yields predicted values for magnitudes that have an upper limit. Another empirical relationship suggests that the logarithm of the moment of the mainshock increases linearly with the logarithm of the size of the precursory event search diameter. The relative seismicity of the region also influences the optimum search
diameter used to find precursory events. In addition to the evaluation of the acceleration sequences associated with the mainshocks, an analysis of the occurrence of false-positive acceleration sequences (acceleration sequences that do not end in a mainshock) was conducted. The preliminary false-positive analysis was conducted by randomly selecting potential mainshock locations. The results yielded a false-positive acceleration sequence occurrence rate of 2%. With the incorporation of the empirical relationships into the time-to-failure method, the potential for future intermediate-term earthquake predictions for the NMSZ is encouraging.

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**Keywords:** null

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**Keywords:** earthquake prediction, fitting, seismicity, statistics

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**Keywords:** null
We present a simple model of earthquakes on a pre-existing hierarchical fault structure. The system self-organizes at large times in a stationary state with a power law Gutenberg-Richter distribution of earthquake sizes. The largest fault carries irregular great earthquakes preceded by precursors developing over long time scales and followed by aftershocks obeying an Omori's law. The cumulative energy released by precursors follows a time-to-failure power law with log-periodic structures, qualifying a large event as an effective dynamical (depinning) critical point. Down the hierarchy, smaller earthquakes exhibit the same phenomenology, albeit with increasing irregularities.
mainshocks occurring after 17 August 1998. One region satisfied all the criteria and may be modeled by the modified time-to-failure method. The region likely to have a mainshock is a 65-km-radius area centered at 31.43° N, 115.47° W (northern Baja California, Mexico). The predicted magnitude is 6.36, ±0.55, and the predicted time of failure is 1998.565 (7/25/98), ±1.127 years. The addition of future precursory events will allow refinement of the predicted values."

The modified time-to-failure method for intermediate-term earthquake prediction utilizes empirical relationships to reduce the number of unknown parameters providing a stable and unique solution set. The only unknown parameters in the modified time-to-failure method are the time and size of the impending main shock. The modified time-to-failure equation is used to model the precursory events and a prediction contour diagram is constructed with the magnitude and time-of-failure as the axes of the diagram. The root-mean-square (rms) is calculated for each set of time and magnitude on the prediction diagram representing the difference between the model (calculated) acceleration and the actual accelerated energy release of the precursory events. A small region, corresponding to the low rms region on the diagram, defines the prediction. The prediction has been shown to consistently under-estimate the magnitude and over-estimate the time-of-failure. These shortcomings are caused by an underestimation in energy release of the modified time-to-failure equation at the very end of the sequence. An empirical correction can be applied to the predicted results to minimize this problem. A main shock location search technique has been developed for use with the modified time-to-failure method. The location technique is used to systematically search an earthquake catalog and identify locations corresponding to precursory sequences that display accelerated energy releases. It has shown good results when applied in ‘retrospective predictions’, and is essential for the practical application of the modified time-to-failure method. In addition, an observed linear characteristic in long-term energy release can be used to minimize false predictions. The refined empirical relationships that eliminate or constrain unknown constants used in the modified time-to-failure method and the main shock location search technique are used in a
practical application in the New Madrid Seismic Zone (NMSZ). The NMSZ, which is ‘over due’ for a magnitude 6 event according to recurrence rates (Johnston and Nava, 1985), makes this region ideal for testing the method. One location was identified in the NMSZ as a ‘high risk’ area for an event in the magnitude 4.5 range. The prediction, if accurate, is of scientific interest only because of the relatively small size of the main shock.

There is growing evidence that some proportion of large and great earthquakes are preceded by a period of accelerating seismic activity of moderate-sized earthquakes. These moderate earthquakes occur during the years to decades prior to the occurrence of the large or great event and over a region larger than its rupture zone. The size of the region in which these moderate earthquakes occur scales with the size of the ensuing mainshock, at least in continental regions. A number of numerical simulation studies of faults and fault systems also exhibit similar behavior. The combined observational and simulation evidence suggests that the period of increased moment release in moderate earthquakes signals the establishment of long wavelength correlations in the regional stress field. The central hypothesis in the critical point model for regional seismicity is that it is only during these time periods that a region of the earth’s crust is truly in or near a “self-organized critical” (SOC) state, such that small earthquakes are capable of cascading into much larger events. The occurrence of a large or great earthquake appears to dissipate a sufficient proportion of the accumulated regional strain to destroy these long wavelength stress correlations and bring the region out of a SOC state. Continued tectonic strain accumulation and stress transfer during smaller earthquakes eventually re-establishes the long wavelength stress correlations that allow for the occurrence of larger events. These increases in activity occur over longer periods and larger regions than quiescence, which is usually observed within the rupture zone of a coming large event. The two phenomena appear to have different physical bases and are not incompatible with one another.

The New Madrid Seismic Zone (NMSZ) is considered an area 'over due' for a major earthquake according to recurrence rates (Johnston and Nava, 1985). One location in the NMSZ was identified as a 'high risk' area for an event in the magnitude 4.5 range. The prediction, if accurate, is of scientific interest only because of the relatively small size of the main shock.

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The keywords include: "Energy Release", "Structural Geology", "Main Shock", "Empirical Relationship", "Seismic Zone", "Accelerating seismic moment/energy", "earthquake forecasting", "critical point hypothesis", "self-organized criticality", "stress correlations".
We examine quantitatively the ranges of applicability of the equation \( \Omega = A + B[1 - t/t_f]^m \) for predicting \('system-sized' failure times \( t_f \) in the Earth. In applications \( \Omega \) is a proxy measure for strain or crack length, and \( A, B \) and the index \( m \) are model parameters determined by curve fitting. We consider constitutive rules derived from (a) Charles' law for subcritical crack growth; (b) Voight's equation; and (c) a simple percolation model, and show in each case that this equation holds only when \( m < 0 \). When \( m > 0 \), the general solution takes the form \( \Omega = A + B[1 + t/T]^m \), where \( T \) is a positive time constant, and no failure time can be defined. Reported values for volcanic precursors based on rate data are found to be within the range of applicability of time-to-failure analysis (\( m < 0 \)). The same applies to seismic moment release before earthquakes, at the expense of poor retrospective predictability of the time of the a posteriori-defined main shock. In contrast, reported values based on increasing cumulative Benioff strain occur in the region where a system-sized failure time cannot be defined (\( m > 0 \); commonly \( m \approx 0.3 \)). We conclude on physical grounds that cumulative seismic moment is preferred as the most direct measure of seismic strain. If cumulative Benioff strain is to be retained on empirical grounds, then it is important that these data either be re-examined with the independent constraint \( m < 0 \), or that for the case \( 0 < m < 1 \), a specific correction for the time-integration of cumulative data be applied, of the form \( \sum \Omega = A + B\{1 - [1 - t/t_f]^m + 1\} \).
hierarchies are compared with those having a uniform cell size. Conservative models in which all the stress is transferred at each step of a cascade are compared with nonconservative ("lossy") models in which a specified fraction of the stress energy is lost from each step. Particular attention is given to the behavior of the system as it is driven toward the critical state by uniform external loading. All automata exhibit a scaling region at times close to the critical state in which the events become larger and energy release increases as a power-law of the time to the critical state. For the hierarchical fractal automata, this power-law behavior is often modulated by fluctuations that are periodic in the logarithm of the time to criticality. These fluctuations are enhanced in the nonconservative models, but are not robust. The degree to which they develop appears to depend on the particular distribution of stresses in the larger cells which varies from cycle to cycle. Once the critical state is reached, seismicity in the uniform conservative automaton remains random in time, space, and magnitude. Large events do not significantly perturb the stress distribution in the system. However, large events in the nonconservative uniform automaton and in the fractal systems produce large stress perturbations that move the system out of the critical state. The result is a seismic cycle in which a large event is followed by a shadow period of quiescence and then a new approach back toward the critical state. This seismic cycle does not depend on the fractal structure, but is a direct consequence of large-scale heterogeneity of these systems in which the size of the largest cell (or the size of the largest nonconservative event) is a significant fraction of the size of the network. In essence, seismic cycles in these models are boundary effects. The largest events tend to cluster in time and the rate of small events remains relatively constant throughout a cycle in agreement with observed seismicity."
equation given by Sornette and Sammis (1995), we analysis the
seismicity of each region. To those strong earthquakes already
occurred in these region, the model can give close fitting of
magnitude and occurrence time, and the result in this article
indicates that the seismicity acceleration model can also be
used for describing the seismicity of intraplate. In the
article, we give the magnitude and occurrence time of possible
strong earthquakes in Shanxi, Ordos, Bole-Tuokexun, Ayinke-Wuqia
earthquake regions. In the same subplate or block, the
earthquake periods for each earthquake region are similar in
time interval. The constant $\alpha$ in model can be used to describe
the intensity of regional seismicity, and for the Chinese
Mainland, $\alpha$ is 0.4 generally. To the seismicity in Taiwan and
other regions with complex tectonic conditions, the model does
not fit well at present.

"keywords": ["seismicity acceleration model", "subcritical
crack growth", "China", "earthquake region", "fit"],
"refs": null,
"journal": "Acta Seismologica Sinica",
"year": 1999,
"doi": null
}

"refID": "2000-1_Huang-Y_JGR",
"title": "Reexamination of log periodicity observed in the
seismic precursors of the 1989 Loma Prieta earthquake",
"authors": ["Huang-Y", "Saleur-H", "Sornette-D"],
"abstract": "Based on several empirical evidence, a series
of papers has advocated the concept that seismicity prior to a
large earthquake can be understood in terms of the statistical
physics of a critical phase transition. In this model, the
cumulative seismic Benioff strain release $\epsilon$ increases as a power
law time-to-failure before the final event. This power law
reflects a kind of scale invariance with respect to the distance
to the critical point: $\epsilon$ is the same up to a simple reseating
$\lambda z$ after the time-to-failure has been scaled by a factor $\lambda$. A
few years ago, on the basis of a fit of the cumulative Benioff
strain released prior to the 1989 Loma Prieta earthquake,
Sornette and Sammis [1995] proposed that this scale invariance
could be partially broken into a discrete scale invariance,
defined such that the scale invariance occurs only with respect
to specific integer powers of a fundamental scale ratio. The
observable consequence of discrete scale invariance takes the
form of log-periodic oscillations decorating the accelerating
power law. They found that the quality of the fit and the
predicted time of the event are significantly improved by the
introduction of log periodicity. Here we present a battery of
synthetic tests performed to quantify the statistical
significance of this claim. We put special attention to the
definition of synthetic tests that are as much as possible
identical to the real time series except for the property to be
tested, namely, log periodicity. Without this precaution, we
would conclude that the existence of log periodicity in the Loma Prieta cumulative Benioff strain is highly statistically significant. In contrast, we find that log-periodic oscillations with frequency and regularity similar to those of the Loma Prieta case are very likely to be generated by the interplay of the low-pass filtering step due to the construction of cumulative functions together with the approximate power law acceleration. Thus the single Loma Prieta case alone cannot support the initial claim, and additional cases and further study are needed to increase the signal-to-noise ratio, if any. The present study will be a useful methodological benchmark for future testing of additional events when the methodology and data to construct reliable Benioff strain function become available.

"keywords": null,
"refs": null,
"journal": "Journal of Geophysical Research",
"year": 2000,
"doi": "10.1029/2000JB900308"
},
{
"refID": "2000-1_Jaume-SC_GeophysMonogrSer",
"title": "Changes in earthquake size-frequency distributions underlying accelerating seismic moment/energy release",
"authors": ["Jaume-SC"],
"abstract": "A considerable number of moderate to great earthquakes have been preceded by an increase in the rate of smaller events in the surrounding region, resulting in an acceleration in the rate of seismic energy/moment release as the time of the mainshock is approached. The so-called 'critical point' models for this behavior postulate that a growing correlation length in the earth's crust underlies this phenomenon. In these models, the correlation length controls the maximum size of events in the earthquake population. As it grows it allows progressively larger earthquakes to occur, and thus changes the earthquake size-frequency distribution at large magnitudes. Here I test this hypothesis by examining changes in the earthquake size-frequency distribution of 17 known cases of accelerating seismic energy/moment release for which the space-time dimensions of this behavior have been defined and adequate earthquake catalogs exist. I find that for 15 of these 17 cases, observed changes in the earthquake size-frequency distribution are consistent with the predictions of the critical point hypothesis. For the other two cases, an increase in the rate of seismicity at all magnitudes appears to have occurred. These results suggest that critical point behavior underlies most but not all cases of accelerating seismic energy/moment release."
,"keywords": null,
"refs": null,
"journal": "Geophysical Monograph Series",
"year": 2000,
"doi": "10.1029/GM120p0199"
The evolution of event time and size statistics in two heterogeneous cellular automaton models of earthquake behavior are studied and compared to the evolution of these quantities during observed periods of accelerating seismic energy release prior to large earthquakes. The two automata have different nearest neighbor laws, one of which produces self-organized critical (SOC) behavior (PSD model) and the other which produces quasi-periodic large events (crack model). In the PSD model periods of accelerating energy release before large events are rare. In the crack model, many large events are preceded by periods of accelerating energy release. When compared to randomized event catalogs, accelerating energy release before large events occurs more often than random in the crack model but less often than random in the PSD model; it is easier to tell the crack and PSD model results apart from each other than to tell either model apart from a random catalog. The evolution of event sizes during the accelerating energy release sequences in all models is compared to that of observed sequences. The accelerating energy release sequences in the crack model consist of an increase in the rate of events of all sizes, consistent with observations from a small number of natural cases, however inconsistent with a larger number of cases in which there is an increase in the rate of only moderate-sized events. On average, no increase in the rate of events of any size is seen before large events in the PSD model.

Twenty-four regions where accelerating deformation has been observed for a few decades before corresponding strong (M = 6.0–7.5) mainshocks are identified in the broader Aegean area. To a first approximation these preshock regions have elliptical shapes and the radius, R (in km), of a circle with an area equal to the corresponding ellipse is related to the moment magnitude, M, of the mainshock by the equation:
\[ \log R = 0.42 M - 0.68. \] The dimension of each preshock region is about seven to ten times larger than the rupture zone (fault length) of the corresponding mainshock. The time variation of the cumulative Benioff strain was satisfactorily fitted by a power-law relation, which is predicted by statistical physics if the mainshock to which accelerating strain rates leads is considered as a critical point. The duration, \( t \) (in years), of the accelerating Benioff strain release period is given by the relation: \[ \log t = 5.94 - 0.75 \log s_r \] where \( s_r \) is the mean Benioff strain rate release (per year for 104 km²) in the preshock region calculated by the complete available data (\( M \geq 5.2 \)) for the entire instrumental period (1911–1998). The importance of identifying and investigating such regions for better understanding the dynamics of the active part of the lithosphere as well as for earthquake prediction and time-dependent seismic hazard assessment is discussed.

"keywords": ["Accelerated preshock deformation", "Benioff strain", "critical phenomena", "Aegean area"],
"refs": null,
"journal": "Pure and Applied Geophysics",
"year": 2000,
"doi": null
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{
"refID": "2000-1_Robinson-R_GJI",
"title": "A test of the precursory accelerating moment release model on some recent New Zealand earthquakes",
"authors": ["Robinson-R"],
"abstract": "The proposal that the moment release rate increases in a systematic way in a large region around a forthcoming large earthquake is tested using three recent, large New Zealand events. The three events, 1993–1995, magnitudes 6.7–7.0, occurred in varied tectonic settings. For all three events, a circular precursory region can be found such that the moment release rate of the included seismicity is modelled significantly better by the proposed accelerating model than by a linear moment release model, although in one case the result is dubious. The 'best' such regions have radii from 122 to 167 km, roughly in accord with previous observations world-wide, but are offset by 50–60 km from the associated main shock epicentre. A grid-search procedure is used to test whether these three earthquakes could have been forecast using the accelerating moment release model. For two of the earthquakes the result is positive in terms of location, but the main shock times are only loosely constrained.

"keywords": ["earthquake prediction", "New Zealand", "seismicity"],
"refs": null,
"journal": "Geophysical Journal International",
"year": 2000,
"doi": "10.1046/j.1365-246X.2000.00054.x"
In this paper we relate the behavior of seismicity prior to a characteristic earthquake to the excitation in proximity to a spinodal instability. We illustrate the spinodal instability as the upper limit of superheated water prior to a steam explosion. We draw an analogy between the steam explosion and a characteristic earthquake, and show that the power-law activation associated with the spinodal instability is essentially identical to the power-law increase in Benioff strain observed prior to characteristic earthquakes. We find that theory and actual data give very similar results.

The stress field that existed before a large earthquake can be calculated based on the known source parameters of the event. This stress field can be used to define a region that shows greater seismic moment rate changes prior to the event than arbitrarily shaped regions, allowing us to link two previously unrelated subjects: Coulomb stress interactions and accelerating seismicity before large earthquakes. As an example, we have examined all $M \geq 6.5$ earthquakes in California since 1950. While we illustrate the model using seismicity in California, the technique is general and can be applied to any tectonically active region. We show that where sufficient knowledge of the regional tectonics exists, this method can be used to augment current techniques for seismic hazard estimation.
In recent years, observational and theoretical descriptions of spatio-temporal patterns of seismicity have focused on two fundamental (and controversial) observations: static stress (Coulomb) interactions between earthquakes and accelerating seismic moment release before large earthquakes. While there have been several documented examples of static stress changes influencing the space-time pattern of seismicity following great earthquakes (main shocks and aftershocks), there have been few attempts to link this method to the evolution of seismicity before great earthquakes (precursory seismicity and foreshocks). In this paper, we describe a simple physical model that links static stress modeling to accelerating moment release before a large event. For practical reasons, it is not straightforward to apply this technique as a method of forecasting future large earthquakes. However, after the large event has occurred, the region of stress accumulation can be calculated with precision based on the known source parameters of the earthquake. This region can then be examined for seismic moment rate changes prior to the event. As examples, we have examined all $M > 6.5$ earthquakes in California since 1950 in regions defined by their pre-event stress fields, and find a period of accelerating moment release before all of these events. While we illustrate the model using seismicity in California, the technique is general and can be applied to any tectonically active region. Where sufficient knowledge of the regional tectonics exists, this method can be used to augment current techniques for seismic hazard estimation.

The time-to-failure model is a technique in which a failure function is fitted to a time series of accumulated Benioff strain before a large earthquake. We analyze the relation of the time-to-failure model to the hypothesis of fractal structure of seismicity. A power law failure function (Varnes, 1989; Bufe and Varnes, 1993) and its log-periodic generalization Sornette and Sammis, 1995 are discussed. The results of application of the log-periodic time-to-failure model to the analysis of the process of acceleration of seismic energy emission in the laboratory experiments on rock destruction and...
before strong earthquakes on Kamchatka and in Italy are presented.

"keywords": ["earthquake prediction", "precursory seismic activity", "foreshock", "fractal dimension", "fractal manifold"],
"refs": null,
"journal": "Tectonophysics",
"year": 2001,
"doi": "10.1016/S0040-1951(01)00088-9"
},

{"refID": "2001-1_Papazachos-CB_AnnGeofis",
"title": "Precursory accelerated Benioff strain in the Aegean area",
"authors": ["Papazachos-CB", "Papazachos-BC"],
"abstract": "Accelerating seismic crustal deformation due to the occurrence of intermediate magnitude earthquakes leading to the generation of a mainshock has recently been considered a critical phenomenon. This hypothesis is tested by the use of a large data sample concerning the Aegean area. Elliptical critical regions for fifty-two strong mainshocks, which have occurred in the Aegean area since 1930, have been identified by applying a power-law relation between the cumulative Benioff strain and the time to the main rupture. Empirical relations between the parameters of this model have been further improved by the use of a large data sample. The spatial distribution of preshocks with respect to the mainshock is examined and its tectonic significance is pointed out. The possibility of using the results of this work to predict the epicentre, magnitude and time of ensuing mainshocks are discussed and further work towards this goal is suggested.

"keywords": ["Benioff strain", "critical point", "Aegean area"],
"refs": null,
"journal": "Annali di Geofisica",
"year": 2001,
"doi": null
},

{"refID": "2001-1_VereJones-D_GJI",
"title": "Remarks on the accelerated moment release model: problems of model formulation, simulation and estimation",
"authors": ["VereJones-D", "Robinson-R", "Yang-WZ"],
"abstract": "This report summarizes a variety of issues concerning the development of statistical versions of the so-called 'accelerated moment release model' (AMR model). Until such statistical versions are developed, it is not possible to develop satisfactory procedures for simulating, fitting or forecasting the model. We propose a hierarchy of simulation models, in which the increase in moment is apportioned in varying degrees between an increase in the average size of events and an increase in their frequency. To control the size
distribution, we propose a version of the Gutenberg–Richter power law with exponential fall-off, as suggested in recent papers by Kagan. The mean size is controlled by the location of the fall-off, which in turn may be related to the closeness to criticality of the underlying seismic region. Other points touched on concern the logical structure of the model, in particular the identifiability of the parameter assumed to control the size of the main shock, and appropriate procedures to use for simulation and estimation. An appendix summarizes properties of the Kagan distribution. The simulations highlight the difficulty in identifying an AMR episode with only limited data.

"keywords": null,
"refs": null,
"journal": "Geophysical Journal International",
"year": 2001,
"doi": "10.1046/j.1365-246x.2001.01348.x"
},

"refID": "2001-1_Yang-WZ_JGR",
"title": "A proposed method for locating the critical region of a future earthquake using the critical earthquake concept",
"authors": ["Yang-WZ", "VereJones-D", "Ma-L"],
"abstract": "Using the critical point concept and extending Bowman's idea of critical earthquake, we develop an intersecting circle method to locate the critical region. A simulation check shows that this method is effective in finding a given critical region. We selected several real cases from New Zealand and China and used this method to find the critical regions before the occurrence of large earthquakes. The result shows that this method is valid for detecting a critical region and the epicenter of mainshock might be in the critical region."

"keywords": null,
"refs": null,
"journal": "Journal of Geophysical Research",
"year": 2001,
"doi": "10.1029/2000JB900311"
},

"refID": "2001-1_Zoeller-G_JGR",
"title": "Observation of growing correlation length as an indicator for critical point behavior prior to large earthquakes",
"authors": ["Zoeller-G", "Hainzl-S", "Kurths-J"],
"abstract": "We test the critical point concept for earthquakes in terms of the spatial correlation length. A system near a critical point is associated with a diverging correlation length following a power law time-to-failure relation. We estimate the correlation length directly from an earthquake catalog using single-link cluster analysis. Therefore we assume that the distribution of moderate earthquakes reflects the state
of the regional stress field. The parameters of the analysis are determined by an optimization procedure, and the results are tested against a Poisson process with realistic distributions of epicenters, magnitudes, and aftershocks. A systematic analysis of all earthquakes with $M \geq 6.5$ in California since 1952 is conducted. In fact, we observe growing correlation lengths in most cases. The null hypothesis that this behavior can be found in random data is rejected with a confidence level of more than 99%. Furthermore, we find a scaling relation $\log R \sim 0.7M$ ($\log \langle \xi_{\text{max}} \rangle \sim 0.5M$), between the mainshock magnitude $M$ and the critical region $R$ (the correlation length $\langle \xi_{\text{max}} \rangle$ before the mainshock), which is in good agreement with theoretical values.

"keywords": null,
"refs": null,
"journal": "Journal of Geophysical Research",
"year": 2001,
"doi": "10.1029/2000JB900379"
},

{ "refID": "2002-1_BenZion-Y_PAGEOPH",
 "title": "Accelerated Seismic Release and Related Aspects of Seismicity Patterns on Earthquake Faults",
 "authors": ["BenZion-Y", "Lyakhovsky-V"],
 "abstract": "Observational studies indicate that large earthquakes are sometimes preceded by phases of accelerated seismic release (ASR) characterized by cumulative Benioff strain following a power law time-to-failure relation with a term $(t_f - t)^m$, where $t_f$ is the failure time of the large event and observed values of $m$ are close to 0.3. We discuss properties of ASR and related aspects of seismicity patterns associated with several theoretical frameworks. The subcritical crack growth approach developed to describe deformation on a crack prior to the occurrence of dynamic rupture predicts great variability and low asymptotic values of the exponent $m$ that are not compatible with observed ASR phases. Statistical physics studies assuming that system-size failures in a deforming region correspond to critical phase transitions predict establishment of long-range correlations of dynamic variables and power-law statistics before large events. Using stress and earthquake histories simulated by the model of BEN-ZION (1996) for a discrete fault with quenched heterogeneities in a 3-D elastic half space, we show that large model earthquakes are associated with nonrepeating cyclical establishment and destruction of long-range stress correlations, accompanied by nonstationary cumulative Benioff strain release. We then analyze results associated with a regional lithospheric model consisting of a seismogenic upper crust governed by the damage rheology of LYAKHOVSKY et al. (39) over a viscoelastic substrate. We demonstrate analytically for a simplified 1-D case that the employed damage rheology leads to a singular power-law equation for strain proportional to $(t_f - t)^{-1/3}$, and a nonsingular
power-law relation for cumulative Benioff strain proportional to \((t_f - t)^{-1/3}\). A simple approximate generalization of the latter for regional cumulative Benioff strain is obtained by adding to the result a linear function of time representing a stationary background release. To go beyond the analytical expectations, we examine results generated by various realizations of the regional lithospheric model producing seismicity following the characteristic frequency-size statistics, Gutenberg-Richter power-law distribution, and mode switching activity. We find that phases of ASR exist only when the seismicity preceding a given large event has broad frequency-size statistics. In such cases the simulated ASR phases can be fitted well by the singular analytical relation with \(m = -1/3\), the nonsingular equation with \(m = 0.2\), and the generalized version of the latter including a linear term with \(m = 1/3\). The obtained good fits with all three relations highlight the difficulty of deriving reliable information on functional forms and parameter values from such data sets. The activation process in the simulated ASR phases is found to be accommodated both by increasing rates of moderate events and increasing average event size, with the former starting a few years earlier than the latter. The lack of ASR in portions of the seismicity not having broad frequency-size statistics may explain why some large earthquakes are preceded by ASR and other are not. The results suggest that observations of moderate and large events contain two complementary end-member predictive signals on the time of future large earthquakes. In portions of seismicity following the characteristic earthquake distribution, such information exists directly in the associated quasi-periodic temporal distribution of large events. In portions of seismicity having broad frequency-size statistics with random or clustered temporal distribution of large events, the ASR phases have predictive information. The extent to which natural seismicity may be understood in terms of these end-member cases remains to be clarified. Continuing studies of evolving stress and other dynamic variables in model calculations combined with advanced analyses of simulated and observed seismicity patterns may lead to improvements in existing forecasting strategies.

"keywords": ["Continuum mechanics", "damage rheology", "heterogeneous faults", "seismicity patterns", "large earthquake cycles"],
"refs": null,
"journal": "Pure and Applied Geophysics",
"year": 2002,
"doi": null
}
A recently developed algorithm has been applied to define regions of the northern Aegean in which accelerating seismic crustal deformation is currently occurring. An elliptical such region has been found in the western part of the North Aegean. Accelerating deformation, which started three decades ago and has been released by the generation of intermediate-magnitude earthquakes (M ≥ 4.5), is still occurring. Based on these observations we can assume that this region is now in a state (pre-shock deformation) that will lead to a critical point (main shock). The estimated basic parameters of this impending main shock are φ = 39.7°N, λ = 23.7°E for the epicentre, M = 6.0 for the moment magnitude, and tc = 2001.1 for the origin time. The corresponding uncertainties are less than 100 km for the epicentre, ± 0.4 for the magnitude, and ±1.5 yr for the origin time.

We present the results of a systematic search for the identification of accelerating seismic crustal deformation in the broader northern Aegean area and in northwestern Turkey. We found that accelerating seismic deformation release, expressed by the generation of intermediate magnitude earthquakes, is currently observed in NW Turkey. On the basis of the critical earthquake model and by applying certain constraints which hold between the basic quantities involved in this phenomenon, it can be expected that this accelerating seismic activity may culminate in the generation of two strong earthquakes in this area during the next few years. The estimated epicenter coordinates of the larger of these probably impending earthquakes are 39.7°N–28.8°E, its magnitude is 7.0 and its occurrence time tc=2003.5. The second strong event is expected to occur at tc=2002.5 with a magnitude equal to 6.4 and epicenter coordinates 40.0°N–27.4°E. The uncertainties in the calculated focal parameters for these expected events are of the order of 100 km for the epicenter, ±0.5 for their magnitude and ±1.5 years for their occurrence time.

We present the results of a systematic search for the identification of accelerating seismic crustal deformation in the broader northern Aegean area and in northwestern Turkey. We found that accelerating seismic deformation release, expressed by the generation of intermediate magnitude earthquakes, is currently observed in NW Turkey. On the basis of the critical earthquake model and by applying certain constraints which hold between the basic quantities involved in this phenomenon, it can be expected that this accelerating seismic activity may culminate in the generation of two strong earthquakes in this area during the next few years. The estimated epicenter coordinates of the larger of these probably impending earthquakes are 39.7°N–28.8°E, its magnitude is 7.0 and its occurrence time tc=2003.5. The second strong event is expected to occur at tc=2002.5 with a magnitude equal to 6.4 and epicenter coordinates 40.0°N–27.4°E. The uncertainties in the calculated focal parameters for these expected events are of the order of 100 km for the epicenter, ±0.5 for their magnitude and ±1.5 years for their occurrence time.
A region of intense accelerating seismic crustal deformation has been identified in the southwestern part of the Hellenic arc (broader area of Cythera island). The identification is performed using a detailed parametric grid search of the broader southern Aegean area for accelerating energy release behavior. The identified region has similar properties with past preshock (critical) regions, which have been identified for strong mainshocks in the Aegean area. Based on such observations, which suggest that this region is at a critical state that can lead to a critical point, that is, to the generation of a mainshock, an estimation is made of the possible epicenter coordinates, magnitude, and origin time of this oncoming large (M $\sim$7.0) earthquake. The estimation procedure is validated on the basis of retrospective analysis of strong events in the Aegean area, as well as by appropriate application on synthetic random catalogs. These results, the existence of similar observations of accelerating seismic deformation in eastern part of southern Aegean and independent information on the time distribution of large earthquakes (M $\geq$6.8) for the whole southern Aegean indicate that the generation of strong earthquakes in this area in the next few years must be considered as very probable.

On the basis of growing evidence that strong earthquakes are preceded by a period of accelerating seismicity of moderate magnitude earthquakes, an attempt is made to search for such seismicity pattern in NW Aegean area. Accelerating seismic crustal deformation has been identified in the area of southern Albanides mountain range (border region between Greece, former Yugoslavia and Albania). Based on certain properties of
this activity and on its similarity with accelerating seismic deformation observed before a strong earthquake which occurred in the same region on 26 May 1960 (M = 6.5), we can conclude that a similar earthquake may be generated in the same region during the next few years. This conclusion is in agreement with independent results which have been derived on the basis of the time-predictable model.

We review the 'critical point' concept for large earthquakes and enlarge it in the framework of so-called 'finite-time singularities.' The singular behavior associated with accelerated seismic release is shown to result from a positive feedback of the seismic activity on its release rate. The most important mechanisms for such positive feedback are presented. We solve analytically a simple model of geometrical positive feedback in which the stress shadow cast by the last large earthquake is progressively fragmented by the increasing tectonic stress.

We introduce a conceptual model for the in-plane physics of an earthquake fault. The model employs cellular automaton techniques to simulate tectonic loading, earthquake rupture, and strain redistribution. The impact of a hypothetical crustal elastodynamic Green's function is approximated by a long-range strain redistribution law with a r−p dependance. We investigate the influence of the effective elastodynamic interaction range upon the dynamical behavior of the model by conducting experiments with different values of the exponent (p). The results indicate that this model has two distinct,
stable modes of behaviour. The first mode produces a characteristic earthquake distribution with moderate to large events preceded by an interval of time in which the rate of energy release accelerates. A correlation function analysis reveals that accelerating sequences are associated with a systematic, global evolution of strain energy correlations within the system. The second stable mode produces Gutenberg-Richter statistics, with near-linear energy release and no significant global correlation evolution. A model with effectively short-range interactions preferentially displays Gutenberg-Richter behaviour. However, models with long-range interactions appear to switch between the characteristic and GR modes. As the range of elastodynamic interactions is increased, characteristic behaviour begins to dominate GR behaviour. These models demonstrate that evolution of strain energy correlations may occur within systems with a fixed elastodynamic interaction range. Supposing that similar mode-switching dynamical behaviour occurs within earthquake faults then intermediate-term forecasting of large earthquakes may be feasible for some earthquakes but not for others, in alignment with certain empirical seismological observations. Further numerical investigation of dynamical models of this type may lead to advances in earthquake forecasting research and theoretical seismology.

"keywords": ["Critical point hypothesis", "cellular automata", "correlation evolution"],
"refs": null,
"journal": "Pure and Applied Geophysics",
"year": 2002,
"doi": null
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{"refID": "2002-1_Yin-XC_PAGEOPH",
"title": "Load-Unload Response Ratio and Accelerating Moment/Energy Release Critical Region Scaling and Earthquake Prediction",
"authors": ["Yin-XC", "Mora-P", "Peng-K", "Wang-Y", "Weatherley-D"],
"abstract": "The main idea of the Load-Unload Response Ratio (LURR) is that when a system is stable, its response to loading corresponds to its response to unloading, whereas when the system is approaching an unstable state, the response to loading and unloading becomes quite different. High LURR values and observations of Accelerating Moment/Energy Release (AMR/AER) prior to large earthquakes have led different research groups to suggest intermediate-term earthquake prediction is possible and imply that the LURR and AMR/AER observations may have a similar physical origin. To study this possibility, we conducted a retrospective examination of several Australian and Chinese earthquakes with magnitudes ranging from 5.0 to 7.9, including Australia’s deadly Newcastle earthquake and the devastating Tangshan earthquake. Both LURR values and best-fit power-law
time-to-failure functions were computed using data within a range of distances from the epicenter. Like the best-fit power-law fits in AMR/AER, the LURR value was optimal using data within a certain epicentral distance implying a critical region for LURR. Furthermore, LURR critical region size scales with mainshock magnitude and is similar to the AMR/AER critical region size. These results suggest a common physical origin for both the AMR/AER and LURR observations. Further research may provide clues that yield an understanding of this mechanism and help lead to a solid foundation for intermediate-term earthquake prediction.

"keywords": ["LURR (Load-Unload Response Ratio)", "AMR (Accelerating Moment Release)", "AER (Accelerating Energy Release)", "CPH (Critical Point Hypothesis) ", "earthquake prediction", "critical region scaling"],
"refs": null,
"journal": "Pure and Applied Geophysics",
"year": 2002,
"doi": null
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"refID": "2002-1_Zoeller-G_GRL",
"title": "A systematic spatiotemporal test of the critical point hypothesis for large earthquakes",
"authors": ["Zoeller-G", "Hainzl-S"],
"abstract": "The critical point hypothesis for large earthquakes predicts two different precursory phenomena in space and time, an accelerating moment release and the growth of the spatial correlation length. The objective of this work is to investigate both methods with respect to their predictive power. A systematic statistical test based on appropriate random earthquake catalogs allows to quantify the correlations of a precursory pattern with the subsequent mainshock activity. The analysis of target earthquakes in California since 1960 with magnitudes $M \geq M_{\text{cut}}$ reveals that these correlations increase systematically with growing $M_{\text{cut}}$, and correlations at greater than 95% confidence are observed for $M_{\text{cut}} \geq 6.5$ in the case of the spatial correlation length. In particular, the seismicity patterns are found to be significantly correlated with each of the largest earthquakes ($M \geq 7.0$), individually. The acceleration of the moment release has a similar trend, but is less significant.",
"keywords": null,
"refs": null,
"journal": "Geophysical Research Letters",
"year": 2002,
"doi": "10.1029/2002GL014856"
},
{
"refID": "2003-1_Chen-CC_GJI",
"title": "Accelerating seismicity of moderate-size earthquakes before the 1999 Chi-Chi, Taiwan, earthquake: Testing
time-prediction of the self-organizing spinodal model of earthquakes",
"authors": ["Chen-CC"],
"abstract": "Seismic activation of moderate-size earthquakes for the 1999 Chi-Chi, Taiwan, earthquake has been found. A self-organizing spinodal (SOS) model can explain some observations concerning seismic activation, but the equal time durations of the mid and precursory periods during an earthquake cycle conjectured in the original, published, SOS model have not been supported in this case. The Chi-Chi test presented here shows unequal time durations of the mid and precursory periods of an earthquake cycle. This, in turn, makes the possibility of time prediction of a characteristic earthquake impossible in the context of the SOS model. In addition, comparisons with numerical simulations of the sliding-block model suggest the change in the system's stiffness is a potential mechanism of seismic activation.",
"keywords": ["Chi-Chi earthquake", "seismic activation", "self-organizing spinodal model"],
"refs": null,
"journal": "Geophysical Journal International",
"year": 2003,
"doi": "10.1046/j.1365-246X.2003.02071.x"
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{
"refID": "2003-1_Helmstetter-A_JGR",
"title": "Foreshocks explained by cascades of triggered seismicity",
"authors": ["Helmstetter-A", "Sornette-D"],
"abstract": "The observation of foreshocks preceding large earthquakes and the suggestion that foreshocks have specific properties that may be used to distinguish them from other earthquakes have raised the hope that large earthquakes may be predictable. Among proposed anomalous properties are the larger proportion than normal of large versus small foreshocks, the power law acceleration of seismicity rate as a function of time to the mainshock, and the spatial migration of foreshocks toward the mainshock when averaging over many sequences. Using southern California seismicity, we show that these properties and others arise naturally from the simple model that any earthquake may trigger other earthquakes, without arbitrary distinction between foreshocks, aftershocks, and mainshocks. We find that foreshock precursory properties are independent of the mainshock size. This implies that earthquakes (large or small) are predictable to the same degree as seismicity rate is predictable from past seismicity by taking into account cascades of triggering. The cascades of triggering give rise naturally to long-range and long-time interactions, which can explain the observations of correlations in seismicity over surprisingly large length scales.",
"keywords": null,
"refs": null,
The large Izmit (NW Turkey) mainshock (1999 August 17, Mw= 7.6), followed by another large earthquake on 1999 November 12 (Mw= 7.2), caused extensive damage and loss of life in a zone approximately 170 km long along the coastal area of the Gulf of Izmit and further east to Adapazarı and Düzce. On the basis of the critical earthquake concept and by applying a recently developed optimization algorithm, an elliptical area surrounding the 1999 August 17 mainshock epicentre was identified, in which accelerating moderate magnitude seismic activity started in 1981 and culminated in the generation of the mainshock. On the other hand, the space and time distribution of the aftershocks of the first mainshock (1999 August 17) and the time variations of the b value of the Gutenberg–Richter recurrence law and the mean aftershock magnitude, suggest that the second mainshock (1999 November 12) might have been anticipated.

The time variation of two parameters related to accelerating preshock crustal deformation in the Aegean area is examined. The first is the b parameter of the Gutenberg–Richter relation and the second is the curvature parameter C, which is a measure of deviation of the accelerating preshock deformation from a linear time variation of this deformation. Following two different procedures, it was found that the b value exhibits a decreasing trend prior to the oncoming earthquake, in agreement with the results of laboratory experiments and other independent observations. C values also show a decreasing trend before main shocks. These results indicate that such time variations of these parameters can be considered as precursory phenomena of ensuing strong earthquakes.
We describe a simple model that links static stress (Coulomb) modeling to the regional seismicity around a major fault. Unlike conventional Coulomb stress techniques, which calculate stress changes, we model the evolution of the stress field relative to the failure stress. Background seismicity is attributed to inhomogeneities in the stress field which are created by adding a random field that creates local regions above the failure stress. The inhomogeneous field is chosen such that when these patches fail, the resulting earthquake size distribution follows a Gutenberg-Richter law. Immediately following a large event, the model produces regions of increased seismicity (aftershocks) where the overall stress field has been elevated and regions of reduced seismicity where the stress field has been reduced (stress shadows). The high stress levels in the aftershock regions decrease due to loading following the main event. Combined with the stress shadow from the main event, this results in a broad seismically quiet region of lowered stress around the epicenter. Pre-event seismicity appears as the original stress shadows finally fill as a result of loading. The increase in seismicity initially occurs several fault lengths away from the main fault and moves inward as the event approaches. As a result of this effect, the seismic moment release in the region around the future epicenter increases as the event approaches. Synthetic catalogues generated by this model are virtually indistinguishable from real earthquake sequences in California and Washington.
damage model can give exactly the same solution for material failure as the fibre-bundle model. We compare both models with laboratory experiments on the time-dependent failure of chipboard and fibreglass. The power-law scaling obtained in both models and in the experiments is consistent with the power-law seismic activation observed prior to some earthquakes.

"keywords": ["critical point", "damage mechanics", "fibre-bundle model", "fracture", "power-law scaling"],
"refs": null,
"journal": "Geophysical Journal International",
"year": 2003,
"doi": "10.1046/j.1365-246X.2003.01884.x"
},

{ 
"refID": "2003-1_Tzanis-A_NHESS",
"title": "Distributed power-law seismicity changes and crustal deformation in the SW Hellenic ARC",
"authors": ["Tzanis-A", "Vallianatos-F"],
"abstract": "A region of definite accelerating seismic release rates has been identified at the SW Hellenic Arc and Trench system, of Peloponnese, and to the south-west of the island of Kythera (Greece). The identification was made after detailed, parametric time-to-failure modelling on a 0.1° square grid over the area 20° E ? 27° E and 34° N?38° N. The observations are strongly suggestive of terminal-stage critical point behaviour (critical exponent of the order of 0.25), leading to a large earthquake with magnitude 7.1 ± 0.4, to occur at time 2003.6 ± 0.6. In addition to the region of accelerating seismic release rates, an adjacent region of decelerating seismicity was also observed. The acceleration/deceleration pattern appears in such a well structured and organised manner, which is strongly suggestive of a causal relationship. An explanation may be that the observed characteristics of distributed power-law seismicity changes may be produced by stress transfer from a fault, to a region already subjected to stress inhomogeneities, i.e. a region defined by the stress field required to rupture a fault with a specified size, orientation and rake. Around a fault that is going to rupture, there are bright spots (regions of increasing stress) and stress shadows (regions relaxing stress); whereas acceleration may be observed in bright spots, deceleration may be expected in the shadows. We concluded that the observed seismic release patterns can possibly be explained with a family of NE-SW oriented, left-lateral, strike-slip to oblique-slip faults, located to the SW of Kythera and Antikythera and capable of producing earthquakes with magnitudes MS ~ 7. Time-to-failure modelling and empirical analysis of earthquakes in the stress bright spots yield a critical exponent of the order 0.25 as expected from theory, and a predicted magnitude and critical time perfectly consistent with the figures given above. Although we have determined an approximate location, time and magnitude, it is as yet difficult to assert a prediction for reasons discussed in the text. However, our
results, as well as similar independent observations by another
research team, indicate that a strong earthquake may occur at
the SW Hellenic Arc, in the next few years.

"keywords": null,
"refs": null,
"journal": "Natural Hazards and Earth System Science",
"year": 2003,
"doi": null
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{
"refID": "2004-1_Bowman-DD_PAGEOPH",
"title": "Intermittent Criticality and the Gutenberg-Richter Distribution",
"authors": ["Bowman-DD", "Sammis-CG"],
"abstract": "In recent years there has been renewed interest in observations of accelerating moment release before large earthquakes, as well as theoretical descriptions of seismicity in terms of statistical physics. Most aspects of these works are encompassed by a concept called intermittent criticality in which a region alternately approaches and retreats from a critical -point. From this perspective, the evolution of seismicity in a region is described in terms of the growth and destruction of correlation in the stress field over the course of the seismic cycle. In this paper we test the concept of intermittent criticality by investigating the temporal evolution of the Gutenberg-Richter distribution before and after two successiveM ≥5.0 earthquakes in western Washington State. The largest event in this distribution, M max is observed to systematically increase before each event, producing accelerating moment release, and then to subsequently decrease. Associated variations in the b-value are minimal. This is the predicted result if M max is a measure of the correlation length of the regional stress field.

"keywords": null,
"refs": null,
"journal": "Pure and Applied Geophysics",
"year": 2004,
"doi": "10.1007/s00024-004-2541-z"
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{
"refID": "2004-1_Bufe-CG_BSSA",
"title": "Comparing the November 2002 Denali and November 2001 Kunlun Earthquakes",
"authors": ["Bufe-CG"],
"abstract": "Major strike-slip earthquakes recently occurred in Alaska on the central Denali fault (M 7.9) on 3 November 2002, and in Tibet on the central Kunlun fault (M 7.8) on 14 November 2001. Both earthquakes generated large surface waves with MS [U.S. Geological Survey (USGS)] of 8.5 (Denali) and 8.0 (Kunlun). Each event occurred on an east–west-trending strike-slip fault situated near the northern boundary of an intense deformation zone that is characterized by lateral
extrusion and rotation of crustal blocks. Each earthquake produced east-directed nearly unilateral ruptures that propagated 300 to 400 km. Maximum lateral surface offsets and maximum moment release occurred well beyond 100 km from the rupture initiation, with the events exhibiting by far the largest separations of USGS hypocenter and Harvard Moment Tensor Centroid (CMT) for strike-slip earthquakes in the 27-year CMT catalog. In each sequence, the largest aftershock was more than two orders of magnitude smaller than the mainshock. Regional moment release had been accelerating prior to the main shocks. The close proximity in space and time of the 1964 Prince William Sound and 2002 Denali earthquakes, relative to their rupture lengths and estimated return times, suggests that these events may be part of a recurrent cluster in the vicinity of a complex plate boundary.

"keywords": null,
"refs": null,
"journal": "Bulletin of the Seismological Society of America",
"year": 2004,
"doi": "10.1785/0120030185"
},

{"refID": "2004-1_DiGiovambattista-R_Tectonophys",
"title": "Seismicity patterns before the M=5.8 2002, Palermo (Italy) earthquake: seismic quiescence and accelerating seismicity",
"authors": ["DiGiovambattista-R", "Tyupkin-YS"],
"abstract": "Seismic quiescence and accelerating seismic energy release are considered as possible spatio-temporal patterns of the preparation process of the 6 September 2002 Palermo, Italy, earthquake (M 5.8). The detailed properties of the quiescence are analyzed applying the RTL algorithm. The RTL algorithm is based on the analysis of the RTL prognostic parameter, which is designed in such a way that it has a negative value if, in comparison with long-term background, there is a deficiency of events in the time–space vicinity of the tested point. The RTL parameter increases if activation of seismicity takes place. The RTL algorithm identified that a seismic quiescence started from the beginning of November 2001 and reached its minimum at the end of May 2002. The Palermo 2002 earthquake occurred 2 months after the RTL parameter restored its long-term background level. The application of a log-periodic time-to-failure model gives a “predicted” (in retrospect) magnitude M=6.2 main shock on 5 May 2002.",
"keywords": ["Seismicity", "Earthquakes", "Seismic quiescence", "Accelerating moment release", "Time-to-failure"],
"refs": null,
"journal": "Tectonophysics",
"year": 2004,
"doi": "10.1016/j.tecto.2004.04.001"}
We investigate the conditions under which the "stress-release model," a stochastic version of the elastic rebound model, produces synthetic earthquake sequences characterized by Accelerating Seismic Release (ASR). In this model, the level, or "stress," of the process accumulates linearly with time through tectonic input and decreases as the result of earthquakes. These "stress drops" correspond to some power of the energy released in the earthquakes, either $E^{0.5}$ (Benioff strain) or $E$ (seismic moment). Earthquakes occur in a point process with rate controlled by the level of the process. We hypothesize that the critical factor in the appearance of ASR is the manner in which the event sizes depend on the level of the process. This is modeled by the square root of energy released following either a tapered Pareto or truncated Gutenberg-Richter distribution, with maximum earthquake size controlled by a "tail-off" or "truncation" point. As the tail-off point becomes large, so does the average size, corresponding to an "acceleration to criticality" of the system. We found that those cases where the underlying level of the process corresponded to accumulated seismic moment produced numerous ASR sequences, whereas those cases using accumulated Benioff strain as the level did not. These results suggest that the occurrence of ASR is strongly dependent on how large earthquakes affect the dynamics of the fault system in which they are embedded, and hopefully provide some insight into the mechanics of acceleration to criticality, i.e., on the possible causes of occurrence/nonoccurrence of ASR."
the Izmit 1999 earthquake (M=7.6). We have applied the method of accelerating seismic crustal deformation, which is based on concepts of critical point dynamics in an attempt to locate more precisely those regions along the NAB where seismic excitation is more likely to occur. For this reason, a detailed parametric grid search of the broader NAB area was performed for the identification of accelerating energy release behavior. Three such elliptical critical regions have been identified with centers along this boundary. The first region, (A), is centered in the eastern part of this boundary (40.2°N, 27.2°E: southwest of Marmara), the second region, (B), has a center in the middle part of the boundary (38.8°N, 23.4°E: East Central Greece) and the third region, (C), in the westernmost part of the boundary (38.2°N, 20.9°E: Ionian Islands). The study of the time variation of the cumulative Benioff strain in two of the three identified regions (A and B) revealed that intense accelerating seismicity is observed especially after the occurrence of the 1999 Izmit mainshock. Therefore, it can be suggested that the seismic excitation, at least in these two regions, has been triggered by the Izmit mainshock. Estimations of the magnitudes and origin times of the expected mainshocks in these three critical regions have also been performed, assuming that the accelerating seismicity in these regions will lead to a critical point, that is, to the generation of mainshocks.

"keywords": ["Accelerating seismic deformation", "Aegean", "Earthquake prediction"],
"refs": null,
"journal": "Tectonophysics",
"year": 2004,
"doi": "10.1016/j.tecto.2004.03.005"
}
accelerating seismicity, which can then be analyzed using signal optimization time-to-failure techniques."

"keywords": ["Seismicity", "seismic hazard assessment", "earthquake prediction", "earthquake physics", "earthquake stress interactions"],
"refs": null,
"journal": "Pure and Applied Geophysics",
"year": 2004,
"doi": "10.1007/s00024-004-2569-3"
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"refID": "2004-1_Scordilis-EM_JOSE",
"title": "Accelerating seismic crustal deformation before strong mainshocks in Adriatic and its importance for earthquake prediction",
"keywords": ["accelerating seismic deformation", "Adriatic sea", "earthquake prediction"],
"refs": null,
"year": 2004,
"doi": null
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"refID": "2004-1_Wang-JC_TAO",
"title": "Investigation of Seismicity in Central Taiwan Using the Accelerating Seismic Energy Release Model",
"keywords": ["Scordilis-EM", "Papazachos-CB", "Karakaisis-GF", "Karakostas-VG"],
"abstract": "Time accelerating Benioff strain release before the mainshock has been observed in all five cases of strong (M > 6.0) shallow mainshocks, which have occurred during the last four decades in the area surrounding the Adriatic Sea. This observation supports the idea that strong mainshocks are preceded by accelerating seismic crustal deformation due to the generation of intermediate magnitude shocks (preshocks). It is further shown that the values of parameters calculated from these data follow appropriately modified relations, which have previously been proposed as additional constraints to the critical earthquake model and to the corresponding method of intermediate term earthquake prediction. Thus, these results show that the identification of regions where time-accelerating Benioff strain follows such constraints may lead to useful information concerning the epicenter, magnitude and origin time of oncoming strong mainshocks in this area. The procedure for identification of time-acceleration is validated by appropriate application on synthetic but realistic random catalogues. Larger dimension of critical regions in Adriatic compared to such regions in the Aegean is attributed to an order of magnitude smaller seismic deformation of the crust in the former in comparison to the latter.";
"refs": null,
"journal": "Pure and Applied Geophysics",
"year": 2004,
"doi": null
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A time-to-failure method developed from the accelerating seismic energy release model is used to scrutinize the seismicity of central Taiwan for 40 earthquakes with magnitude greater than 4.5. First, mainshocks and their pre-events are identified, and then adopted as observed data set. The nonlinear time-to-failure equation is separated into two linear equations, and then parameters are estimated by using linear least-square twice. The model constructed from the estimated local parameters, is then used to predict time-of-failure and magnitude of mainshocks. Comparing predicted results and 40 mainshocks, the maximum misfits are only 0.98 years in time and 1.2 unit in magnitude, which indicate that accelerating seismic energy release model could be applied in central Taiwan as a useful tool for the study of seismicity.

In the paper, we analyze 117 moderate-strong earthquakes occurred in Chinese mainland (M S ≥ 5.5 in the east and M S ≥ 6.0 in the west) since 1970, among them, 11 earthquakes (about 9%) have direct foreshocks and 63 earthquakes (about 51%) have generalized foreshocks. The predominant time interval between foreshock and main earthquake is no more than 30 days with a spatial distance less than 50 km and a magnitude difference over 1. From the digital seismic data in liaoning Province, we know that direct foreshock had an obvious shear-stress background before the M S = 5.6 and M S = 5.1 Xiuyan earthquakes occurred on Nov. 29, 1999 and Jan.15, 2000.

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In the paper, we analyze 117 moderate-strong earthquakes occurred in Chinese mainland (M S ≥ 5.5 in the east and M S ≥ 6.0 in the west) since 1970, among them, 11 earthquakes (about 9%) have direct foreshocks and 63 earthquakes (about 51%) have generalized foreshocks. The predominant time interval between foreshock and main earthquake is no more than 30 days with a spatial distance less than 50 km and a magnitude difference over 1. From the digital seismic data in liaoning Province, we know that direct foreshock had an obvious shear-stress background before the M S = 5.6 and M S = 5.1 Xiuyan earthquakes occurred on Nov. 29, 1999 and Jan.15, 2000.
"abstract": "The Accelerating Moment Release (AMR) preceding earthquakes with magnitude above 5 in Australia that occurred during the last 20 years was analyzed to test the Critical Point Hypothesis. Twelve earthquakes in the catalog were chosen based on a criterion for the number of nearby events. Results show that seven sequences with numerous events recorded leading up to the main earthquake exhibited accelerating moment release. Two occurred near in time and space to other earthquakes preceded by AMR. The remaining three sequences had very few events in the catalog so the lack of AMR detected in the analysis may be related to catalog incompleteness. Spatio-temporal scanning of AMR parameters shows that 80% of the areas in which AMR occurred experienced large events. In areas of similar background seismicity with no large events, 10 out of 12 cases exhibit no AMR, and two others are false alarms where AMR was observed but no large event followed. The relationship between AMR and Load-Unload Response Ratio (LURR) was studied. Both methods predict similar critical region sizes, however, the critical point time using AMR is slightly earlier than the time of the critical point LURR anomaly."

"keywords": ["Critical Point Hypothesis", "Accelerating Moment Release (AMR) model", "earthquake prediction", "Load-Unload Response Ratio (LURR)", "Australia earthquakes"],
"refs": null,
"journal": "Pure and Applied Geophysics",
"year": 2004,
"doi": "10.1007/s00024-004-2563-9"
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{ "refID": "2004-1_Weatherley-D_PAGEOPH",
 "title": "Accelerating Precursory Activity within a Class of Earthquake Analogue Automata",
 "authors": ["Weatherley-D", "Mora-P"],
 "abstract": "A statistical fractal automaton model is described which displays two modes of dynamical behaviour. The first mode, termed recurrent criticality, is characterised by quasi-periodic, characteristic events that are preceded by accelerating precursory activity. The second mode is more reminiscent of SOC automata in which large events are not preceded by an acceleration in activity. Extending upon previous studies of statistical fractal automata, a redistribution law is introduced which incorporates two model parameters: a dissipation factor and a stress transfer ratio. Results from a parameter space investigation indicate that a straight line through parameter space marks a transition from recurrent criticality to unpredictable dynamics. Recurrent criticality only occurs for models within one corner of the parameter space. The location of the transition displays a simple dependence upon the fractal correlation dimension of the cell strength distribution. Analysis of stress field evolution indicates that recurrent criticality occurs in models with significant long-
range stress correlations. A constant rate of activity is associated with a decorrelated stress field.

"keywords": ["Critical point hypothesis", "cellular automata", "accelerating moment release"],
"refs": null,
"journal": "Pure and Applied Geophysics",
"year": 2004,
"doi": "10.1007/s00024-004-2546-x"
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"refID": "2005-1_Jiang-CS_BSSA",
"title": "Test of the Preshock Accelerating Moment Release (AMR) in the Case of the 26 December 2004 Mw 9.0 Indonesia Earthquake",
"authors": ["Jiang-CS", "Wu-ZL"],
"abstract": "A case study of the 26 December 2004 Mw 9.0 earthquake off the west coast of northern Sumatra, Indonesia, was conducted to explore whether there was a preshock accelerating moment release (amr) process for the intermediate timescale. The Harvard cmt catalog was used to calculate the cumulative moment tensor directly, with clearer physical significance with regard to the deformation prior to the great earthquake. We observed that average moment tensors at different times over the last decade before the great earthquake are consistent, and are similar to the focal mechanism of the great earthquake. However, the widely used cumulative scalar seismic moment and cumulative Benioff strain are only an approximation of the preshock deformation. To test the robustness of the accelerating property with respect to the selection of spatiotemporal parameters, we calculated the scaling coefficient m for different spatiotemporal ranges. The curvature parameter q was used to quantify the difference between the power-law fit and the linear fit to ensure the statistical significance of the power-law-like accelerating behavior. Grid searching over the (tf, m) space was conducted to explore the global stability of the solution. The result showed that there existed a reliable preshock amr process before this great earthquake, with duration of a quarter of a century and a spatial range from 800 to 1500 km, providing seemingly positive evidence for the amr model. However, the failure time tf was not well constrained by the amr analysis, and the amr model may be problematic for a longer timescale."
,"keywords": null,
"refs": null,
"journal": "Bulletin of the Seismological Society of America",
"year": 2005,
"doi": "10.1785/0120050018"
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"refID": "2005-1_Jiang-CS_ActaSeismSinica"
The December 26, 2004, off the west coast of northern Sumatra, Indonesia, MW=9.0, earthquake and the critical-point-like model of earthquake preparation,

Long-term seismic activity prior to the December 26, 2004, off the west coast of northern Sumatra, Indonesia, M W=9.0 earthquake was investigated using the Harvard CMT catalogue. It is observed that before this great earthquake, there exists an accelerating moment release (AMR) process with the temporal scale of a quarter century and the spatial scale of 1,500 km. Within this spatial range, the M W=9.0 event falls into the piece-wise power-law-like frequency-magnitude distribution. Therefore, in the perspective of the critical-point-like model of earthquake preparation, the failure to forecast/predict the approaching and/or the size of this earthquake is not due to the physically intrinsic unpredictability of earthquakes.

The preshock (critical) regions of 20 mainshocks with magnitudes between 6.4 and 8.3, which occurred recently (since 1980) in a variety of seismotectonic regimes (Greece, Anatolia, Himalayas, Japan, California), were identified and investigated. All these strong earthquakes were preceded by accelerating time-to-mainshock seismic crustal deformation (Benioff strain). The time variation of the cumulative Benioff strain follows a power law with a power value (m = 0.3) in very good agreement with theoretical considerations. We observed that the dimension of the critical region increased with increasing mainshock magnitude and with decreasing long-term seismicity rate of the region. An increase of the duration of this critical (preshock) phenomenon with decreasing long-term seismicity rate was also observed. This spatial and temporal scaling expresses characteristics of the critical earthquake model, which are of importance for earthquake prediction research. We also showed that the critical region of an oncoming mainshock coincides with the preparing
region of this shock, where other precursory phenomena can be observed.

"keywords": null,
"refs": null,
"journal": "Bulletin of the Seismological Society of America",
"year": 2005,
"doi": "10.1785/0120040181

"},

{ "refID": "2005-1_Robinson-R_GRL",
"title": "Precursory accelerating seismic moment release (AMR) in a synthetic seismicity catalog: A preliminary study",
"authors": ["Robinson-R", "Zhou-S", "Johnston-S", "VereJones-D"],
"abstract": "A power-law like acceleration of seismic moment release (AMR) has been proposed as a precursor to large earthquakes. Because of problems with real-world data, we have used a synthetic seismicity model of 256 interacting faults embedded in a 3-D elastic half-space to search for periods of AMR preceding the largest events (Mw ~ 7.1). In only 5 of 18 cases does the AMR model fit the data significantly better than a linear moment release, and then only weakly so. This proportion, or higher, occurs in 8% of 1000 randomized catalogs. We conclude that either AMR is unlikely to be a common precursor, or that factors contributing to the AMR pattern in the real world are missing from the synthetic model.",
"keywords": null,
"refs": null,
"journal": "Geophysical Research Letters",
"year": 2005,
"doi": "10.1029/2005GL022576

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{ "refID": "2006-1_Jiang-CS_PAGEOPH",
"title": "Benioff Strain Release Before Earthquakes in China: Accelerating or Not?",
"authors": ["Jiang-CS", "Wu-ZL"],
"abstract": "We systematically analyzed the Benioff strain release before 65 earthquakes with M_S over 6.0 in China from 1978 to 2003 to investigate the generality of the widely discussed accelerating moment release (AMR) phenomenon before strong and intermediate-strength earthquakes. In this approach, a strong or intermediate-strength earthquake is selected as a "target earthquake," and retrospective analysis of seismic activity before the "target earthquake" is performed. Simple searching area (three circular areas with different radius centered at the epicenter of the "target earthquake") and unified temporal range (8 years) are taken in the analysis. Justification of whether AMR exists is by both visual inspection and by power-law curve fitting. It is found that more than 3/5
of the earthquakes under consideration exhibit clear pre-shock AMR property, and 1/3 of the events seem to be sensitive to the searching area. AMR behavior shows apparent focal mechanism dependence: 15 out of 17 dip-slip earthquakes with stable moment release characteristics against the changing of searching areas exhibit AMR behavior, while 16 out of 25 strike-slip earthquakes with stable moment release characteristics exhibit AMR behavior.

"keywords": ["Accelerating moment release (AMR)", "earthquakes in China", "critical-point-like model of earthquakes", "intermediate-term earthquake prediction"],
"refs": null,
"journal": "Pure and Applied Geophysics",
"year": 2006,
"doi": "10.1007/s00024-006-0107-1"
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"refID": "2006-1_Mignan-A_JGR",
"title": "An observational test of the origin of accelerating moment release before large earthquakes",
"authors": ["Mignan-A", "Bowman-DD", "King-GCP"],
"abstract": "A progressive increase of seismic activity distributed over a wide region around a future earthquake epicenter is termed accelerating moment release (AMR). This phenomenon has been observed in several studies over the last 15 years, although there is no consensus about the physical origin of the effect. In a recent hypothesis known as the stress accumulation (SA) model, the AMR is thought to result from the last stage of loading in the earthquake cycle. In this view, the increasing seismicity is due to minor stress release as the whole region becomes sufficiently stressed for the major event to occur. The stress accumulation model makes specific predictions about the distribution of events in an AMR sequence. Because the AMR is predicted to be a result of loading on the main fault, the precursory activity should be concentrated in the positive lobes of the far-field stresses calculated by a backslip dislocation model of the main shock. To test this model, AMR is first found in optimal circular regions around the epicenters of each of the Mw ≥ 6.5 earthquakes in central and southern California since 1950. A backslip dislocation model is then used to determine which of the precursory events occur in the regions predicted by stress accumulation. AMR is shown to occur preferentially in the lobes of the backslip stress field predicted by the stress accumulation model.",
"keywords": null,
"refs": null,
"journal": "Journal of Geophysical Research",
"year": 2006,
"doi": "10.1029/2006JB004374"
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"refID": "2006-1_Mignan-A_EPSL",}
A promising approach to assessing seismic hazards has been to combine the concept of seismic gaps with Coulomb-stress change modeling to refine short-term earthquake probability estimates. However, in practice the large uncertainties in the seismic histories of most tectonically active regions limit this approach since a stress increase is only important when a fault is already close to failure. In contrast, recent work has suggested that Accelerated Moment Release (AMR) can help to identify when a stretch of fault is approaching failure without any knowledge of the seismic history of the region. AMR can be identified in the regions around the Sumatra Subduction system that must have been stressed before the 26 December 2004 and 28 March 2005 earthquakes. The effect is clearest for the epicentral regions with less than a 2% probability that it could occur in a random catalogue. Less clear AMR is associated with the regions north of Sumatra around the Nicobar and Andaman islands where rupture in the December 2004 earthquake was less vigorous. No AMR is found for the region of the 1833 Sumatran earthquake suggesting that an event in this region in the near future is unlikely. AMR similar to that before the December 2004 and March 2005 events is found for a 750 km stretch of the southeastern Sumatra and western Java subduction system suggesting that it is close to failure. Should the whole of this stretch break in a single event the magnitude could be similar to the December 2004 earthquake.
attributed to stress relaxation due to pre-seismic sliding. To facilitate the identification of such patterns an algorithm has been developed on the basis of data concerning accelerating and decelerating preshock sequences of globally distributed already occurred strong mainshocks. This algorithm is applied in the present work to identify regions, which are currently in a state of accelerating seismic deformation and are associated with corresponding narrower regions, which are in a state of decelerating seismic deformation in California. It has been observed that a region which includes known faults in central California is in a state of decelerating seismic strain release, while the surrounding region (south and north California, etc.) is in a state of accelerating seismic strain release. This pattern corresponds to a big probably oncoming mainshock in central California. The epicenter, magnitude and origin time, as well as the corresponding model uncertainties of this probably ensuing big mainshock have been estimated, allowing a forward testing of the model's efficiency for intermediate-term earthquake prediction.

"keywords": ["Accelerating strain", "decelerating strain", "earthquake prediction", "California"],
"refs": null,
"journal": "Journal of Seismology",
"year": 2006,
"doi": "10.1007/s10950-005-9009-4"
}

"refID": "2006-1_Zhou-S_JGR",
"title": "Tests of the precursory accelerating moment release model using a synthetic seismicity model for Wellington, New Zealand",
"authors": ["Zhou-S", "Johnston-S", "Robinson-R", "VereJones-D"],
"abstract": "We have constructed a synthetic seismicity model of the Wellington region, New Zealand, including seven superfaults and 500 subfaults which are randomly positioned. From this model, a synthetic catalogue of 2000 years duration, containing events of magnitude 5.0 or more, has been generated. The properties of the catalogue, such as the long-term slip rates, b value, average activity rate, and hypocenter distribution, are in accord with paleoseismic studies and the real seismicity over the last 40 years. Such a synthetic catalogue can replace the short, incomplete, and inhomogeneous historic and instrumental records in research which needs a long time duration and many strong shocks. We have used our catalogue to examine tests for the existence of accelerating moment release (AMR) before large events and compared the results with those from random (Poisson) catalogues. We find that (1) the apparent success rate is very dependent on the rules used to define the test window; (2) when appropriately defined, the AMR pattern occurs before about 20% of the strong (M ≥ 7.0) shocks with a typical precursor time of about 22 years; (3) the AMR
pattern is found almost equally frequently before large events in random catalogues; and (4) there are some false alarms (AMR pattern without a large event). This extended study reinforces the conclusion in our preliminary report: that in synthetic catalogues of the kind we have constructed, the AMR pattern is essentially an artefact of the method of sampling."

"keywords": null,
"refs": null,
"journal": "Journal of Geophysical Research",
"year": 2006,
"doi": "10.1029/2005JB003720"
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}

"refID": "2007-1_Mignan-A_JGR",
"title": "A mathematical formulation of accelerating moment release based on the stress accumulation model",
"authors": ["Mignan-A", "King-GCP", "Bowman-DD"],
"abstract": "Large earthquakes can be preceded by a period of accelerating seismic activity of moderate-sized earthquakes. This phenomenon, usually termed accelerating moment release, has yet to be clearly understood. A new mathematical formulation of accelerating moment release is obtained from simple stress transfer considerations, following the recently proposed stress accumulation model. This model, based on the concept of elastic rebound, simulates accelerating seismicity from theoretical stress changes during an idealized seismic cycle. In this view, accelerating moment release is simply the consequence of the decrease, due to loading, of the size of a stress shadow due to a previous earthquake. We show that a power law time-to-failure equation can be expressed as a function of the loading rate on the fault that is going to rupture. We also show that the m value, which is the power law exponent, can be defined as m = D/3, with D a parameter that takes into account the geometrical shape of the stress lobes and the distribution of active faults. In the stress accumulation model, the power law is not due to critical processes."

"keywords": null,
"refs": null,
"journal": "Geophysical Research Letters",
"year": 2007,
"doi": "10.1029/2006JB004671"
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"refID": "2007-1_Papazachos-BC_BSSA",
"title": "Evaluation of the Results for an Intermediate-Term Prediction of the 8 January 2006 Mw 6.9 Cythera Earthquake in the Southwestern Aegean",
"authors": ["Papazachos-BC", "Karakaisis-GF", "Papazachos-CB", "Scordilis-EM"],
"abstract": "During the past few decades the critical earthquake model, which is based on observations concerning
accelerating seismic deformation and concepts of the critical point dynamics, has been proposed by various seismologists as a useful tool for intermediate-term earthquake prediction. A refined approach of this model has been previously applied to search for preshock (critical) regions in the southern Aegean, using all available data until the middle of 2002. A critical region corresponding to a large mainshock had been identified (Papazachos et al., 2002a,b) in the southwestern part of the Aegean, near the Cythera island. The predicted (in 2002) parameters for this ensuing earthquake are $\varphi = 36.5^\circ$ N, $\lambda = 22.7^\circ$ E for the epicentral geographic coordinates (with a model uncertainty of 120 km), focal depth $\leq 100$ km, moment magnitude $M = 6.9 \pm 0.5$, and origin time $t_c = 2006.4 \pm 2.0$. The generation of the strong Cythera earthquake on 8 January 2006 with $M = 6.9$, epicenter coordinates $\varphi = 36.2^\circ$ N and $\lambda = 23.4^\circ$ E and a focal depth of $h = 65$ km satisfies this intermediate-term prediction. The region where significant macroseismic effects were anticipated from the predicted mainshock (Cythera, south Peloponnesus, west Crete, and west Cyclades) corresponds to the area where damage by the 8 January 2006 strong earthquake has been observed. The verification of this prediction is strong evidence that the intermediate-term prediction of strong earthquakes is potentially feasible, but additional forward testing of the model is needed to validate this result.

Accelerating preshock seismic strain in a broad (critical) region and decelerating preshock seismic strain in a narrower (seismogenic) region constitute a model for intermediate-term prediction of strong main shocks. An effort is made in the present work for a forward test of the Decelerating-Accelerating Seismic Strain (D-AS) model by identifying such patterns and estimating the corresponding, probably ensuing, strong main shocks ($M \geq 7.0$) in central Asia ($20^\circ$N–45$^\circ$N, 42$^\circ$E–105$^\circ$E). Five such patterns have been identified, and the origin time, magnitude, and epicentral geographic coordinates of each of the corresponding main shocks have been estimated (predicted). Model uncertainties of the estimated time, magnitude, and space parameters of these probably ensuing main shocks, as well as appropriate statistical tests against a standard Gutenberg-Richter seismicity distribution, are also

"keywords": null,
"refs": null,
"journal": "Bulletin of the Seismological Society of America",
"year": 2007,
"doi": "10.1785/0120060075"}
presented to allow a future objective evaluation of the model's efficiency for intermediate-term earthquake prediction.

We test the hypothesis that accelerating moment release (AMR) is a precursor to large earthquakes, using data from California, Nevada, and Sumatra. Spurious cases of AMR can arise from data fitting because the time period, area, and sometimes magnitude range analyzed before each main shock are often optimized to produce the strongest AMR signal. Optimizing the search criteria can identify apparent AMR even if no robust signal exists. For both 1950–2006 California–Nevada M ≥ 6.5 earthquakes and the 2004 M9.3 Sumatra earthquake, we can find two contradictory patterns in the pre-main shock earthquakes by data fitting: AMR and decelerating moment release. We compare the apparent AMR found in the real data to the apparent AMR found in four types of synthetic catalogs with no inherent AMR. When spatiotemporal clustering is included in the simulations, similar AMR signals are found by data fitting in both the real and synthetic data sets even though the synthetic data sets contain no real AMR. These tests demonstrate that apparent AMR may arise from a combination of data fitting and normal foreshock and aftershock activity. In principle, data-fitting artifacts could be avoided if the free parameters were determined from scaling relationships between the duration and spatial extent of the AMR pattern and the magnitude of the earthquake that follows it. However, we demonstrate that previously proposed scaling relationships are unstable, statistical artifacts caused by the use of a minimum magnitude for the earthquake catalog that scales with the main shock magnitude. Some recent AMR studies have used spatial regions based on hypothetical stress loading patterns, rather than circles, to select the data. We show that previous tests were biased and that unbiased tests do not find this change to the method to be an improvement. The use of declustered catalogs has also been proposed to eliminate the effect of clustering but we demonstrate that this does not increase the statistical significance of AMR. Given the ease with which data fitting can find desired patterns in seismicity, future studies of AMR-like observations must include complete tests against synthetic catalogs that include spatiotemporal clustering.
The hypothesis that Accelerating Moment Release (AMR) is a precursor to large earthquakes is still debated. On one hand, AMR has been claimed to be observed in many cases and on the other hand, it has been proposed that apparent AMR is only due to data-fitting. The debate is in general focused on the validity of the c-value (curvature parameter), which permits to quantify AMR (i.e. cumulative Benioff strain through time), or more generally Precursory Accelerating Seismicity (PAS, i.e. cumulative number of events through time). Contrary to previous studies, which compare c-value optimization in real seismicity catalogues and in random synthetic catalogues, I test c-value optimization in theoretical synthetic catalogues. In that particular case, I assume that PAS exists and that it can be explained by the Non-Critical Precursory Accelerating Seismicity Theory (NC PAST). This theory demonstrates that PAS can emerge from the background seismicity because of the decrease, due to loading, of the size of a stress shadow due to a previous earthquake. I improve the NC PAST by integrating the following characteristics of the background seismicity, (1) the density of random events outside the stress shadow \( \delta b_0 \) and (2) the noise ratio \( \delta b^-/\delta b_0 \), with \( \delta b^- \) being the density of random events inside the stress shadow. Then I perform a spatiotemporal search of PAS using the power-law fit methodology (i.e. c-value) and compare the optimal signal to the expected spatiotemporal extent of the theoretical signal. First I show that the optimal starting time and spatial extent of PAS are poorly controlled, due in part to the intrinsic properties of the c-value, but also to the random behavior of background seismicity. Second I show that theoretical PAS is identified by an optimal c-value (clear acceleration) only if the regional seismic activity \(- \delta b_0\) is high and the noise ratio \(\delta b^-/\delta b_0\) is low. Otherwise the signal tends to disappear and the c-value becomes unstable. As a consequence, even if the power-law fit methodology is a simple approach to test the presence of PAS and can help provide a better understanding of the process engaged, it seems inadequate for robust systematic prospective forecasts.

Earthquake Forecast, Precursory seismicity, AMR, Stress loading, Stress shadow, Synthetic catalogue]
This chapter shows that the Stress Accumulation model can be defined with simple stress transfer considerations. At present, a parallel can be made between accelerating moment release and aftershocks, which seem symmetrical about the mainshock time (acceleration/deceleration). Aftershocks are located in positive stress lobes of the stress field caused by the mainshock whereas accelerating moment release is located in positive stress lobes of the prestress field of the future mainshock. Aftershocks are due to the change of stress at the time of the mainshock and accelerating moment release is due to the change of stress during loading before the time of the mainshock. This view permits to better understand the possible behavior of precursory seismicity by defining a simple pattern. This is in contrast with critical concepts where patterns emerge from chaos and are difficult to catch. This has important consequences in earthquake forecasting. Indeed many precursors have been proposed, based on different mathematical or statistical tools around the criticality concepts. However, the application of the Stress Accumulation model to earthquake forecasting also shows that a systematic use of accelerating moment release is complex and depends of the studied region. It shows that proper statistics are necessary to determine correctly the reliability of precursory patterns.

The Non-Critical Precursory Accelerating Seismicity Theory (PAST) has been proposed recently to explain the formation of accelerating seismicity (increase of the a-value) observed before large earthquakes. In particular, it predicts that precursory accelerating seismicity should occur in the same spatiotemporal window as quiescence. In this first combined study we start by determining the spatiotemporal extent of quiescence observed prior to the 1997 Mw = 6 Umbria-Marche earthquake, Italy, using the RTL (Region-Time-Length) algorithm. We then show that background events located in that
spatiotemporal window form a clear acceleration, as expected by the Non-Critical PAST. This result is a step forward in the understanding of precursory seismicity by relating two of the principal patterns that can precede large earthquakes.

A useful way of understanding both seismotectonic processes and earthquake prediction research is to conceive seismic patterns as a function of space and time. The present work investigates seismic precursors before the occurrence of an earthquake. It does so by means of a methodology designed to study spatiotemporal characteristics of seismicity in a selected area. This methodology is based on two phenomena: the decelerating moment release (DMR) and the accelerating moment release (AMR), as they occur within a period ranging from several months to a few years before the oncoming event. The combination of these two seismic sequences leads to the proposed decelerating-accelerating moment release (DAMR) earthquake sequence, which appears as the last stage of loading in the earthquake cycle. This seismic activity appears as a foreshock sequence and can be supported by the stress accumulation model (SAM). The DAMR earthquake sequence constitutes a double seismic precursor identified in space and time before the occurrence of an earthquake and can be used to improve seismic hazard assessment research. In this study, the developed methodology is applied to the data of the 1989 Loma Prieta (California), the 1995 Kobe (Japan), and the 2003 Lefkada (Greece) earthquakes. The last part of this study focuses on the application of the methodology to the Ionian Sea (western Greece) and forecasts two earthquakes in that area.

The epicentral area of the Mw=6.4, 8 June 2008, main shock in northwestern Peloponesus, Western Greece, had been
forecasted as a candidate for the occurrence of a strong earthquake by independent scientific investigations. This study concerns the seismicity of a large area surrounding the epicenter of the main shock using the seismological data from the monthly bulletins of the Institute of Geodynamics of the National Observatory of Athens. This data set is the most detailed earthquake catalog available for anomalous seismicity pattern investigations in Greece. The results indicate a decrease in seismicity rate seven years prior to the 8 June main shock which constituted a two and a half year long seismic quiescence surrounding the epicentral area. This quiescence anomaly was succeeded by a period of acceleration in seismic activity for five years approximately, until the occurrence of the main shock.

"keywords": null,
"refs": null,
"journal": "Natural Hazards and Earth System Science",
"year": 2009,
"doi": "10.5194/nhess-9-327-2009"
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{
"refID": "2009-2_Chouliaras-G_NHESS",
"title": "Seismicity anomalies prior to the 13 December 2008, Ms=5.7 earthquake in Central Greece",
"authors": ["Chouliaras-G"],
"abstract": "This investigation has applied a recent methodology to identify seismic quiescence and seismic acceleration, prior to the occurrence of the 13 December 2008, Ms=5.7 earthquake in Central Greece. Anomalous seismic quiescence is observed around the epicentral area almost twelve years prior to the main shock and it lasted for a period of about four and a half years. After this period an acceleration in seismic activity began and lasted until the main shock. Modeling this seismic sequence with the time-to-failure equation and with a fixed value of the exponent 'm' equal to 0.32, shows a successful estimation of the occurrence time of the main event within a few days. The physical meaning of this particular choice of the 'm' value is discussed.

"keywords": null,
"refs": null,
"journal": "Natural Hazards and Earth System Science",
"year": 2009,
"doi": "10.5194/nhess-9-501-2009"
},
{
"refID": "2009-1_Greenhough-J_GRL",
"title": "Comment on 'Relationship between accelerating seismicity and quiescence, two precursors to large earthquakes' by Arnaud Mignan and Rita Di Giovambattista",
"authors": ["Greenhough-J", "Bell-AF", "Main-IG"],
"abstract": "The significance levels of many reported episodes of Accelerating Moment Release (AMR, a cumulative func-
tion of earthquake magnitude with time) have been shown to be too low to reject a range of alternative hypotheses [Hardebeck et al., 2008]. While Mignan [2008] acknowledges the deficiency of power-law fitting alone for forecasting large events via AMR, this and the proceeding study [Mignan and Di Giovambattista, 2008] do not address an underlying problem of applying standard regression methods to cumulative data. We consider this a timely opportunity to emphasize why regression on any cumulative quantity requires the utmost care and is at best avoided. This cautionary comment is relevant to a wide range of applications in geophysics and elsewhere.

"keywords": null,
"refs": null,
"journal": "Geophysical Research Letters",
"year": 2009,
"doi": "10.1029/2009GL039846"
},

{ "refID": "2009-1_Mignan-A_GRL",
"title": "Reply to comment by J. Greenhough et al. on 'Relationship between accelerating seismicity and quiescence, two precursors to large earthquakes'",
"authors": ["Mignan-A", "DiGiovambattista-R"],
"abstract": "The existence of Accelerating Seismic Release (ASR) prior to large earthquakes has been largely debated in the last decade and opponents are even stronger since the landmark paper by Hardebeck et al. [2008] (personal communication from StatSeis 2007, 2008 and 2009 meet- ings attendees). In this reply, we discuss the limits of approaches employed to verify the 'non-existence' of ASR and we emphasize the advantages of the method proposed by Mignan and Di Giovambattista [2008] to identify ASR, over the classic ASR regression method [e.g., Bowman et al., 1998].",
"keywords": null,
"refs": null,
"journal": "Geophysical Research Letters",
"year": 2009,
"doi": "10.1029/2009GL039871"
},

{ "refID": "2010-1_Bebbington-MS_PAGEOPH",
"title": "Repeated Intermittent Earthquake Cycles in the San Francisco Bay Region",
"authors": ["Bebbington-MS", "Harte-DS", "Jaume-SC"],
"abstract": "Forecasts of future earthquake hazard in the San Francisco Bay region (SFBR) are dependent on the distribution used for the possible magnitude of future events. Based on the limited observed data, it is not possible to statistically distinguish between many distributions with very different tail behavior. These include the modified and truncated Gutenberg–Richter distributions, and a composite distribution assembled by the Working Group on California
Earthquake Probabilities. There is consequent ambiguity in the estimated probability of very large, and hence damaging, events. A related question is whether the energy released in earthquakes is a small or large proportion of the stored energy in the crust, corresponding loosely to the ideas of self-organized criticality, and intermittent criticality, respectively. However, the SFBR has experienced three observed accelerating moment release (AMR) cycles, terminating in the 1868 Hayward, 1906 San Andreas and 1989 Loma Prieta events. A simple stochastic model based on elastic rebound has been shown to be capable of producing repeated AMR cycles in large synthetic catalogs. We propose that such catalogs can provide the basis of a test of a given magnitude distribution, via comparisons between the AMR properties of the real and synthetic data. Our results show that the truncated Gutenberg–Richter distribution produces AMR behavior closest to the observed AMR behavior. The proviso is that the magnitude parameters b and m max are such that a sequence of large events that suppresses activity for several centuries is unlikely to occur. Repeated simulation from the stochastic model using such distributions produces 30-year hazard estimates at various magnitudes, which are compared with the estimates from the 2003 Working Group on California Earthquake Probabilities.

"keywords": ["Earthquake magnitude", "accelerating moment release", "truncated Gutenberg–Richter", "tail behavior", "hazard estimates"],
"refs": null,
"journal": "Pure and Applied Geophysics",
"year": 2010,
"doi": "10.1007/s00024-010-0064-6"

"refID": "2010-1_Jiang-CS_ConcurrComput",
"title": "Seismic moment release before the May 12, 2008, Wenchuan earthquake in Sichuan of southwest China",
"authors": ["Jiang-CS", "Wu-ZL"],
"abstract": "Whether seismic moment release before great earthquakes exhibits accelerating or quiescence behavior is one of the controversial topics in the study of intermediate-term earthquake forecast or time-dependent seismic hazard. The May 12, 2008, Wenchuan earthquake provides a unique opportunity to check whether accelerating moment release (AMR) or quiescence existed before this great earthquake. To systematically analyze the precursory moment release, considering the special characteristics of this great inland thrust event, we took four upgraded approaches using the local earthquake catalogue with cutoff magnitude ML3.0. We propose a BIC criterion as a development of the curvature parameter q to identify the statistically significant acceleration or quiescence behavior as compared with linear increase. We use an ‘eclipse method’ as a development of the ‘interfering event consideration’ to eliminate the interference from the nearby seismically active
fault zones. We consider the distribution of m-coefficient in the (T, R, Mc) space, to explore the variation of moment release behavior with temporal window length T and spatial window radius R centered at the nucleation point, and cutoff magnitude Mc of the catalogue in use. We use not only circular windows but also 'crack-like' windows to investigate the overall behavior of the moment release associated with the Wenchuan earthquake. Through this retrospective case study, it is observed that moment release before the Wenchuan earthquake did show accelerating moment release (AMR) and quiescence behavior for different spatio-temporal ranges, with robustness to some extent against the changing of parameters, indicating the preparation process of this great earthquake. However, for this earthquake, to constrain the failure time in a forward forecasting mode is shown to be difficult.

"keywords": null,
"refs": null,
"journal": "Concurrency and Computation",
"year": 2010,
"doi": "10.1002/cpe.1522"
},

"refID": "2010-1_Mignan-A_Tectonophys",
"title": "Testing the Pattern Informatics index on synthetic seismicity catalogs based on the Non-Critical PAST",
"authors": ["Mignan-A", "Tiampo-K"],
"abstract": "The Non-Critical Precursory Accelerating Seismicity Theory (or Non-Critical PAST) has recently been proposed to explain the formation of accelerating seismicity that may be observed before large earthquakes. It has led to the possibility of constructing synthetic seismicity catalogs where patterns of accelerating seismicity (activation) and quiescence, which occur in the same space–time window, can be evaluated by existing forecasting techniques. In this study, the Pattern Informatics (or PI) index is tested on synthetic catalogs where a realistic spatiotemporal clustering has been added on top of the theoretical precursory seismicity. We show that the PI index is successful at identifying the precursory quiescent signal but fails in identifying precursory accelerating seismicity directly, being more sensitive to aftershock sequences of background events than to the activation-like behavior of the acceleration, formed by background events alone. We also show that the PI index has a high success rate in finding precursory quiescence, even for a low signal-to-noise ratio. As for the few false negatives, they are usually due to interfering aftershocks as well, which skew seismicity rates to higher means. The Non-Critical PAST, by helping to better understand the behavior of the PI algorithm in synthetic catalogs, gives new perspectives on how to improve it and on how to use it in real catalogs.

"keywords": ["AMR", "Pattern informatics", "Earthquake simulator", "Power-law"]
Decelerating generation of preshocks in a narrow (seismogenic) region and accelerating generation of other preshocks in a broader (critical) region, called decelerating–accelerating seismic strain (D-AS) model has been proposed as appropriate for intermediate-term earthquake prediction. An attempt is made in the present work to identify such seismic strain patterns and estimate the corresponding probably ensuing large mainshocks (M ≥ 7.0) in south Japan (30–38° N, 130–138° E). Two such patterns have been identified and the origin time, magnitude, and epicenter coordinates for each of the two corresponding probably ensuing mainshocks have been estimated. Model uncertainties of predicted quantities are also given to allow an objective forward testing of the efficiency of the model for intermediate-term earthquake prediction.

In this paper we demonstrate that the seismic sequence of foreshocks culminating with the recent Mw = 6.3 main shock on April 6, 2009 in L'Aquila (Central Italy) evolved as a chaotic process. To do this, we apply a nonlinear retrospective prediction to this seismic sequence and look at the temporal behaviour of the error between predicted and actual occurrence of the main shock when gradually increasing parts of the sequence are considered. This is a generalisation of the typical nonlinear approach which is quite powerful to detect chaos in relatively short time series. The method of prediction is based on the Accelerated Strain Release (ASR) analysis in time and on the nonlinear forecasting approach in a reconstructed phase space. We find that 1) the temporal decay of the prediction error is consistent with an exponential function with a time
constant $\tau$ of about 10 days and ii) at around 6 days before the main shock, ASR analysis is quite powerful for anticipating the time of occurrence with an uncertainty of about a day. Due to its retrospective characteristics, the latter result could be affected by changes on some a-priori parameters used in the application of the ASR technique. However, we consider these findings, together with those obtained from the phase-space analysis, to be strong evidence that the studied sequence of foreshocks was produced by a physical process dominated by a significant chaotic component characterised by a K-entropy $= 1/\tau$ of about 0.1 day$^{-1}$. This result could have important implications for the predictability of the possible main shock for those seismic sequences showing analogous nonlinear chaotic properties.

"keywords": ["Seismic sequence", "Chaotic process", "Accelerated Strain Release", "Nonlinear prediction", "Phase-space reconstruction"],
"refs": null,
"journal": "Tectonophysics",
"year": 2010,
"doi": "10.1016/j.tecto.2010.10.005"
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{ "refID": "2012-l_Jiang-CS_EPS",
"title": "Insights into the long-to-intermediate-term pre-shock accelerating moment release (AMR) from the March 11, 2011, off the Pacific coast of Tohoku, Japan, M 9 earthquake",
"authors": ["Jiang-C\textquotesingle S", "Wu-ZL"],
"abstract": "Great earthquakes with extending rupture areas, such as the March 11, 2011, off the Pacific coast of Tohoku, Japan, M 9 earthquake, provide opportunities to inspect some details of the pre-shock moment release with the reference of the earthquake preparation and rupture processes. To this end, we investigated the cumulative seismic moment tensor for different segments of the earthquake fault. For the 3 decades time scale, pre-shock accelerating moment release (AMR) can be observed, with potential correlation with the segmentation of earthquake fault.",
"keywords": ["Accelerating moment release", "Tohoku M 9 earthquake", "fault segmentation"],
"refs": null,
"journal": "Earth, Planets and Space",
"year": 2012,
"doi": null
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{ "refID": "2012-l_Lagios-E_Tectonophys",
"title": "Combined Seismicity Pattern Analysis, DGPS and PSInSAR studies in the broader area of Cephalonia (Greece)",
"authors": ["Lagios-E", "Papadimitriou-P", "Novali-F", "Sakka-V", "Fumagalli-A", "Vlachou-K", "DelConte-S"],
Ground deformation studies based on Differential GPS (DGPS) measurements and Permanent Scatterer Interferometric (PSI) analysis have been conducted on the islands of Cephalonia and Ithaca covering the period 1992 to 2010. DGPS measurements for the period 2001 to 2010 revealed horizontal clockwise rotation of Cephalonia and velocities ranging from 3 to 8 mm/yr with the largest values occurring at the western and southern parts of the island. Considering its vertical deformation, two periods are distinguished on the basis of DGPS and PSI: The first one (1992 to 2003) shows generally an almost linear slight subsidence (around 1 mm/yr) which is consistent with expected neotectonic movements of the island. The second one (2003 to 2010) has been tentatively attributed to dilatancy in which reversal to uplift (2–4 mm/yr) occurred mainly along the southern and southeastern parts of the island, while larger magnitudes (>4 mm/yr) took place at the western part. These non-linear high rates of uplift started at about mid-2005, and were of increasing rate at the southern part, but of decreasing rate at the western part; they may indicate a major regional crustal deformation process in an environment that has previously supported offshore large magnitude earthquakes. Parallel analysis of the observed seismicity in the broader area identified two seismically critical areas on the basis of the decelerating–accelerating seismicity: a major one south of Cephalonia and west of Zakynthos, and another minor one at the NW part of Peloponnese. Critical time estimates of the occurrence of a future strong seismic event in the above critical areas were also made based on: (i) accelerating seismicity, and (ii) the temporal analysis of the seismicity.

Various seismicity patterns before large earthquakes have been reported in the literature. They include foreshocks (medium-term acceleration and short-term activation), quiescence, doughnut patterns and event migration. The existence of these precursory patterns is however debated. Here, we develop an approach based on the concept of stress accumulation to unify and categorize all claimed seismic precursors in a same physical framework. We first extend the Non-Critical Precursory Accelerating Seismicity Theory (N-C PAST), which already explains most precursors, to additionally include short-term activation. Theoretical results are then
compared to the time series observed prior to the 2009Mw = 6.3 L'Aquila, Italy, earthquake. We finally show that different precursory paths are possible before large earthquakes, with possible coupling of different patterns or non-occurrence of any. This is described by a logic tree defined from the combined probabilities of occurrence of the mainshock at a given stress state and of precursory silent slip on the fault. In the case of the L'Aquila earthquake, the observed precursory path is coupling of quiescence and accelerating seismic release, followed by activation. These results provide guidelines for future research on earthquake predictability.

"keywords": null,
"refs": null,
"journal": "Geophysical Research Letters",
"year": 2012,
"doi": "10.1029/2012GL053946"
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"refID": "2012-1_Pliakis-D_AnnGeophys",
"title": "A first principles approach to understand the physics of precursory accelerating seismicity",
"authors": ["Pliakis-D", "Papakostas-T", "Vallianatos-F"],
"abstract": "Observational studies from rock fractures to earthquakes indicate that fractures and many large earthquakes are preceded by accelerating seismic release rates (accelerated seismic deformation). This is characterized by cumulative Benioff strain that follows a power law time-to-failure relation of the form C(t) = K + A(Tf – t)m, where Tf is the failure time of the large event, and m is of the order of 0.2–0.4. More recent theoretical studies have been related to the behavior of seismicity prior to large earthquakes, to the excitation in proximity of a spinodal instability. These have show that the power-law activation associated with the spinodal instability is essentially identical to the power-law acceleration of Benioff strain observed prior to earthquakes with m = 0.25–0.3. In the present study, we provide an estimate of the generic local distribution of cracks, following the Wackentrapp-Hergarten-Neugebauer model for mode I propagation and concentration of microcracks in brittle solids due to remote stress. This is a coupled system that combines the equilibrium equation for the stress tensor with an evolution equation for the crack density integral. This inverse type result is obtained through the equilibrium equations for a solid body. We test models for the local distribution of cracks, with estimation of the stress tensor in terms of the crack density integral, through the Nash-Moser iterative method. Here, via the evolution equation, these estimates imply that the crack density integral grows according to a (Tf – t)0.3-law, in agreement with observations.

"keywords": ["seismicity", "fracture", "Benioff"],
"refs": null,
"journal": "Annals of Geophysics"
The long precursory phase of most large interplate earthquakes

Bouchon-M, Durand-V, Marsan-D, Karabulut-H, Schmittbuhl-J

Many earthquakes are preceded by foreshocks. However, the mechanisms that generate foreshocks and the reason why they occur before some earthquakes and not others are unknown. Here we use seismic catalogues from the best instrumented areas of the North Pacific to analyse the foreshock sequences preceding all earthquakes there between 1999 and 2011, of magnitude larger than 6.5 and at depths shallower than 50 km. The data set comprises 31 earthquakes at plate boundaries, and 31 in plate interiors. We find that there is a remarkable contrast between the foreshock sequences of interplate compared with intraplate earthquakes. Most large earthquakes at plate interfaces in the North Pacific were preceded by accelerating seismic activity in the months to days leading up to the mainshock. In contrast, foreshocks are much less frequent in intraplate settings. We suggest that at plate boundaries, the interface between the two plates begins to slowly slip before the interface ruptures in a large earthquake. This relatively long precursory phase could help mitigate earthquake risk at plate boundaries.

Testing the accelerating moment release (AMR) hypothesis in areas of high stress

Guilhem-A, Buergmann-R, Freed-AM, Ali-ST

Several retrospective analyses have proposed that significant increases in moment release occurred prior to many large earthquakes of recent times. However, the finding of accelerating moment release (AMR) strongly depends on the choice of three parameters: (1) magnitude range, (2) area being considered surrounding the events and (3) the time period prior to the large earthquakes. Consequently, the AMR analysis has been criticized as being a posteriori data-fitting exercise with no new predictive power. As AMR has been hypothesized to relate to changes in the state of stress around the eventual epicentre, we compare here AMR results to models of stress accumulation in California. Instead of assuming a complete stress drop on all
surrounding fault segments implied by a back-slip stress lobe method, we consider that stress evolves dynamically, punctuated by the occurrence of earthquakes, and governed by the elastic and viscous properties of the lithosphere. We study the seismicity of southern California and extract events for AMR calculations following the systematic approach employed in previous studies. We present several sensitivity tests of the method, as well as grid-search analyses over the region between 1955 and 2005 using fixed magnitude range, radius of the search area and period of time. The results are compared to the occurrence of large events and to maps of Coulomb stress changes. The Coulomb stress maps are compiled using the coseismic stress from all M > 7.0 earthquakes since 1812, their subsequent post-seismic relaxation, and the interseismic strain accumulation. We find no convincing correlation of seismicity rate changes in recent decades with areas of high stress that would support the AMR hypothesis. Furthermore, this indicates limited utility for practical earthquake hazard analysis in southern California, and possibly other regions.

"keywords": ["Earthquake interaction", "forecasting, and prediction", "Seismicity and tectonics", "Fractures and faults", "Crustal structure"],
"refs": null,
"journal": "Geophysical Journal International",
"year": 2013,
"doi": "10.1093/gji/ggt298"
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"refID": "2013-1_Jiang-CS_PAGEOPH",
"title": "Intermediate-Term Medium-Range Precursory Accelerating Seismicity Prior to the 12 May 2008, Wenchuan Earthquake",
"authors": ["Jiang-CS", "Wu-ZL"],
"abstract": "In the study of the predictability of great earthquakes in the perspective of seismicity analysis, two issues are presently controversial, and need more detailed studies based on real earthquake cases. The first issue is whether there exists pre-shock accelerating behavior of seismicity which is robust against the changing of spatio-temporal ranges for the sampling of seismic events, and the second is whether such an accelerating behavior is physically associated with an approach to the critical point. To answer these two questions, a retrospective case study was conducted on the 12 May 2008, Wenchuan earthquake, using the local earthquake catalogue in Sichuan and Yunnan Provinces, China, with cutoff magnitude M L3.0, from 1977 to 2008. The results show that the answer to the first question appears to be ‘yes’; that is, in a finite spatial domain within the last couple of years before the event, clear accelerating seismicity could be observed. The answer to the second question cannot be obtained merely by examining seismicity data. However, detailed analysis of the accelerating behavior reveals a potential spatial
correlation between the accelerating region and a known asperity, which might be an evidence for that the observed acceleration may have a geometrical or mechanical rather than statistical origin.

"keywords": ["Precursory accelerating seismicity", "2008 Wenchuan earthquake", "asperity", "critical point model of earthquakes", "intermediate-term medium-range earthquake forecast"],
"refs": null,
"journal": "Pure and Applied Geophysics",
"year": 2013,
"doi": "10.1007/s00024-011-0413-0"
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"refID": "2013-1_Karakaisis-GF_JOSE",
"title": "Recent reliable observations and improved tests on synthetic catalogs with spatiotemporal clustering verify precursory decelerating–accelerating seismicity",
"authors": ["Karakaisis-GF", "Papazachos-CB", "Scordilis-EM"],
"abstract": "We examined the seismic activity which preceded six strong mainshocks that occurred in the Aegean (M = 6.4–6.9, 33–43° N, 19–28° E) and two strong mainshocks that occurred in California (M = 6.5–7.1, 32–41° N, 115–125° W) during 1995–2010. We find that each of these eight mainshocks has been preceded by a pronounced decelerating and an equally easily identifiable accelerating seismic sequence with the time to the mainshock. The two preshock sequences of each mainshock occurred in separate space, time, and magnitude windows. In all eight cases, very low decelerating seismicity, as well as very low accelerating seismicity, is observed around the actual epicenter of the ensuing mainshock. Statistical tests on the observed measures of decelerating, q d, and accelerating, q a, seismicity against similar measures calculated using synthetic catalogs with spatiotemporal clustering based on the ETAS model show that there is an almost zero probability for each one of the two preshock sequences which preceded each of the eight mainshocks to be random. These results support the notion that every strong shallow mainshock is preceded by a decelerating and an accelerating seismic sequence with predictive properties for the ensuing mainshock.",
"keywords": ["Precursory accelerating seismicity", "Precursory decelerating seismicity"],
"refs": null,
"journal": "Journal of Seismology",
"year": 2013,
"doi": "10.1007/s10950-013-9372-5"
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{
"refID": "2015-1_Bouchon-M_NatureGeo",
"title": "Reply to ‘Artificial seismic acceleration’",
"refs": null,
"journal": "Nature Geoscience",
"year": 2015,
"doi": "10.1038/ngeo1580"}
In our study, we show that most large magnitude $M \geq 6.5$ interplate earthquakes are preceded by an acceleration of seismic activity. The Correspondence from Felzer et al. questions our interpretation of this acceleration. It has long been recognized that one characteristic of seismic events is their natural tendency to cluster both in space and time, as evidenced by the presence of aftershocks following an earthquake. The debate raised by Felzer et al. is whether foreshocks result only from this tendency to cluster, that is, a first shock triggers others and eventually one of them triggers a large earthquake by something akin to a random throw. Felzer and colleagues advocate this interpretation. Alternatively, foreshocks may indicate an underlying mechanical process, such as slow fault slip, in which the foreshocks are simply the seismically visible signature — an interpretation we claim our observations favour.

From simple considerations we propose a revision of the Accelerating Moment Release (AMR) methodology for improving our knowledge of seismic sequences and then, hopefully in a close future, to reach the capability of predicting the main-shock location and occurrence with sufficient accuracy. The proposed revision is based on the introduction of a "reduced" Benioff strain for the earthquakes of the seismic sequence where, for the same magnitude and after a certain distance from the main-shock epicentre, the closer the events the more they are weighted. In addition, we retain the usual expressions proposed by the ordinary AMR method for the estimation of the corresponding main-shock magnitude, although this parameter is the weakest of the analysis. Then, we apply the revised method to four case studies in Italy, three of which are the most recent seismic sequences of the last 9 years culminating with a shallow main-shock, and one is instead a 1995–1996 swarm with no significant main-shock. The application of the R-AMR methodology provides the best results in detecting the precursory seismic acceleration, when compared with those found by ordinary AMR technique. We verify also the stability of the results in space, applying the analysis to real data with moving circles in a large area around each main-shock epicentre,
and the efficiency of the revised technique in time, comparing the results with those obtained when applying the same analysis to simulated seismic sequences."

"keywords": ["Earthquake interaction", "Forecasting and prediction", "Seismicity and tectonics", "Seismic attenuation", "Seismic sequence", "Foreshocks"],
"refs": null,
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"year": 2015,
"doi": "10.1016/j.tecto.2014.11.015"
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{ "refID": "2015-1_Felzer-KR_NatureGeo",
"title": "Artificial seismic acceleration",
"authors": ["Felzer-KR", "Page-MT", "Michael-AJ"],
"abstract": "In their 2013 Letter, Bouchon et al. claim to see a significant acceleration of seismicity before magnitude ≥6.5 mainshock earthquakes that occur in interplate regions, but not before intraplate mainshocks. They suggest that this accelerating seismicity reflects a preparatory process before large plate-boundary earthquakes. We concur that their interplate data set has significantly more foreshocks than their intraplate data set; however, we disagree that the foreshocks indicate a precursory phase that is predictive of large events in particular. Acceleration of seismicity in stacked foreshock sequences has been seen before and has been explained by the cascade model, in which earthquakes occasionally trigger aftershocks larger than themselves. In this model, the time lags between the smaller mainshocks and larger aftershocks follow the inverse power law common to all aftershock sequences, creating an apparent acceleration when stacked (see Supplementary Information).",
"keywords": null,
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"journal": "Nature Geosciences",
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{ "refID": "2016-1_Christou-EV_ResGeophys",
"title": "Time dependent seismicity along the western coast of Canada",
"authors": ["Christou-EV", "Karakaisis-GF", "Scordilis-EM"],
"abstract": "Decelerating generation of intermediate magnitude earthquakes (preshocks) in a narrow region (seismogenic region) and accelerating generation of relatively larger such earthquakes in a broader region (critical region) has been proposed as an appropriate model for intermediate-term earthquake prediction. We examined the seismic activity which preceded the Mw=7.7 (October 28, 2012) thrust event that occurred off the west coast of Haida Gwaii, Canada (formerly the
Queen Charlotte islands), by applying the decelerating-accelerating seismic strain model. We found that this mainshock was preceded by a pronounced accelerating seismic sequence with the time to the mainshock, as well as by an equally easily identifiable decelerating seismic sequence. Both precursory seismic sequences occurred in different space, time and magnitude windows. The behavior of previous mainshocks that occurred close to the 2012 earthquake was also examined by the time and magnitude predictable regional model. An attempt was also made to identify such seismic strain patterns, which may also be related to the generation of strong mainshocks along the western coast of Canada.

"keywords": ["Time dependent seismicity", "Canada", "Haida Gwaii 2012 earthquake"],
"refs": null,
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"refID": "2017-1_Adamaki-AK_PAGEOPH",
"title": "Precursory Activity Before Larger Events in Greece Revealed by Aggregated Seismicity Data",
"authors": ["Adamaki-AK", "Roberts-RG"],
"abstract": "We investigate the seismicity rate behaviour in and around Greece during 2009, seeking significant changes in rate preceding larger events. For individual larger events it is difficult to clearly distinguish precursory rate changes from other, possibly unrelated, variations in seismicity. However, when we aggregate seismicity data occurring within a radius of 10 km and in a 50-day window prior to earthquakes with, e.g. magnitude ≥3.5, the resulting aggregated time series show a clearly increasing trend starting 2–3 weeks prior to the "mainshock" time. We apply statistical tests to investigate if the observed behaviour may be simply consistent with random (poissonian) variations, or, as some earlier studies suggest, with clustering in the sense that high activity rates at some time may imply increased rates later, and thus (randomly) greater probability of larger coming events than for periods of lower seismicity. In this case, rate increases have little useful predictive power. Using data from the entire catalogue, the aggregated rate changes before larger events are clearly and strongly statistically significant and cannot be explained by such clustering. To test this we choose events at random from the catalogue as potential "mainshocks". The events preceding the randomly chosen earthquakes show less pronounced rate increases compared to the observed rate changes prior to larger events. Similar behaviour is observed in data sub-sets. However, statistical confidence decreases for geographical subsets containing few "mainshocks" as it does when data are weighted such that "mainshocks" with many preceding events are strongly downweighted relative to those with fewer. The analyses suggest
that genuine changes in aggregated rate do occur prior to larger events and that this behaviour is not due to a small number of mainshocks with many preceding events dominating the analysis. It does not automatically follow that it will be possible to routinely observe precursory changes prior to individual larger events, but there is a possibility that this may be feasible, e.g. with better data from more sensitive networks.

"Temporal seismicity patterns", "aggregated data", "precursory activity", "Greece"

"refs": null,
"journal": "Pure and Applied Geophysics",
"year": 2017,
"doi": "10.1007/s00024-017-1465-6"

"Temporal Variations of Seismic Parameters in Tehran Region"

"Earthquake precursors", "b-value variation", "accelerated moment release", "inverse TM metric"

"refs": null,
"journal": "Pure and Applied Geophysics",
"year": 2017,
"doi": "10.1007/s00024-017-1549-3"

"Slow Unlocking Processes Preceding the 2015 Mw 8.4 Illapel, Chile, Earthquake"

"refs": null,
"journal": "Pure and Applied Geophysics",
"year": 2017,
"doi": "10.1007/s00024-017-1549-3"
we employ the matched-filter technique based on an enhanced template data set of previously catalogued events. We perform a continuous search over an ~4-year period before the Illapel mainshock to recover the uncatalogued small events and repeating earthquakes. Repeating earthquakes are found both to the north and south of the mainshock rupture zone. To the south of the rupture zone, the seismicity and repeater-inferred aseismic slip progressively accelerate around the Illapel epicenter starting from ~140 days before the mainshock. This may indicate an unlocking process involving the interplay of seismic and aseismic slip. The acceleration culminates in a M 5.3 event of low-angle thrust mechanism, which occurred ~36 days before the Mw 8.4 mainshock. It is then followed by a relative quiescence in seismicity until the mainshock occurred. This quiescence might correspond to an intermediate period of stable slip before rupture initiation. In addition, to the north of the mainshock rupture area, the last aseismic-slip episode occurs within ~175–95 days before the mainshock and accumulates the largest amount of slip in the observation period. The simultaneous occurrence of aseismic-slip transients over a large area is consistent with large-scale slow unlocking processes preceding the Illapel mainshock.

Table S2.

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| 2017-1_Adamaki-AK_PAGEOPH                 | 0     |
| 2017-1_Kazemian-J_PAGEOPH                 | 0     |
| 2018-1_Huang-H_GRL                        | 0     |
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| 1990-1_Sykes-LR_Nature                    | 0     |
| 1992-1_Jaume-SC_GRL                       | 1     |
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| 1994-1_Bufe-CG_PAGEOPH                    | 1     |
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