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Historical Perspective and Critical Review of the Seismic Swarm Concept

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Abstract

Earthquake swarms are clusters of seismic events occurring in a localized area over a short time span, without a dominant mainshock. Unlike typical mainshock-aftershock sequences, seismic swarms feature earthquakes of similar magnitude and unpredictable temporal patterns. Their occurrence can be put in relation with crustal heterogeneity, fluid migration, and volcanic activity, including related geothermal processes. The concept of earthquake swarm emerged in the late 19th century, with the early key contribution from Josef Knett in Europe. In Japan, renewed interest in the mid-20th century – especially following the development of modern recording techniques and the Matsushiro swarm (1965-1967) – led to major advancements made by researchers like Kiyoo Mogi and Takeo Utsu, who contributed two complementary approaches to swarm classification: quantitative and statistical, respectively. Parallel developments occurred in the United States and Europe, gradually shaping earthquake swarms as a distinct seismological phenomenon. By providing a historical perspective on the concept of seismic swarms, this work establishes a context for our future research, which will focus on the application of statistical models, such as the Epidemic Type Aftershock Sequence (ETAS) model.

Keywords: Earthquake swarms; Mainshock-aftershock sequences; Statistical seismology; Historical perspective; ETAS model

1. Introduction

Earthquake swarms are known as sequences of seismic events occurring in a localized area over a limited period, without a clearly dominant mainshock (e.g., Hainzl, 2002; Horálek et al., 2015; Yellowstone Volcano Observatory, 2019, and references therein).

Unlike the more familiar mainshock-aftershock patterns, which center around a large earthquake – possibly preceded by foreshocks – followed by minor seismic activity, swarms consist of multiple earthquakes of similar magnitude and often lack a discernible temporal hierarchy. This distinction has important implications for both scientific understanding and risk communication, as swarms occur in tectonically active areas, but also in anthropogenically influenced settings, such as during forced fluid injection for the exploitation of petroleum and geothermal resources (e.g., Deichman and Giardini, 2009; Majer et al., 2012; Ellsworth, 2013; Kim, 2013;

Keranen et al., 2014; Zbinden et al., 2020; Zhou et al., 2024). Swarms may pose challenges for forecasting and hazard assessment due to their unpredictable duration and potential evolution into stronger events, still lacking clearly identifiable mainshocks. As such, the study of swarms occupies a unique and necessary space at the intersection of seismology and public safety.

Earthquake swarms have attracted interest since the late 19th century. Early macroseismic observations of earthquakes were reported in Europe by Knett (1899) who laid the groundwork for distinguishing these atypical seismic patterns. After a gap of about half a century, improvements in seismographic technology and data analysis contributed to a more nuanced understanding of swarm phenomena (e.g., Mogi, 1963; Yamakawa, 1966; Utsu, 1969).

Earthquake swarms have been modeled as a result of crustal stress heterogeneity and fluid migration in the Earth's lithosphere, observed in volcanic and geothermal regions (e.g., Kárník, 1963; Mogi, 1963; Yoshihoka et al., 1970; Geissler, 2005; Fischer et al., 2014). This article traces the historical trajectory of the earthquake swarm concept – from its earliest formulations to the refined interpretations emerging by the early 2000s – highlighting the frequent misuse of the term "swarm" in both scientific and public discourse and advocating for its consistent and accurate use in seismology.

Our attempt to frame the evolution and meaning of the term *seismic swarm*, including its use in the scientific community and civil society, is necessarily limited to the review of the main works, which serve as primary bibliographic references for our community.

2. Earliest Observations and Terminology (late 19th Century – early 20th Century)

In 1899, Josef Knett published a pioneering German-language work in which the term "earthquake swarm" (*Erdbebenschwarm*) was introduced for the first time. The author describes two sequences of earthquakes that occurred in the 19th century in the Erzgebirge Mountain range, part of the Bohemian historical region then known as Egerland.

Knett (1899) reports that the oldest event, which occurred in 1824, had already been studied by Stanislav Hallaschka (1824) and Karl von Hoff (1824, 1825). Based on the information collected by those authors, he provides a detailed day-by-day chronology of the earthquakes from January 1 to February 5, 1824. The records include origin times, affected locations, and perceived intensities. Some earthquakes were strong enough to dislodge lime from ceilings, force miners to evacuate tunnels, and produce underground noises like thunder. The author estimated a seismic impact of the strongest shocks that today would be classified as the VI-degree intensity on the Mercalli scale, not yet formulated at the time: Knett referred to the earthquake as "starke" (strong) and "sehr starke" (very strong). The affected area included the towns of Hartenberg, Prünles, Graslitz, Eger (now known by its Czech name, Cheb), Wunsiedel, and surrounding villages. The zone of maximum intensity was an ellipse of approximately 12 × 17 km, centered on Hartenberg and Prünles. The author describes several remarkable effects of the seismic activity, including springs that had suddenly dried up and then resumed their flow, and the Zwodau River breaking through the ice despite very low temperatures. As a folkloric note, he reports that the population organized religious processions to seek protection.

Knett (1899) compares the swarm that occurred in 1824 with the one in 1897, noting great similarities in duration (36-37 days), temporal distribution, and the pattern of shocks. With a modern scientific view, he hypothesizes that the phenomenon was linked to faults transverse to the Eger Graben. Finally, he argues that the Erzgebirge swarms represent a "characteristic seismic type" of the region, with phases of calm, resumption, and major shocks. He also emphasizes the importance of communicating accurate information to the population to reduce panic during such events.

Around the turn of the 20th century, Omori (1894, 1910) and Inamura (1913, 1915) conducted important studies of Japanese earthquake sequences involving foreshocks and aftershocks. Subsequently, Kishita (1938) and Ishimoto and Iida (1939) published their studies on the observation and analysis of seismic sequences in Japan. In particular, the latter study includes a statistical assessment of earthquake size distribution, conceptually consistent with the later and better-known Gutenberg-Richter (G-R) law (Gutenberg and Richter, 1944). Additionally, Matsuzawa (1939) reported on the spatial patterns of seismic sequences occurring in the United States, namely the 1932 sequence in Nevada and the 1934 sequence near Parkfield, in California. Although these studies did not specifically address earthquake swarms, they provided the scientific foundation for the further development of the swarm concept, which began five decades after the pioneering work of Knett (1899).

3. The Seismic Swarm Concept in Japan

In the 1950s, the advancement of recording devices of high sensitivity allowed the collection of low-magnitude seismic data which contributed to renewed interest in swarm phenomena. It is in this context that a report titled "On the Earthquake Swarm near Niijima Island" was published by the Seismological Section of the Japan Meteorological Agency and the Niijima Weather Station (1958). In the following years, several studies on seismic swarms, regarded as a distinct type of earthquake cluster, especially in volcanic areas, were published in Japanese journals (e.g., Yukutake and Tanaoka, 1960; Minakami, 1962; Hagiwara et al., 1963). Among the Japanese papers, we highlight with particular interest those of Mogi (1963) and Utsu (1969, 1970).

Mogi (1963) conducted comprehensive studies of earthquake sequences in Japan, helping to establish the term "earthquake swarm" in global seismological literature. Assuming that the concepts of foreshocks, mainshocks and aftershocks had already been sufficiently consolidated in seismology, even if lacking a rigorous definition, Mogi (1963) classified earthquake sequences in three types:

1) sequences with mainshock and aftershocks
2) sequences with foreshocks, mainshock, and aftershocks
3) earthquake swarms.

Mogi (1963) analyzed approximately 1,500 earthquakes from the *Catalog of Major Earthquakes* (Japan Meteorological Agency, 1958), selecting as principal events those with a minimum magnitude of 4.0 for inland earthquakes and 4.5 for offshore earthquakes, provided that "*they were not foreshocks or aftershocks of another larger earthquakes, or members of earthquake swarms*". Given that, at the time, the average spacing between seismic stations in Japan was about 80 km, Mogi considered foreshocks and aftershocks only earthquakes with magnitudes larger than 3.0.

Regarding the third type of earthquake pattern, i.e., earthquake swarms, Mogi (1963), in addition to the implicit assumption that a "principal earthquake" is not identified, introduced a supplementary quantitative selection based on two conditions:

(i) the total number of earthquakes in a sequence exceeds 10
(ii) $n_m/\sqrt{t} > 2$

where n_m is the maximum daily number of earthquakes and t is the duration, in days, of the earthquakes sequence.

Mogi (1963) correlated the three main earthquake patterns with the material structure and the distribution of external stress (Fig. 1a), providing examples of the three types of earthquake sequences observed in Japan (Fig. 1b).

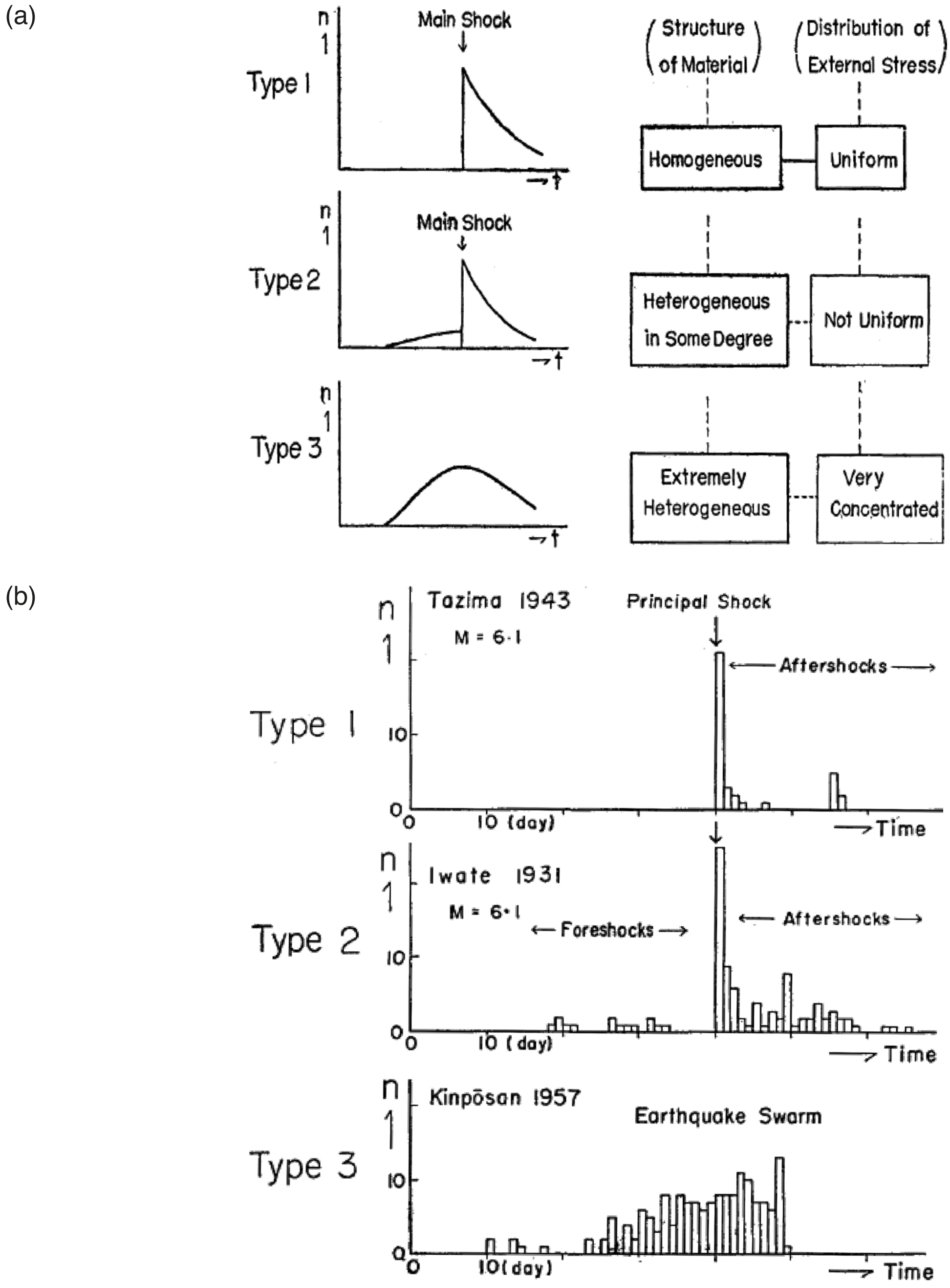
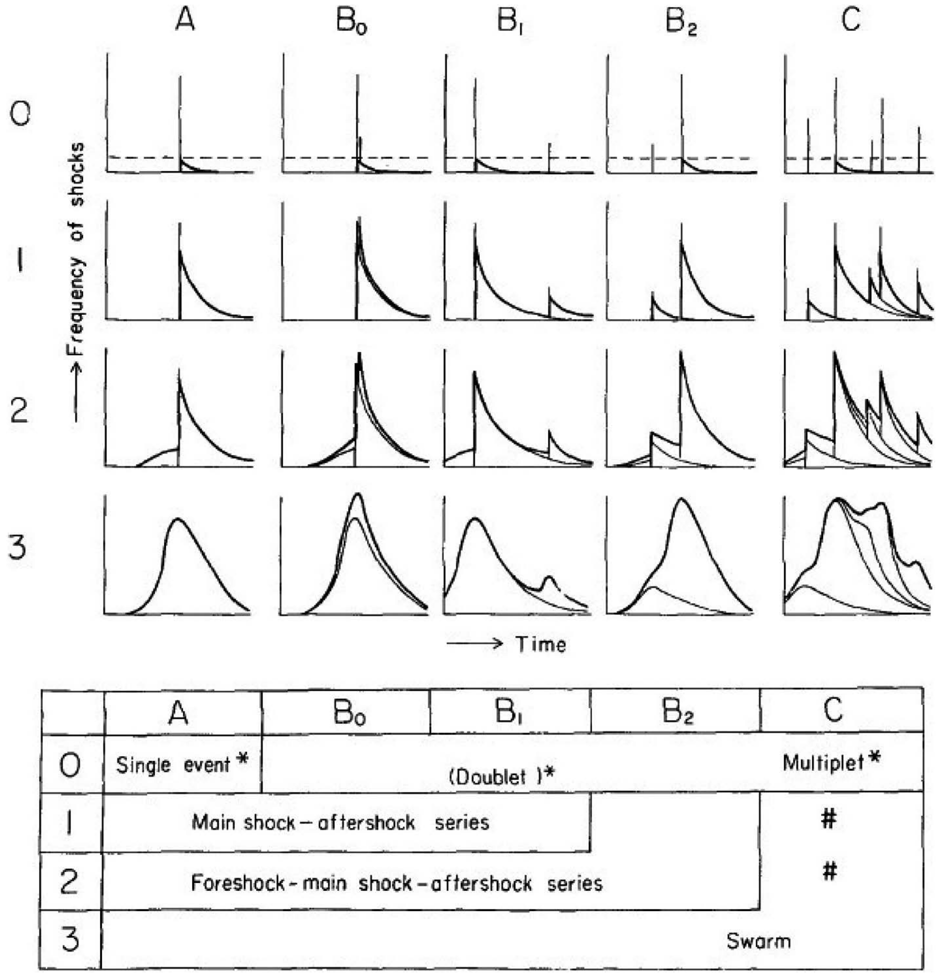


Figure 1. (a) Diagram illustrating the three types of earthquake sequences classified by Mogi (1963) in relation to material structure and external stress distribution; (b) examples of the three sequences observed in Japan (arrow indicates the occurrence of a principal earthquake).

An ideal natural laboratory for studying earthquake swarm behavior was the Matsushiro area in central Japan, which has historically experienced frequent low- to moderate-magnitude earthquakes. The Matsushiro swarm occurred from 1965 to 1967 with more than one million recorded earthquakes, attracting the attention of numerous researchers (Yamakawa, 1966; Ichikawa, 1967; Japan Meteorological Agency, 1968; Yamakawa, 1968; Kasahara, 1969; Yoshihoka et al., 1970). In parallel, observations of other earthquake swarms as a distinct type of seismic sequence were reported by Sasaki and Motoya (1964), Kishimoto and Hashizume (1966), and Nishi (1968).

Utsu (1969, 1970) expanded Mogi's (1963) simple three-type sequence classification by proposing a more detailed, though still qualitative, system that included twenty distinct earthquake patterns (Fig. 2). With this work, Utsu pioneered an approach beyond the rigid distinction of "foreshock", "mainshock", and "aftershock", terms that are still widely used today despite the lack of universally accepted definitions.



	A	B_0	B_1	B_2	C
0	Single event *	(Doublet)*			Multiplet *
1	Main shock – aftershock series				#
2	Foreshock - main shock - aftershock series				#
3	Swarm				

Figure 2. Earthquake sequences classified by Utsu (1970). Curves show earthquake frequency versus time. The length of the vertical bars represents the size of the mainshocks; they are absent in swarms (row 3). With respect to A, columns B and C correspond to sequences with more than one mainshock (doublet and multiplet, respectively). In the lower panel, * marks cases where only events above the detection threshold (dashed line in row 0) are observed; # marks cases in which, according to the author, “if the mainshock has exceedingly large magnitude, the sequence is no more called a swarm”.

In the diagram of Fig. 2, Utsu classifies sequences into columns A, B, and C according to the number of mainshocks, ranging from one to at least three. Subgroups B_0, B_1 and B_2 represent cases in which the two mainshocks are “close” in time (B_0) or not, with the first mainshock having either larger (B_1) or smaller (B_2) magnitude. Rows 0 to 2 indicate sequences with progressively greater numbers of secondary events, i.e., foreshocks and aftershocks, while row 3 illustrates cases where the mainshocks are not sufficiently dominant to be distinguished from secondary events, as occurs in seismic swarms. Utsu’s diagrams, lacking both a time scale and magnitude information, do not provide quantitative criteria for differentiating among the various sequence types presented in Fig. 2; his classification is, therefore, overall qualitative.

It is noteworthy that Utsu (1970) does not assign a specific label to sequences containing more than two large mainshocks (and their aftershocks), i.e., panels C1 and C2, marked with the symbol #, suggesting the existence of a progressive – and subjective – transition between the concept of a “swarm” (C3) and that of a “multiplet” (C0). A sharp distinction between “swarm” and “multiplet” is provided by the definition of a swarm given by Evison and Rhoades (1993), who used it to test the hypothesis that swarms are long-term precursors of major earthquakes. As for C1 and C2, Utsu specifies that “if one of the mainshocks has an exceedingly large magnitude, the sequence is no longer termed a swarm”. Consequently, we argue that the subjective, and possibly ambiguous, distinction between types C1, C2, and C3 calls for a broader interpretation of earthquake sequences, viewing them as a self-organized critical process (e.g., Hainzl, 2002).

4. Parallel Developments in the United States and Europe

In the United States, Gutenberg and Richter (1944) developed methods to classify earthquake sequences based on an empirical relationship, which shows that earthquake frequency decreases exponentially with increasing magnitude, although they noted some limitations in its application. It is remarkable that Gutenberg and Richter (1944), describing the seismicity of California, did not explicitly distinguish between mainshock-aftershock sequences and swarms, defining a swarm as "small earthquakes that always occur as aftershocks following a major event". Even in their later, widely known book *The Seismicity of the Earth and Related Phenomena* (Gutenberg and Richter, 1954), they classify seismic events exclusively by hypocentral depth. In their book, the term "swarm" appears only once, on page 80, in reference to the September 1929 seismic activity in Hawaii.

It is significant that Gutenberg and Richter, the most renowned U.S. seismologists of the mid-20th century, paid little attention to the classification of seismic swarms as a separate type of seismic sequence. In those same years, Pierre Saint-Amand, the U.S. geologist who identified and named Alaska's most famous Denali fault, published a paper titled "*The Central Alaska earthquake swarm of October 1947*" (St. Amand, 1948). Similarly to Gutenberg and Richter (1944), St. Amand also applied the term "swarm" to a sequence of foreshocks, mainshock and aftershocks.

Other researchers in Europe and the United States began reporting observations of seismic swarms, which gradually came to be recognized as a distinct seismic phenomenon deserving specialized study and classification (e.g., Kárník, 1963; Smith et al., 1968; Sykes, 1970; Hill, 1977; Kárník et al., 1987; Hainzl, 2002; Geissler, 2005).

In parallel, technological advances contributed to theoretical debates on the mechanisms driving earthquake swarms, the validity of which we do not address in this study.

Without explicitly referring to swarms, Console et al. (1993) attempted a quantitative classification of the seismicity that would fall into Utsu types 0 to 2. Their study showed that various regions of Italy exhibit distinct types of seismicity. For example, northern Italy, including the Po Plain, typically exhibits seismic sequences with one or two mainshocks and a low number of aftershocks, while the Apennines – especially in central Italy – are characterized by long-lasting sequences with foreshocks and many aftershocks.

5. Discussion

In our work, we observed that the term "swarm" has long appeared in seismological literature without a uniform and objective definition. Furthermore, the term has not always referred to a series of multiple earthquakes lacking a clearly identifiable mainshock, as it is most understood today.

In a study of swarms as long-term precursors of mainshock events in New Zealand, Evison and Rhoades (1993) defined a "multiple event" as a group of at least four earthquakes of magnitude M or greater, including at least three within 1.0 days, with the duration of a multiple event extending forward and backward until a vacant period of at least 50.0 days was reached. They provided magnitude and area criteria to classify each multiple event as either a swarm, a multiplet, or a mainshock event. For mainshock events: $M \geq 3.6$, $M_1\text{-}M_3 \geq 0.9$, or $M_1\text{-}M_3 = 0.8$ and $M_1\text{-}M_4 \geq 1.0$; for swarms and multiplets: $M \geq 3.3$, $M_1\text{-}M_3 \leq 0.7$, or $M_1\text{-}M_3 = 0.8$ and $M_1\text{-}M_4 \leq 0.9$, where M is the magnitude of any earthquake, M_1 is the largest, M_2 the second largest, and so on. For swarms, $A \geq A(M_P)$; for multiplets, $A < A(M_P)$, where A (km^2) is the area of the smallest convex polygon circumscribing the epicentres, and $\log10(M_P) = 0.5\, M_P + 0.4$, where $M_P = (M_1 + M_2 + M_3)/3$. Applying these criteria, Evison and Rhoades (1993) identified 70 multiple events in the New Zealand earthquake catalogue from 1962-1990, including 11 mainshock events, 24 swarms, and 35 multiplets. A similar classification exercise had previously been carried out by Evison (1981, 1982) for the Japan earthquake catalogue in order to test the precursory swarm hypothesis in Japan.

A widely held – yet unproven – assumption is the unquestioned validity of the Gutenberg-Richter (1944) frequency-magnitude distribution, which fits a straight line to the logarithm of the cumulative number of earthquakes versus their magnitude. This belief is so firmly established that deviations from the G-R law are frequently attributed – even by specialists in statistical seismology – to observational errors rather than to the genuine behavior of seismicity.

In addition to the G-R law, seismologists recognize Bath's law (Bath, 1965), which states that the mainshock magnitude is, on average, about 1.2 units larger than that of the largest aftershock. Given that the G-R law predicts a difference of roughly 0.4 units between the two strongest events in a random sample, Utsu (1969) interpreted this discrepancy as evidence that mainshocks belong to a separate class of events. Accordingly, in the context of seismic swarms, the magnitude of swarms and multiplets – whose largest events differ by only a few tenths of a magnitude unit – cannot be considered to follow Bath's law.

Vere-Jones (1969) offered a simpler alternative explanation to the apparent discrepancy between the Bath's and G-R laws: he argued that a correct statistical analysis of the observations suggests that earthquake magnitude within a mainshock-aftershock sequence do not substantially deviate from the exponential distribution predicted by the Gutenberg-Richter law. This idea was later confirmed by Console et al. (2003b), Helmstetter and Sornette (2003), and Lombardi (2009), who demonstrated that the apparent 1.2-unit magnitude difference primarily reflects subjective and different choices of magnitude threshold for selecting mainshocks and aftershocks (e.g., M7+ for mainshocks, M5+ for aftershocks)[1].

The ambiguity associated with strict classification schemes for earthquake sequences can be addressed using a more general statistical approach, such as the Epidemic-Type Aftershock Sequence (ETAS) model (e.g., Ogata, 1998; Console and Murru, 2001; Console et al., 2003a), with an appropriate choice of free parameters. Unlike traditional schemes, the ETAS model does not require classification of individual earthquakes. Instead, it is simply based on the assumption that each earthquake has a probability of generating subsequent events. This probability is modeled, for the offspring of each parent event, by assuming the validity of the G-R magnitude distribution, an inverse power-law for the temporal distribution, and a spatial distribution consistent with elastic stress transfer. This model can be applied in real time to a modern seismic observation system equipped with a telemetered network and electronic processing capabilities.

Continuing our investigation into the statistical modeling of seismicity, we have developed and are currently testing a novel code. This code generates synthetic seismic sequences based on the ETAS model, incorporating a complete randomness in the magnitude of each event, constrained only by minimum and maximum limits set by the user. A key feature of this development is the absence of any subjective constraints on the type of sequence generated. The aim is to demonstrate that a uniform random magnitude model can produce diverse seismic sequences, including swarms. For purely demonstrative and heuristic purposes, we are exploring methods – including the application of artificial intelligence techniques – to associate each simulated sequence with one of the 20 Utsu types. This same procedure could be readily applied to real-world seismic catalogs.

6. Conclusions

From its initial formulation in the late 19th century to its current understanding and use, the concept of earthquake swarm has not really evolved, continuing to describe a distinct class of seismicity compared to mainshock-aftershock sequences. Early descriptive efforts by Knett (1899) prepared the ground for subsequent advances, particularly in Japan, where enhanced monitoring tools and statistical approaches have facilitated a more thorough comprehension of earthquake swarm behavior. The classification schemes introduced by Mogi (1963) and Utsu (1969) remain foundational, offering frameworks that continue to guide both theoretical models and practical applications.

At the same time, the increasing recognition of swarms in tectonically active areas and in anthropogenically influenced environments has expanded their relevance for hazard assessment and public communication.

Our review emphasizes that a quantitative and universally accepted definition of "swarm" has not yet been agreed upon within the seismological community. Furthermore, traditional seismology often assigns rigid labels – foreshock, mainshock, aftershock, seismic swarm – to seismic events. This long-standing practice imposes constraints that limit a more flexible, general understanding of observed seismicity. Modeling earthquake sequences as self-organized critical processes, such as within the framework of the ETAS model, highlights the inherent complexity and variability of seismic processes, not excluding seismic swarms.

While achieving a seismic swarm perspective free from qualitative or arbitrary definitions is possible, a quantitative definition remains necessary to bridge conceptual gaps inherited from traditional seismology. However, it is crucial to recognize that any such quantitative definition will inherently incorporate some subjective criteria and parameters.

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[1] The significance of threshold selection, on which Bath's law ultimately rests, can be clarified with a simple analogy. Imagine estimating the average difference between the tallest individual and the second tallest in a residential building. If the buildings are chosen at random, the result will be a few centimeters. But if we only examine buildings where a professional basketball player – at least two meters tall – resides, the average gap will be artificially inflated. In our view, this is the kind of bias Utsu (1969) assumed to exist between mainshocks and aftershocks: they are drawn from two inherently different populations of events.

Note of the authors. Italy has recently experienced several earthquake sequences, including the damaging events at Nocera Umbra-Colfiorito (1997), L'Aquila (2009), Reggio-Emilia (2012), and Amatrice-Norcia (2016). At the time of preparing this manuscript, the geothermal area of Pozzuoli, in Naples, is experiencing moderate seismic activity in the form of a long-lasting seismic swarm raising serious concerns among authorities and the local population. Despite efforts to define and apply the concept of an earthquake swarm, in Italy this term — "sciame" – is often used by mass media, favoring conventional or sensational terminology over scientific accuracy, and sometimes even by scientific and governmental organizations to refer to some earthquake clusters. In our view, many of these short-lived episodes, lasting only a few days, if containing an identifiable principal event, would be more accurately regarded as mainshock-aftershock sequences.

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