GEOLOGY

Tsunamis in the geological record: Making waves with a cautionary tale from the Mediterranean

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From 2000 to 2015, tsunamis and storms killed more than 430,000 people worldwide and affected a further >530 million, with total damages exceeding US$970 billion. These alarming trends, underscored by the tragic events of the 2004 Indian Ocean catastrophe, have fueled increased worldwide demands for assessments of past, present, and future coastal risks. Nonetheless, despite its importance for hazard mitigation, discriminating between storm and tsunami deposits in the geological record is one of the most challenging and hotly contended topics in coastal geoscience. To probe this knowledge gap, we present a 4500-year reconstruction of "tsunami" variability from the Mediterranean based on stratigraphic but not historical archives and assess it in relation to climate records and reconstructions of storminess. We elucidate evidence for previously unrecognized "tsunami megacycles" with three peaks centered on the Little Ice Age, 1600, and 3100 cal. yr B.P. (calibrated years before present). These ~1500-year cycles, strongly correlated with climate deterioration in the Mediterranean/North Atlantic, challenge up to 90% of the original tsunami attributions and suggest, by contrast, that most events are better ascribed to periods of heightened storminess. This timely and provocative finding is crucial in providing appropriately tailored assessments of coastal hazard risk in the Mediterranean and beyond.

INTRODUCTION

Storms and tsunamis are key, and often devastating, motors of coastal change over large regions of the globe (*1*–*5*). In the present context of global change and sea-level rise (*6*), the threat of these natural hazards sits uneasily with seaboard megacities (*7*) and high coastal population densities, particularly in developing countries (*8*, *9*). Demographic projections suggest that almost 1 billion people will live in low-elevation coastal areas by 2030 (*8*). To aid planners and policy makers in formulating appropriate adaptive strategies and successfully mitigating against future disasters, it is therefore critical to improve the understanding of past littoral hazards, including their driving mechanisms, magnitudes, and frequencies (*10*). Nonetheless, unequivocally differentiating between storm and tsunami deposits in the geological record is a controversial and strongly debated topic (*11*–*15*). Since the early 2000s, in particular, there has been an exponential growth in tsunami science, triggered notably by the tragic events of the 2004 Indian Ocean catastrophe, in which >225,000 people lost their lives (*1*), spawning a rapid demand for assessments of tsunami risk worldwide.

The "storm versus tsunami" debate is particularly strong in the Mediterranean, an area that is prone to both multisite seismic activity (*16*–*18*) and storm events (*19*–*21*). At present, around 130 million people live along the Mediterranean seaboard (*22*). It is also the world's top tourist destination, with more than 230 million international visitors a year (*23*). The Mediterranean accommodates several significant waterfront cities including Istanbul (a megacity of >14 million people), Barcelona (>5.3 million), Alexandria (>4.8 million), Tel Aviv (>3.6 million), Izmir (>3 million), Algiers (>2.6 million), and Naples [>2.1 million; (*24*)]. Many of these cities have been important urban centers for thousands of years, and bygone natural disasters related to storms and tsunamis are well documented by historical records (*25*–*35*).

Since ~2000, much of the Mediterranean literature has focused on Holocene records of tsunami risk, whereas archives of storm events have been relegated to a secondary position (*36*). It is unclear whether this reflects the reality of the Mediterranean's geological record or, by contrast, the rise of a wider neocatastrophist paradigm that has polarized research efforts toward tsunami investigations in the wake of globally mediatized disasters such as Sumatra and Fukushima (*37*).

To put this in perspective, we analyzed "tsunami" and "storm" data contained in the EM-DAT (Emergency Events Database) database, an international data repository of disasters, for the period 1900–2015 (Fig. 1). Worldwide, during this time, a total of 59 tsunami events and 3050 storm events were recorded (*1*). Overall, and in contrast to the present media-driven "discourses of fear" (*36*), the data demonstrate that storms are more than eight times deadlier and more costly than tsunamis. For instance, between 1900 and 2015, storms accounted for 84% of total "tsunami + storm" deaths (n = 1,632,020) and 81% of total tsunami + storm costs (n = US$1,206,648,076). Furthermore, we elucidated an interesting cyclicity in the storm time series (Fig. 2), which is not mirrored in the tsunami data. These trends in storminess mesh tightly with well-known climate pacemakers (for example, the 11-year solar cycle), a finding that provides further context for the storm versus tsunami debate, particularly in the light of the present human-induced global change.

Here, we propose a novel meta-analysis of Mediterranean tsunami events in the geological record for the past 4500 years, which is compared and contrasted with detailed records of storminess (*19*, *21*). This analysis was designed to compare statistical patterns of high-energy events interpreted from the sedimentary, not historical, record using a consistent methodology. The Mediterranean constitutes a textbook study example because natural archives for high-energy coastal events are particularly prevalent along its seaboard (*38*). For instance, lagoon sequences are common in clastic systems, whereas boulder records are frequently used on rocky coasts.

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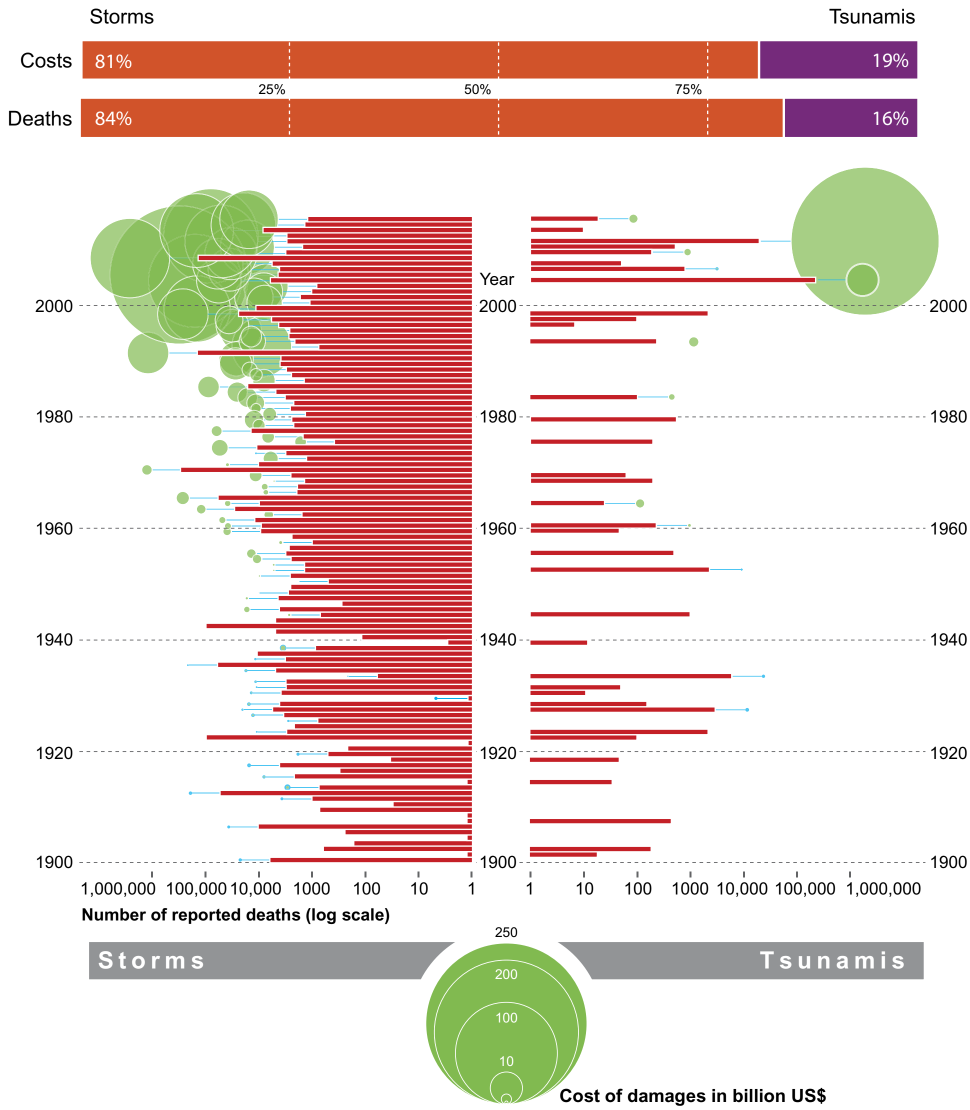

Fig. 1. Costs and deaths associated with storms (left) and tsunamis (right) between 1900 and 2015, based on the EM-DAT disaster database. The data demonstrate that tsunamis are rare and unpredictable natural hazards but that, cumulatively, storms are deadlier and more costly. The threat of storms and tsunami hazards has been aggravated by global change and sea-level rise, particularly in densely populated coastal areas, which presently account for ~40% of the world's population (*8*). In particular, low-lying coastal areas are experiencing rapid and disproportionate demographic growth in comparison to the global average, driven notably by the importance of their natural resources and ocean-related recreation.

In stratigraphic terms, storms and tsunamis constitute "event deposits," namely, episodic facies of short duration resulting from abnormal high-energy processes. There is no formal or precise definition of "event," and unequivocally differentiating between storm and tsunami deposits in the geological record is challenging. Recent research has focused on comparing historical examples of storm and tsunami deposits [for example, see the studies of Goff *et al.* (*39*) and Tuttle *et al.* (*40*)]. Onshore, storms tend to generate wedgelike units dominated by bed load, whereas tsunamis generally produce sheetlike deposits characterized by suspended load. However, the nature of any storm or tsunami deposit is strongly governed by sediment availability and, as such, could be composed entirely of silt or boulders. An important difference between these two depositional processes is wave periodicity: Tsunamis are composed of long period waves and storms are characterized by short period waves. This invariably leads to tsunami deposits extending farther inland than their storm counterparts (*12*, *41*), thus making a study of their lateral continuity a key research criterion. Therefore, differentiating between the two origins in core sequences, which has been a preferred tool for Mediterranean paleotsunami reconstructions, is extremely difficult, particularly in contexts very close to the shoreline that are equally vulnerable to both types of hazard. Some authors have used micropaleontological proxies to help distinguish deposits of storms from tsunamis (*42*). However, on the basis of a foraminifera-based study in Portugal, Kortekaas and Dawson (*43*) found only very subtle differences between historical storm and tsunami facies and concluded that multiproxy lines of investigation were imperative. It is now widely recognized that any realistic attempt to differentiate between storm and tsunami deposits must use a multiproxy approach

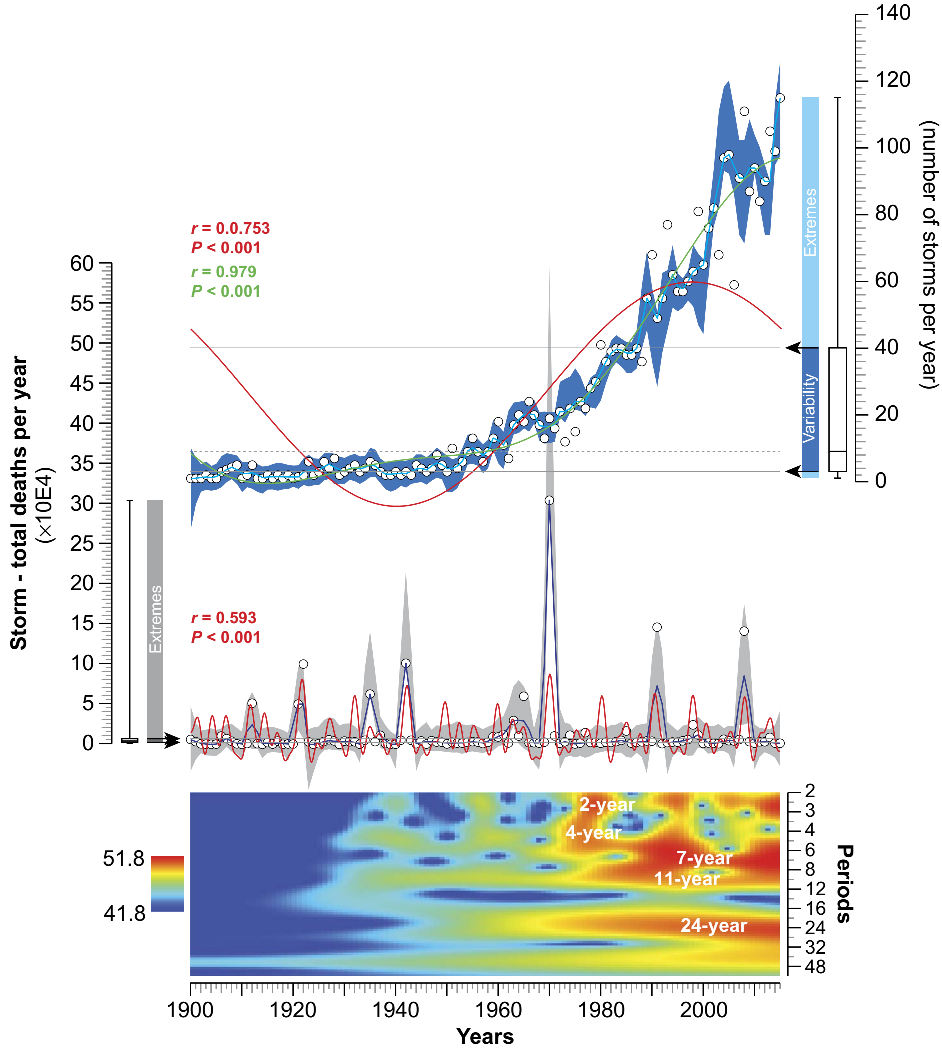

Fig. 2. Occurrence of storm events and related mortality for the period 1900–2015. The data were analyzed using a Loess smoothing (with bootstrap and smoothing of 0.05) and a sinusoidal regression model (phase Free) to detect the periodicity associated with the extreme events. The algorithm used in the model is a "LOWESS" (locally weighted scatterplot smoothing), with a bootstrap that estimates a 95% confidence band (based on 999 random replicates). The sinusoidal regression was used to model periodicities in the time series generated by the Loess smoothing. The "total deaths per year" signal was further investigated using a wavelet transform with Morlet as the basis function. The scalograms are shown as periods on a linear age scale.

including geological, biological, geochemical, geomorphological, archaeological, anthropological, and contextual proxies, where possible (*13*). In essence, the more proxies used, the easier it is to determine the source mechanism. At present, one of the most controversial fields of tsunami geology is the interpretation of coarse-grained deposits, particularly boulders, transported by either storms or tsunamis. Boulders have been widely used to infer tsunami deposition in Mediterranean studies (see references in the database), although, by contrast, based on a study of "megaclast" accumulations produced by large storm surges on the Atlantic coast of Ireland, Williams and Hall (*44*) have cautioned against these systematic tsunami attributions. In addition, geomorphological features such as washover fans, lobes, chevrons, or ridges have also been used as evidence for tsunamis, despite sparse modern analogs and a lack of corroborating proxies, and despite the fact that storm flooding can also generate these deposits. Another controversial hypothesis in Mediterranean tsunami science is that of "homogenites" as evidence for deep-sea tsunamis (*45*–*47*). These wide-ranging examples underscore the challenges of interpreting the stratigraphic record of high-energy coastal events and demonstrate that careful and detailed multiproxy analyses are important to effectively differentiate between geological archives of storms and tsunamis. Furthermore, two potential caveats relating to the preservation potential of these deposits are that (i) not all high-energy events are large enough to cause severe flooding and leave deposits in the geological record and (ii) later events, or even normal on-site conditions, could potentially erode evidence of previous episodes. Although difficult to quantify, we therefore stress that the stratigraphic record of these high-energy events is probably incomplete and underestimates the actual number.

In summary, probing the stratigraphic dimensions of the storm versus tsunami question is paramount to (i) furnishing more accurate quantitative and probabilistic predictions of tsunami and storm risks and (ii) providing robust, cost-effective, and better-adapted assessments of present and future hazards in coastal areas in both the Mediterranean and further afield.

RESULTS AND DISCUSSION

The geological tsunami time series comprises 135 events from 54 Holocene records across the Mediterranean (Fig. 3 and tables S1 to S3). Geological events were dated using either radiocarbon, optically stimulated luminescence (OSL), archaeological, or composite chronologies (see the individual references for details on the dating methods used to constrain particular sedimentary events). Ages of tsunami data range from 4450 cal. yr B.P. (calibrated years before present) to the present day and span eight countries: Algeria ($n = 1$), Cyprus ($n = 1$), Egypt ($n = 2$), Greece ($n = 26$), Israel ($n = 4$), Italy ($n = 15$), Lebanon ($n = 1$), Spain ($n = 3$), and Turkey ($n = 1$). The cumulative number of tsunami events was summed to generate a continuous time series for the Mediterranean region. This method is particularly useful for detecting multicentennial/millennial-scale changes in event frequency. Furthermore, it overcomes problems associated with individual stratigraphic records that can often be fragmentary and affected by local environmental bias. It is stressed that this geological time series does not include (i) Holocene records interpreted as storms and (ii) written historical records of tsunami events (see the Supplementary Materials).

Figure 4 shows the data for tsunami events in the Mediterranean. Collectively, this record constitutes the first geological tsunami chronology with decadal-scale resolution in the Mediterranean. Event numbers range from 2 to 28 at 25-year sampling intervals. Overall, the histogram gives a clear picture of how these Mediterranean coastal hazards have varied during the mid- to late Holocene. Before 2000 cal. yr B.P., tsunami events varied between 2 and 11, whereas after 2000 cal. yr B.P., these figures increased to 8 and 28. The changes are particularly pronounced for the last 2000 years, a factor that we attribute to the better archiving of the more recent events in the geological record.

Cluster analyses differentiate three previously undocumented tsunami peak-and-trough couplets between 4500 cal. yr B.P. and present, with roughly 1500-year (±100 years) spacing between peaks (Figs. 5 and 6). This 1500-year periodicity is statistically supported by REDFIT spectral and wavelet analyses of the data set, which also highlight further periodicities of 740 and 450 years (fig. S1). Tsunami event peaks are centered on 200 cal. yr B.P. (20 events), 1600 cal. yr B.P. (26 events), and 3100 cal. yr B.P. (11 events).

It is striking that the main phases of increased tsunami events in the Mediterranean fit tightly with periods of mid- and late Holocene cooling in the Northern Hemisphere (*48*–*50*). Specifically, our data follow the trajectory of North Atlantic climate cycles, with periods of heightened and prolonged tsunami activity corresponding to increased drift-ice transport in addition to windier and stormier conditions in the North Atlantic (*51*), eastern North America (*52*), and northwestern (NW) Europe (*49*). Furthermore, the deteriorating climate regime may have been amplified by reduced North Atlantic Deep Water formation that was concurrent with several of these cooling events (*53*). Significantly, we find that 90% ($n = 123$) of the sedimentary events interpreted as tsunamis share chronological intercepts with periods of heightened storm activity in the Mediterranean (Fig. 4). There is also significant overlap with periods of storm activity in NW Europe (*49*). These patterns lead us to suggest that most of the geological events previously interpreted as tsunamis could instead be attributed to periods of more intense storm activity. Because chronological overlap is not an unequivocal argument to exclude tsunami origins, we further tested this hypothesis by investigating periodicities in the historical tsunami data (figs. S2 and S3) (*35*). In contrast to the stratigraphic tsunami data, the spectral, REDFIT, and wavelet analyses of the historical data present no statistically significant cycles. One further possibility when assessing these data is that climate cooling favored the generation of meteotsunamis (oceanic waves with tsunami-like characteristics but are meteorological in origin), which are known to occur in the Mediterranean [for example, see previous studies (*54*–*57*)]. Although this is challenging to test based on the available chronostratigraphic data, it is important to note that meteotsunamis are much less energetic than their seismic counterparts. Meteotsunamis are therefore always local, whereas seismic tsunamis can have basin-wide effects. A large meteotsunami, or one that would have the potential to leave a sedimentary record, is the result of a combination of several

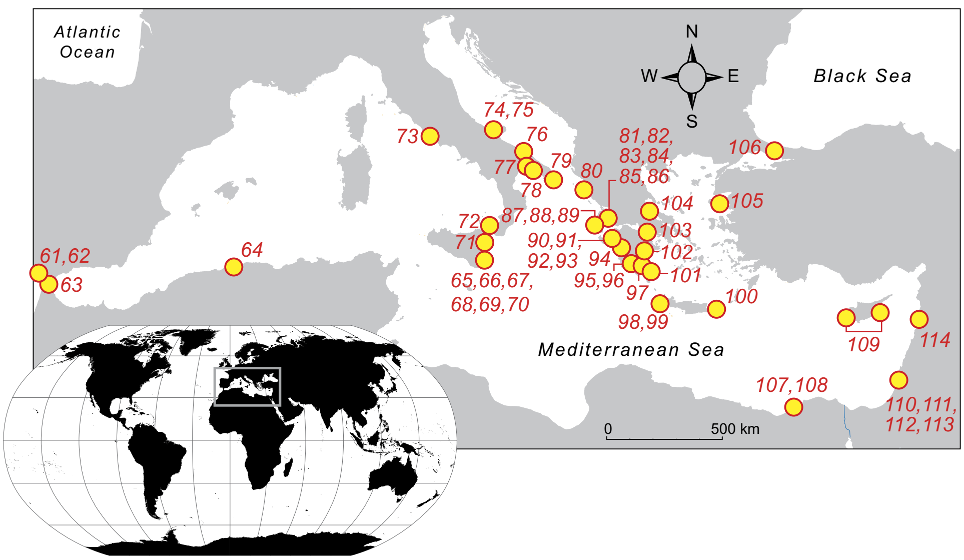

Fig. 3. Location of sites and references used in this study.

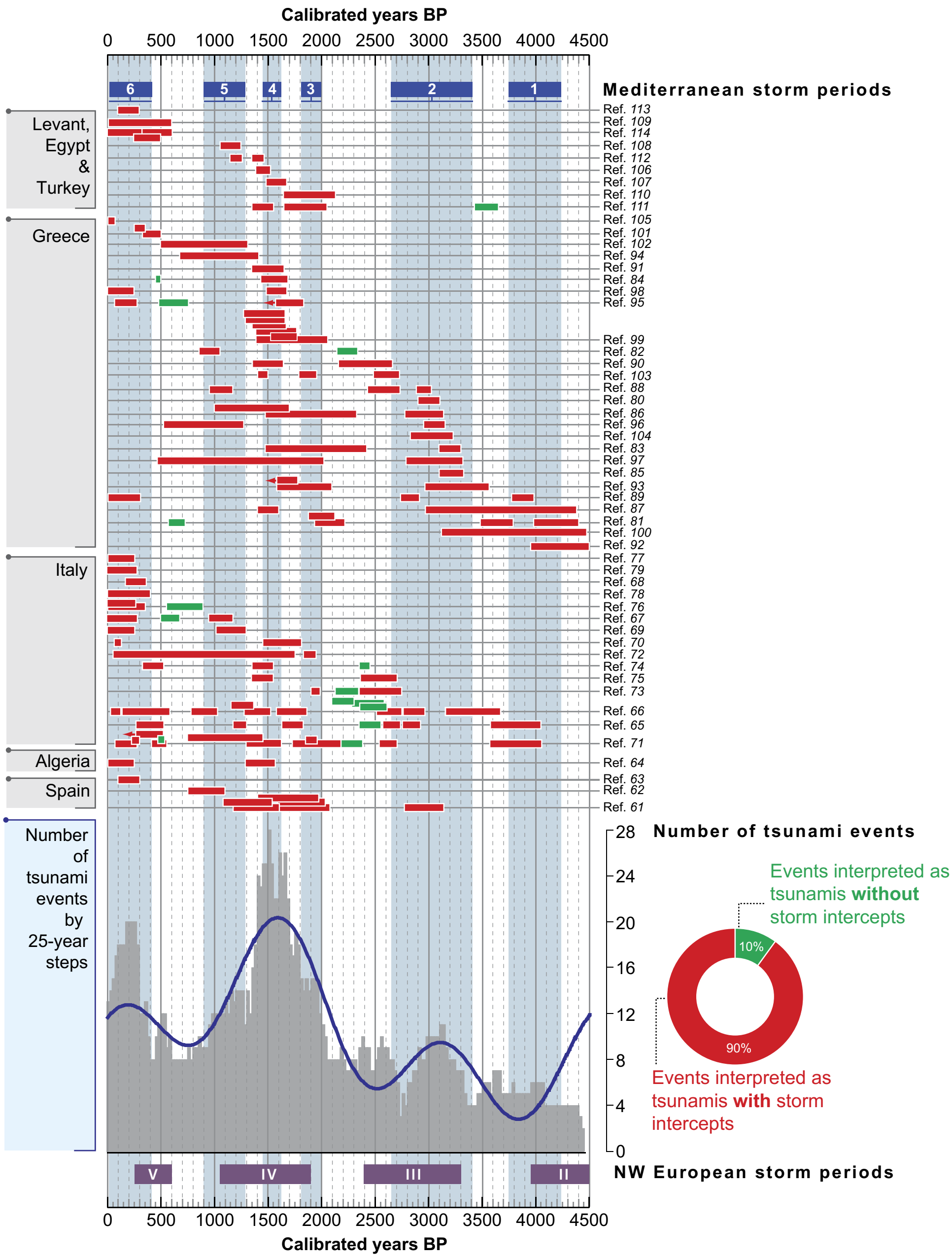

Fig. 4. Temporal distribution of high-energy events interpreted as tsunamis, grouped geographically from the Eastern to Western Mediterranean. The lower histogram plots tsunami frequency at regular 25-year intervals. The blue line denotes the 1500-year sinusoidal filter fitted to these data (phase = Free; $r = 0.839$). The list of references and their locations is provided in Materials and Methods. Mediterranean (*21*) and NW European (*49*) storm periods are also indicated.

resonant factors. The low probability of this combination occurring is the main reason why large meteotsunamis are infrequent and are observed only in some specific embayments (*58*). As such, although climate cooling may (or may not) favor the generation of meteotsunamis, their geological preservation woud be not only be rare but also localized to specific embayments with distinct resonance qualities.

We further probed the relationships between the geological tsunami record and proxies for North Atlantic and Mediterranean cooling/climate deterioration using statistical tools (Fig. 7). In effect, the number of events is high enough and the relative noise is low enough to give us confidence that the record captures a meaningful centennial- to millennial-scale history of coastal hazards. Here, we focused on the entire 4500 years of the time series. We used cross-correlations ($P < 0.05$) based on proxies fitted to a 1500-year sinusoidal filter (with $r > 0.5$ and $P < 0.001$) using sinusoidal regressions to model periodicities and assess their time alignment (Fig. 7). The correlation coefficient is plotted as a function of the alignment position. We found that our tsunami time series is tightly correlated with periodicities of storm conditions in the NW Mediterranean [cross-correlation (CC) $lag_0 = 0.92$] (*19*) and the North Atlantic (CC $lag_0 = 0.96$) (*51*).

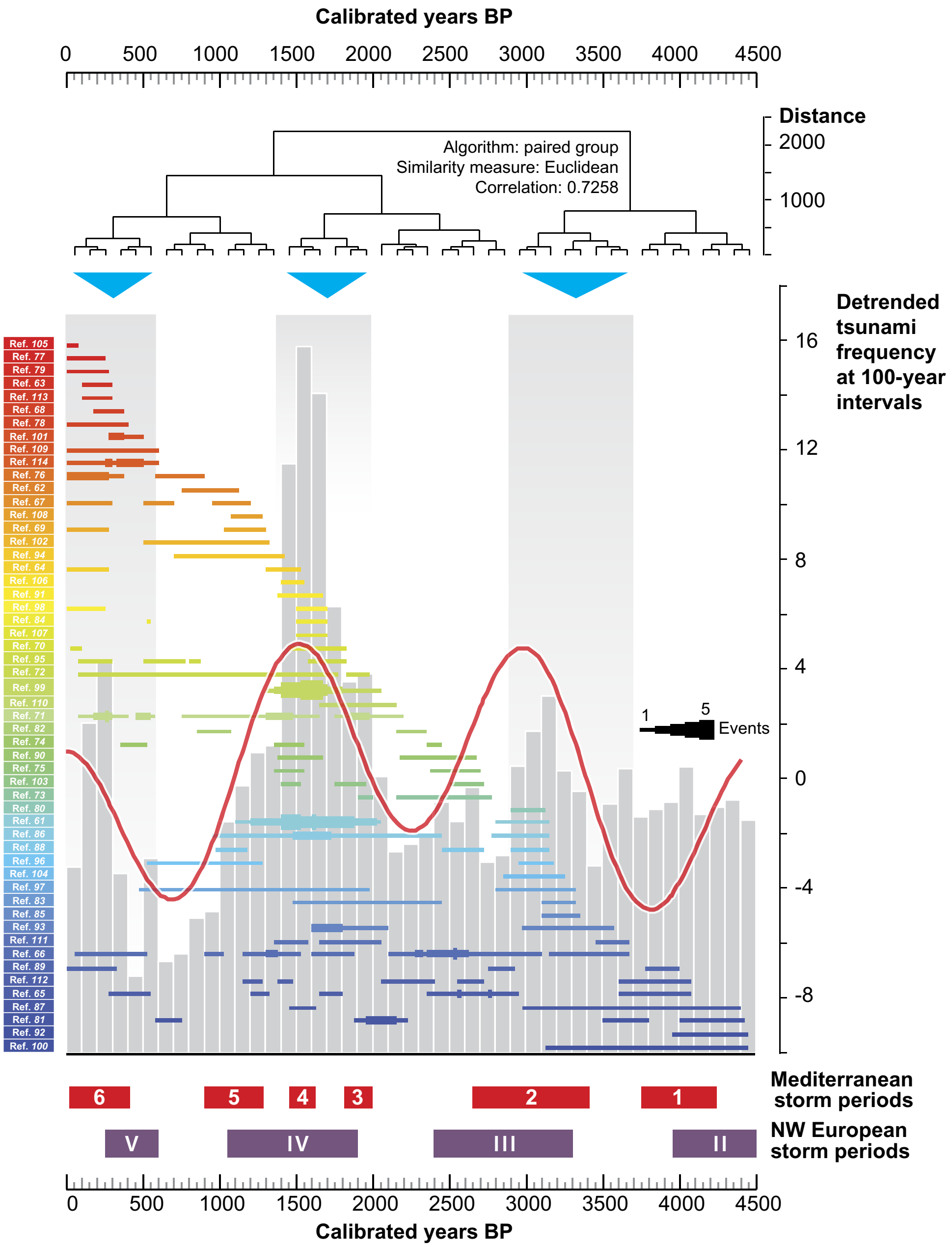

Fig. 5. Histogram of detrended tsunami events at 100-year intervals. Cluster analysis delineates six periods of high and low tsunami frequency (algorithm, paired group; similarity measure, Euclidean; correlation, 0.72). The hierarchical clustering analysis (descending type, clusters joined on the basis of the average distance) was used to calculate the lengths of tree branches using branches as distances between groups of data. The data were also fitted with a sinusoidal filter, which underscores the strength of the 1500-year periodicity and supports the cluster analysis.

A more detailed analysis was carried out on data from the last 2000 years because of the high number of events ($n = 96$) during this period. The initial paleoclimate time series were chronologically standardized using a regular 25-year sampling step. Linear and cross-correlations were used to test the strength of relationships. In addition to strong correlations with stormier conditions in the Mediterranean and the North Atlantic, we found that our Mediterranean tsunami record is also significantly correlated at $P < 0.05$ ($n = 81$) with various indicators of climate deterioration in the Mediterranean including Central Mediterranean pollen data ($r = 0.62$) (*21*) and Eastern Mediterranean speleothem data ($r = 0.66$; Fig. 8) (*59*). These correlations are based on completely independent age models.

Our data underscore strong mid- to late Holocene phasing between high-energy events in the Mediterranean and North Atlantic/NW European storm activity. By contrast, the data do not fit with Holocene records of North Atlantic Oscillation (NAO) activity, which is in disagreement with the storm track seesaw that has been evoked between southern and northern Europe based on recent instrumental records (*19*, *20*). This apparent coupling of Mediterranean and eastern North Atlantic storm activity suggests that the NAO activity was not a major

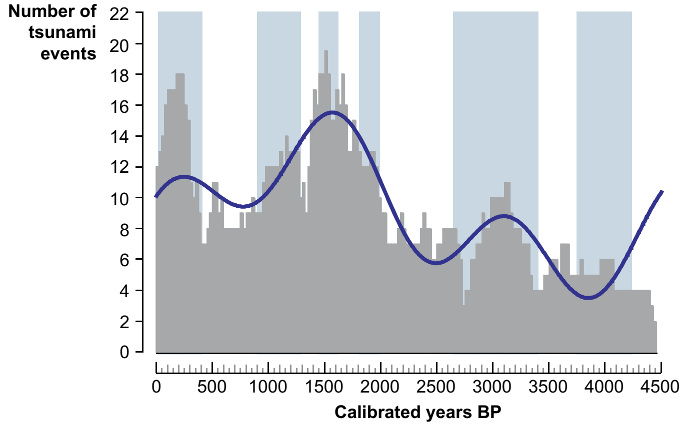

Fig. 6. Histogram of tsunami events at 25-year intervals, where overlapping events from the same record were attributed a score of "1" (presence) or "0" (absence). The data have been fitted using a 1500-year sinusoidal filter (in dark blue; phase = Free; r = 0.798). The more minor peaks linked to Mediterranean storm phases [in light blue; (*21*)] are more clearly defined.

driver of Holocene storminess in these areas at longer centennial to millennial time scales.

CONCLUSIONS

This new meta-analysis of sedimentary tsunami data from the Mediterranean shows strong evidence for a 1500-year periodicity that presents robust statistical correlations with markers of climate cooling and deterioration in both the Mediterranean and North Atlantic (*60*). By analogy with the correlations and prolonged temporal overlaps with Mediterranean and North Atlantic Holocene storm phases, we suggest that up to 90% of tsunami attributions of high-energy events in the Mediterranean's coastal record should be reconsidered. This relationship has significant implications for appropriately tailored hazard strategies in densely populated seaboard areas, in addition to more general-scale geomorphological coastal processes and dynamics. Specifically, our findings invite closer and more robust scrutiny of tsunami events, including greater proxy analysis, in future studies of coastal archives.

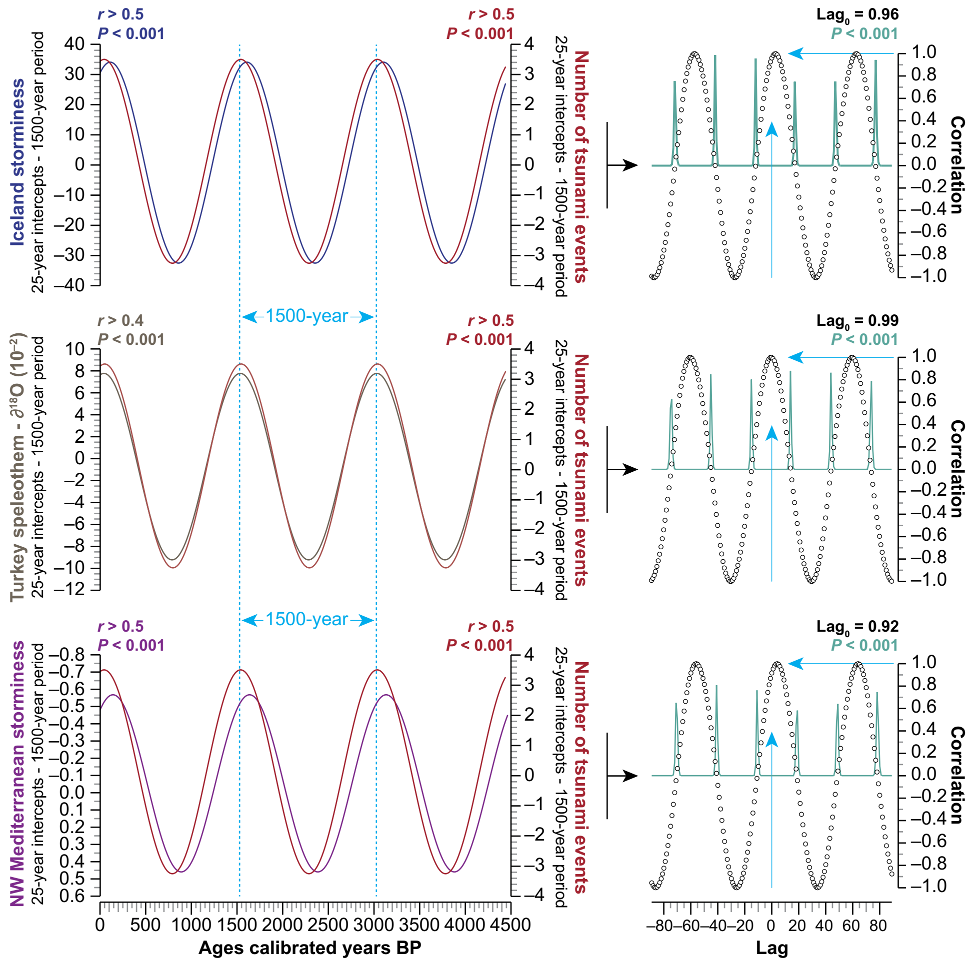

Fig. 7. Long-term trends in tsunami events, North Atlantic storminess, eastern Mediterranean speleothem data, and NW Mediterranean storminess. Sinusoidal regressions (fitted to a 1500-year filter) underscore the periodicity defining the long-term trends in tsunami frequency compared to proxies for North Atlantic and Mediterranean cooling and storm conditions in the NW Mediterranean. The filtered signals were correlated using cross-correlations ($P < 0.05$). The cross-correlations assess the time alignment of two time series by means of the correlation coefficient. The series have been cross-correlated to ascertain the best temporal match and the potential lag between two selected variables. The correlation coefficient was then plotted as a function of the alignment position. Positive and negative correlation coefficients are considered, focusing on the lag_0 value (with +0.50 and −0.50 as significant thresholds).

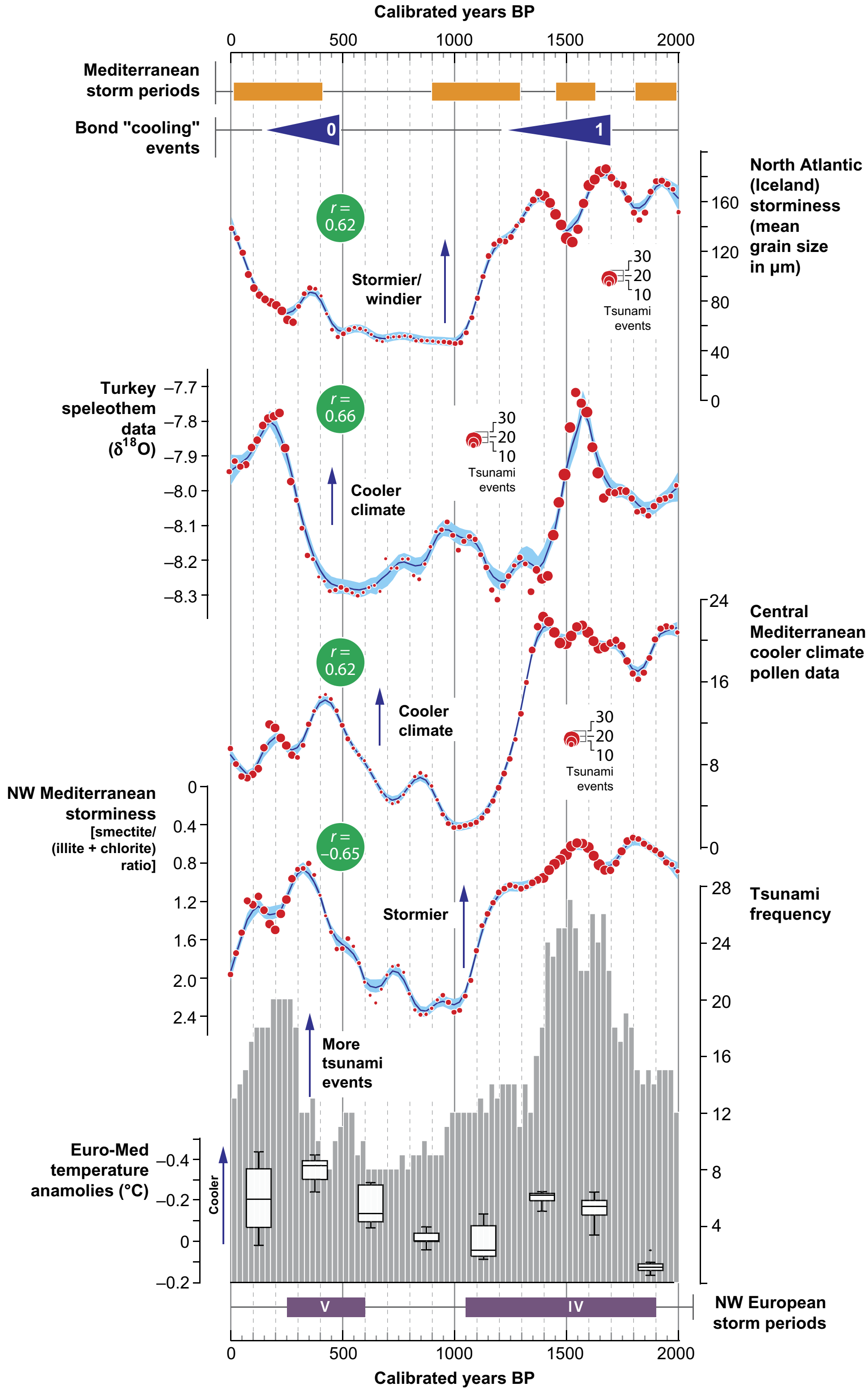

Fig. 8. Tsunami frequency during the last 2000 years compared with evidence for storminess and climate deterioration in the North Atlantic and the Mediterranean. All data sets were normalized to regular 25-year intervals using a linear interpolation model. The paleoclimate and storminess records were smoothed using a five-point moving average. The correlations between these paleoclimate series and the tsunami data are indicated by green circles.

MATERIALS AND METHODS

Proxy data

We used ISI (Institute for Scientific Information) Web of Science, Scopus, and Google Scholar to systematically search the scientific literature for papers reporting on the chronostratigraphic signature of tsunamis in the Mediterranean region. We only considered sedimentary records of tsunamis; written historical records of tsunamis and archives of storms were not included in the database. We retrieved records (n = 54) fulfilling the following criteria:

(i) Temporal coverage. All proxy records covered the last 4500 years.

(ii) Temporal resolution. All chronostratigraphic records of tsunami events were chronologically constrained by either radiocarbon, OSL, or archaeological dates.

(iii) Publication requirements. We only used proxy records that have been published in the scientific literature (journal papers and book chapters).

(iv) Geographical requirements. All the proxy records were located in, or nearly in, the Mediterranean. Three well-dated records from the Atlantic coast of western Spain were included in our analysis. All records were from coastal archives. Offshore records from deep marine locations (that is, turbidites) were not included in our analysis. The location of sites is shown in Fig. 3 (*61–114*). The proxy data were divided into eight countries: Algeria (n = 1), Cyprus (n = 1), Egypt (n = 2), Greece (n = 26), Israel (n = 4), Italy (n = 15), Spain (n = 3), and Turkey (n = 1). Full details of these records are shown in table S1. It is challenging to comment on the reliability of tsunami interpretations in previous studies (*61–114*) because of the significant stratigraphic parallels between tsunami and storm deposits, particularly in onshore records at or near (that is, within 100 m) the shoreline.

Geochronological screening

Because of the different age of publications used, all original radiocarbon data were recalibrated using the latest IntCal13 and Marine13 curves in Calib 7.1 (*115*). Where available, local ΔR values were used for marine samples. For statistical robustness, all dates were quoted to 2σ, which was not always the case in the original papers. The 2-σ calibrations were subsequently fed into the database (see tables S1 to S3).

Data treatment

Before calculating variations in stratigraphic tsunami frequency, all 54 proxy records were converted into time series with annually spaced time steps for the period 0 (that is, 1950 CE) to 4500. Each event was attributed a value of 1 for each of the calibrated years in which it was recorded. In instances where the same event was dated several times using different chronological materials, we attributed an event value of 1 but for the complete chronological range of all the calibrated dates. For rare instances where a specific annual date was provided, we added an error bar of ±100 years. These time series were subsequently summed to create histograms of tsunami frequency for the past 4500 years.

We used various statistical methods to compare and contrast the compiled tsunami data with a number of other paleoclimate records from the North Atlantic and the Mediterranean. Details of these statistics are provided in the figure legends. Most of the records were obtained from public repositories (for example, www.ncdc.noaa.gov/paleo/ and www.pangaea.de/). Records that were not publicly available were acquired directly from the original authors. To facilitate comparisons and statistical analyses between archives, all proxy records were converted into regularly spaced time series using linear interpolation.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/3/10/e1700485/DC1

fig. S1. REDFIT spectral analysis and wavelet analyses of the tsunami data set.

fig. S2. Catalog of Mediterranean tsunami events based on historical records from Maramai *et al.* (*35*).

fig. S3. Spectral analysis, REDFIT analysis, and wavelet analysis of the documentary database of Mediterranean tsunamis.

table S1. Database of sites and stratigraphic tsunami events used in this study.

table S2. Matrix of stratigraphic tsunami events by year and site.

table S3. Annual frequency of tsunami events in the Mediterranean's geological record based on this study.

table S4. Data used to produce Fig. 1.

table S5. Frequency of tsunami events in the geological record at 25-year intervals.

table S6. Data used to produce Fig. 5.

table S7. Data used to produce Fig. 6.

table S8. Data used to produce Fig. 7.

table S9. Data used to produce Fig. 8.

table S10. Catalog of Mediterranean tsunamis in historical documents and number of events by year.

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