Recent Advances in Seismology with Impact to Monument Protection

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This presentation is part of a common work by:

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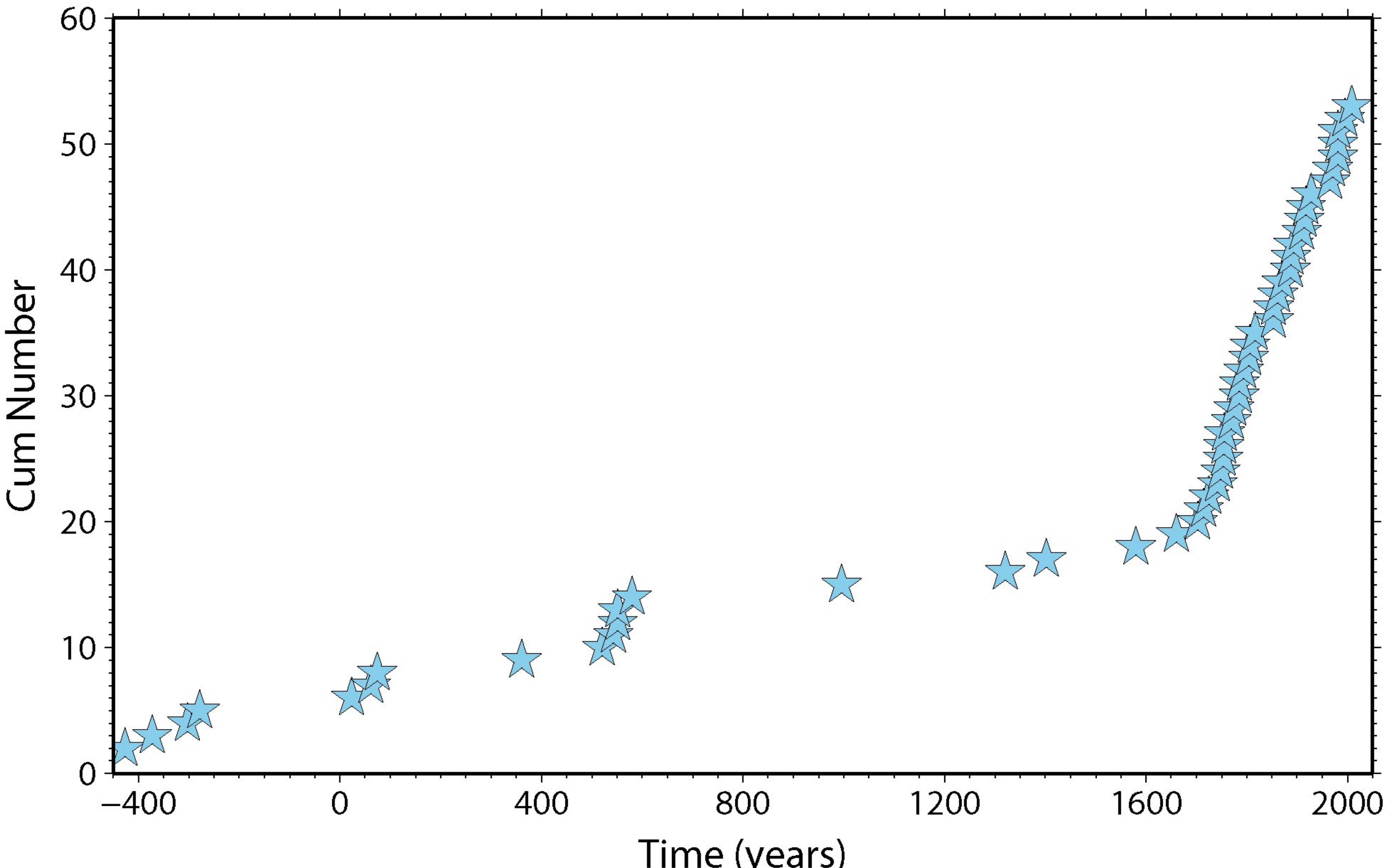
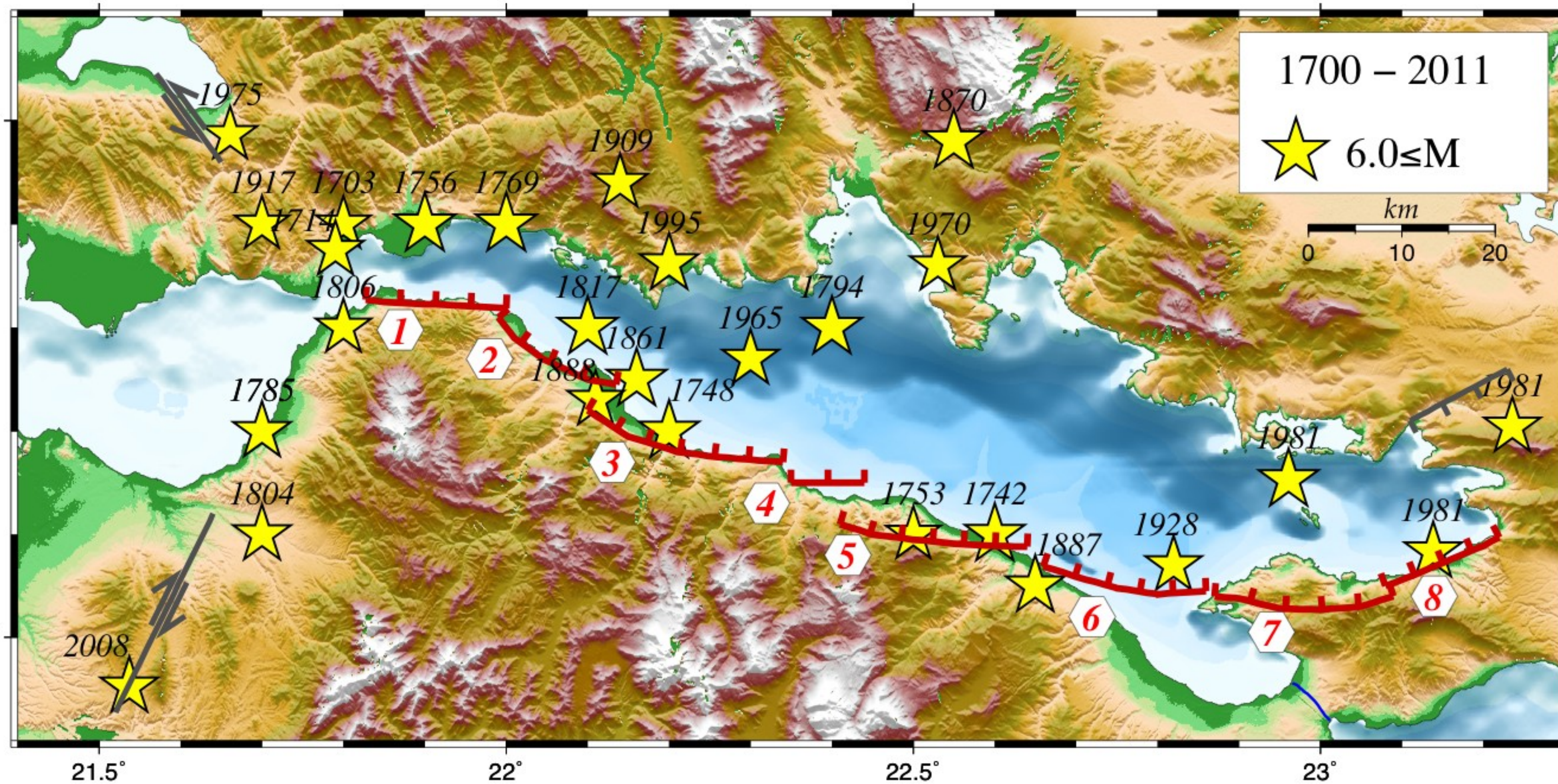
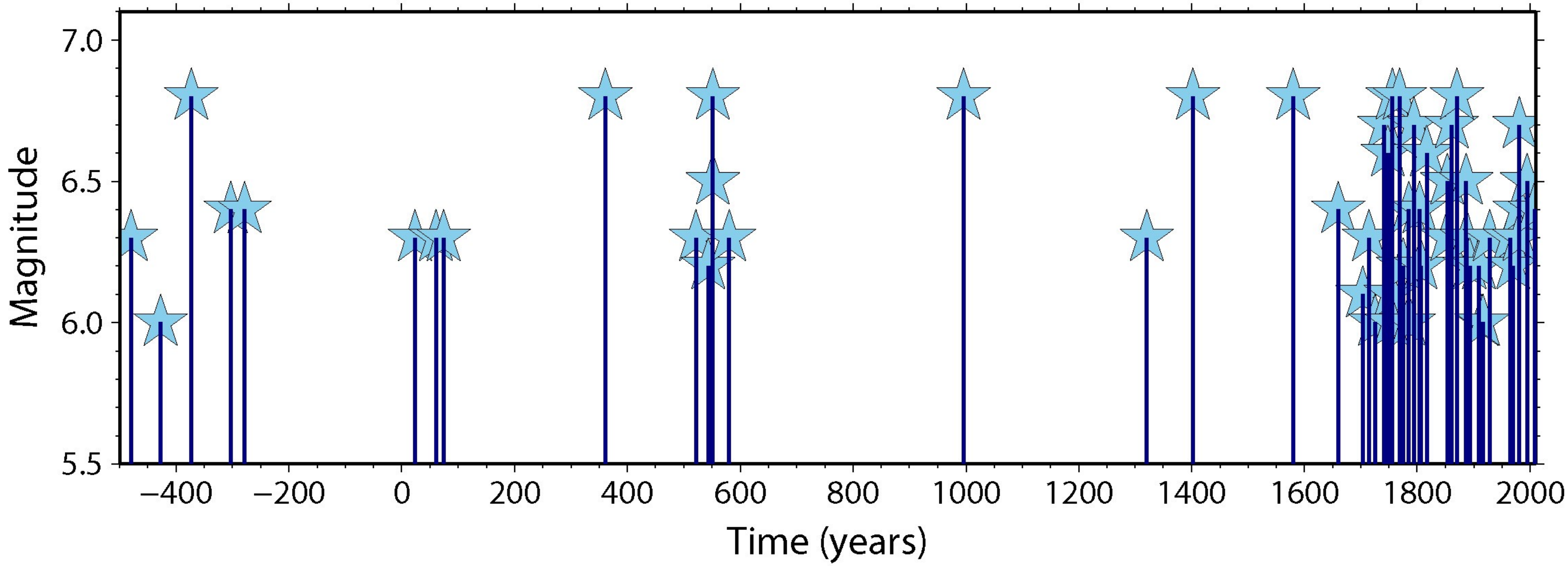


60
50
40
30
20
10
0
Cum Number
−400
0
400
800
1200
1600
2000
Time (years)

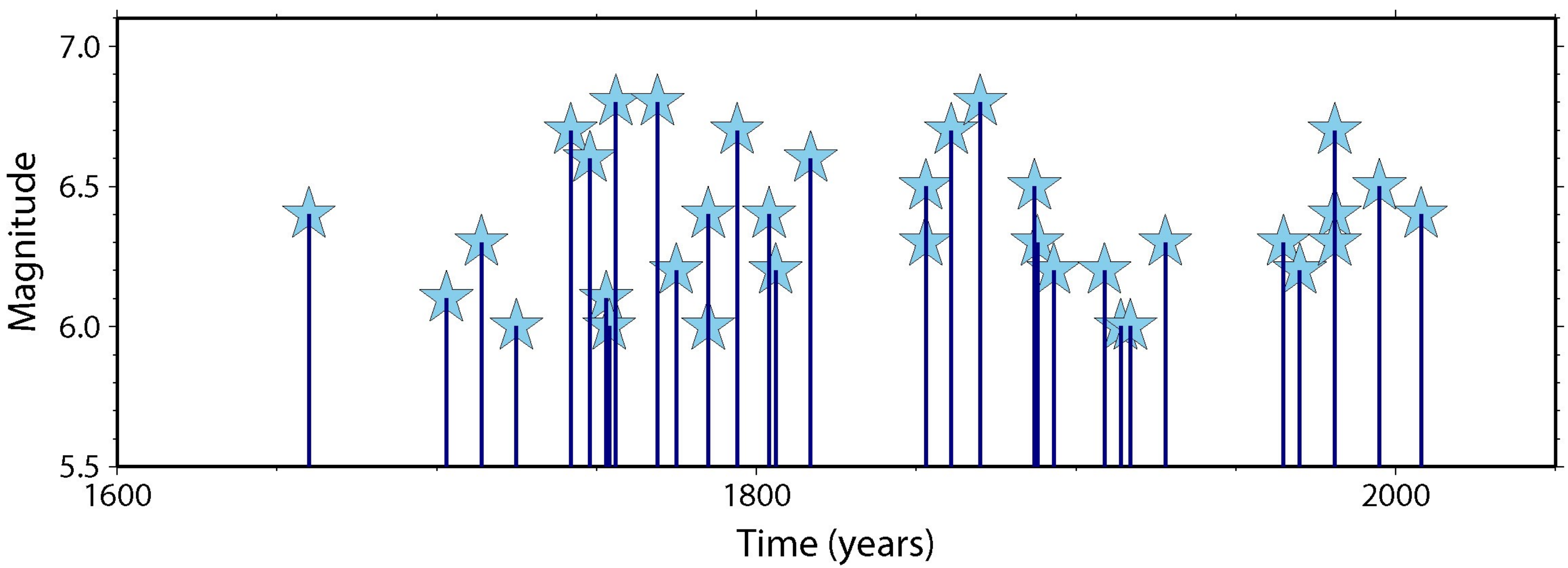

1700 – 2011
6.0≤M
km
0
10
20
1975
1870
1909
1917
1703
1756
1769
1714
1995
1970
1806
1817
1794
1965
1861
1888
1748
1785
1981
1981
1804
1753
1742
1887
1928
1981
2008
1
2
3
4
5
6
7
8
38.5°
38°
21.5°
22°
22.5°
23°

Characteristic earthquakes reported for the southern Corinth gulf fault system

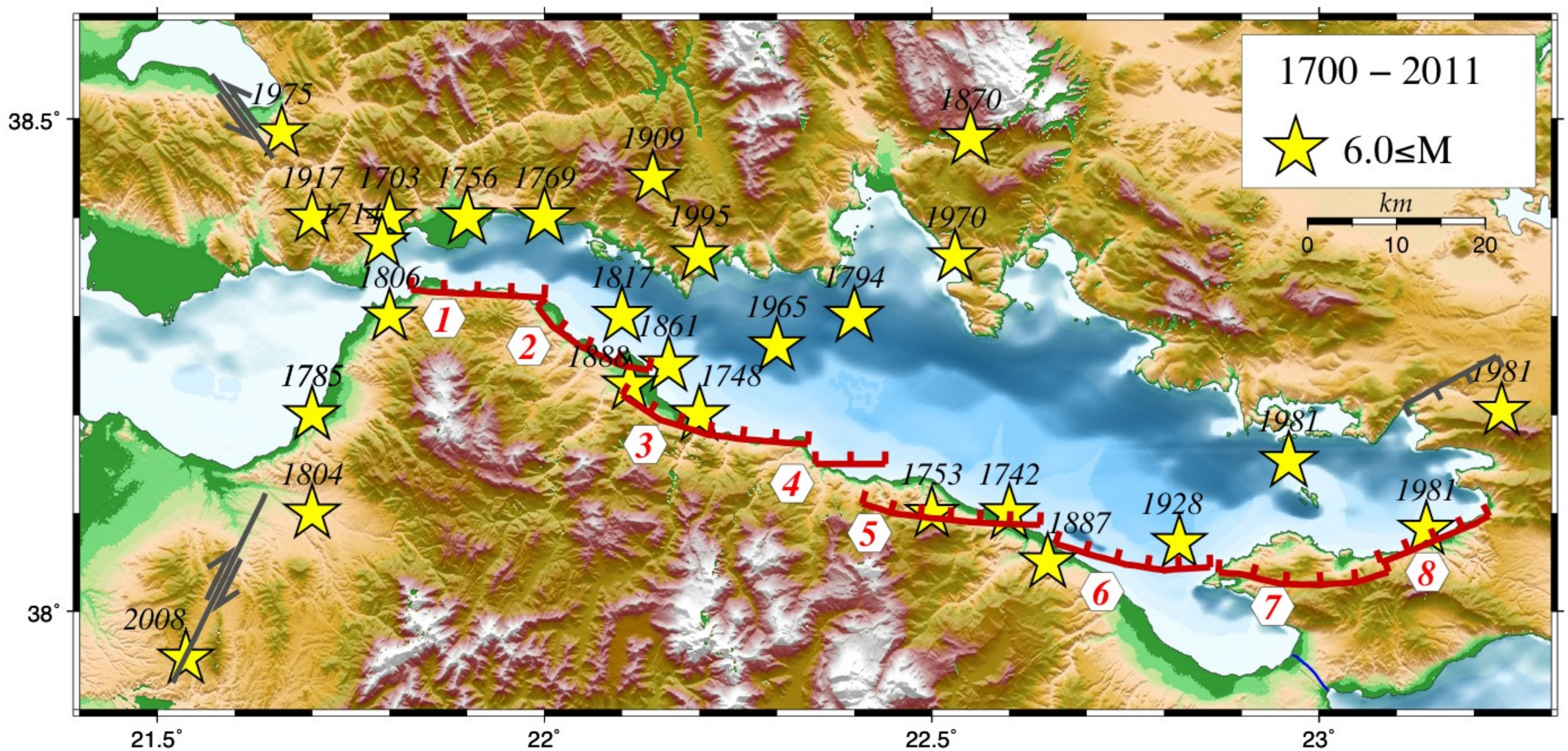
Event number	**Year**	**Month**	**Date**	**M**	**Fault Name**	**Segment number**
1.	1714	7	29	6.2	Psathopyrgos	1
2.	1742	2	21	6.7	Xylokastro	5
3.	1748	5	25	6.6	Aigion	2
4.	1753	3	6	6.1	Xylokastro	5a
5.	1775	4	16	6.0	Offshore Perachora	6
6.	1806	1	24	6.2	Psathopyrgos	1
7.	1817	8	23	6.6	Aigion	2
8.	1861	12	26	6.7	Eliki	3
9.	1887	10	3	6.5	Offshore Perachora	6
10.	1888	9	9	6.3	Aigion	2
11.	1928	4	22	6.3	Offshore Perachora	6
12.	1965	7	6	6.3	East part of Eliki	3a
13.	1970	4	8	6.2	East part of Xylokastro	5b
14.	1981	2	24	6.7	Skinos	7
15.	1981	2	25	6.4	Alepochori	8
16.	1992	11	18	5.7	Offshore Akrata	4
17.	1995	6	15	6.5	Aigion	2



7.0
6.5
6.0
5.5
Magnitude
−400
−200
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (years)



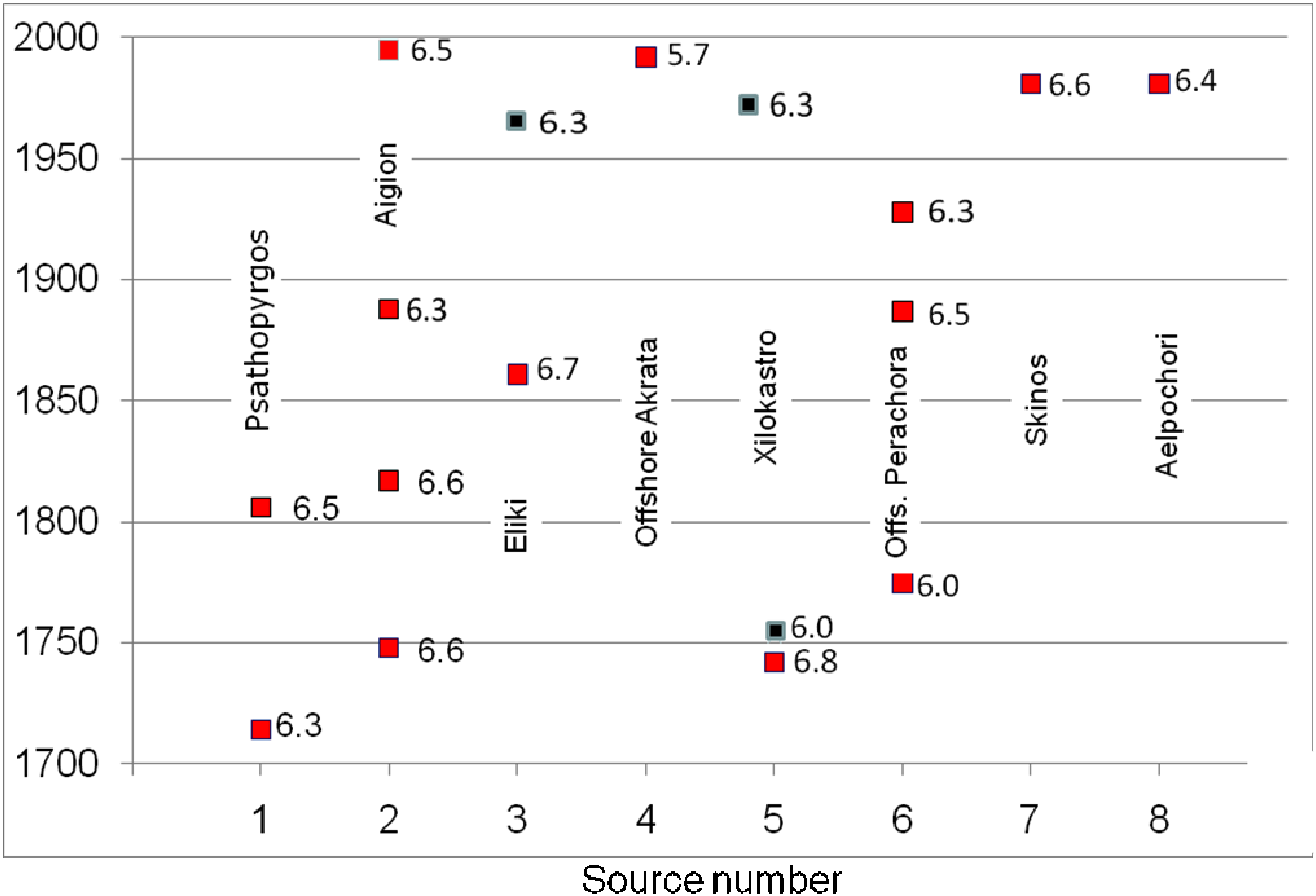
7.0
6.5
6.0
5.5
Magnitude
1600
1800
2000
Time (years)



1700 – 2011
6.0≤M
km
0
10
20
1975
1917
1703
1714
1756
1769
1909
1995
1870
1970
1806
1817
1794
1965
1861
1888
1748
1785
1804
1753
1742
1887
1928
1981
1981
1981
2008
1
2
3
4
5
6
7
8
38.5°
38°
21.5°
22°
22.5°
23°

Fault segments along the southern bound of Corinth gulf considered in this study

Segment number	Segment name	L (km)	W (km)	Mean Slip (m)	Slip rate (mm/yr)	T_r (yrs)
1	Psathopyrgos	15	10	0.75	6	126
2	Aigion	16	10	0.88	6	146
3	Eliki	22	12.5	1.56	6	260
4	Offshore Akrata	8	8	0.19	5	40
5	Xylokastro	20	17	1.26	5	252
6	Offshore Perachora	18	16	0.54	4	135
7	Skinos	19	15	0.96	3	319
8	Alepochori	13	13	0.71	3	285



2000
1950
1900
1850
1800
1750
1700
Psathopyrgos
Aigion
Eliki
Offshore Akrata
Xilokastro
Offs. Perachora
Skinos
Aelpochori
6.5
6.3
6.6
6.6
6.5
6.3
6.3
6.7
5.7
6.3
6.0
6.8
6.3
6.5
6.0
6.6
6.4
1
2
3
4
5
6
7
8
Source number

Conditional probability computed under renewal models

In a simplified approach, only earthquakes that break all or most of the area of a fault segment are considered in the computation of total seismic moment release.

Statistically, their occurrence is represented as a point process, and the ***inter event time*** is modelled by a probability density function (***pdf***).

For a uniform Poisson model, the *pdf* is a negative exponential function:

$$f(t) = \frac{1}{T_r} \exp\left\{ - \frac{t}{T_r} \right\} \qquad (1)$$

The characteristic earthquake hypothesis needs a more elaborate model, called a ***renewal model***, whose *pdf* contains one more free parameter, conditioning the shape of the distribution in terms of its periodicity (Shimazaki and Nakata, 1980).

Consequently, the earthquake hazard is ***small*** immediately following the previous characteristic earthquake and then ***increases*** as time elapses without a further event occurring. (McCann *et al*., 1979).

Under the characteristic earthquake hypothesis, the fault segments are supposed to behave independently from each other according to a probability distribution of the ***interevent times*** as described by the ***Brownian Passage Time (BPT)*** *pdf* (Matthews et al., 2002):

$$f(t;T_r,\alpha) = \left(\frac{T_r}{2\pi\alpha^2 t^3}\right)^{1/2} \exp\left[-\frac{(t-T_r)^2}{2T_r\alpha^2 t}\right] \qquad (2)$$

α is the coefficient of variation (also known as the aperiodicity) of the distribution.

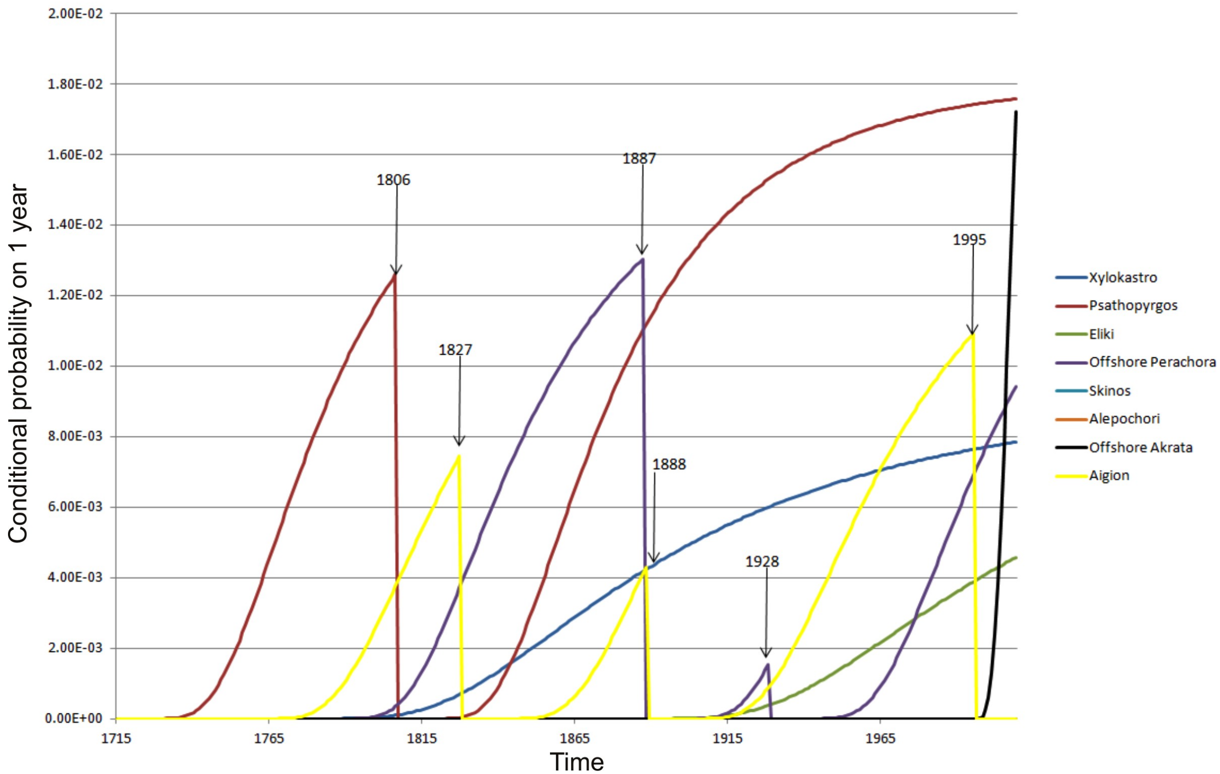
An alternative ***interevent time distribution*** is the ***Weibull*** distribution (Weibull, 1951):

$$f(t;T_r,\gamma) = \frac{\gamma}{T_r}\left(\frac{t}{T_r}\right)^{\gamma-1}\exp\left\{-\left(\frac{t}{T_r}\right)^{\gamma}\right\} \quad (3)$$

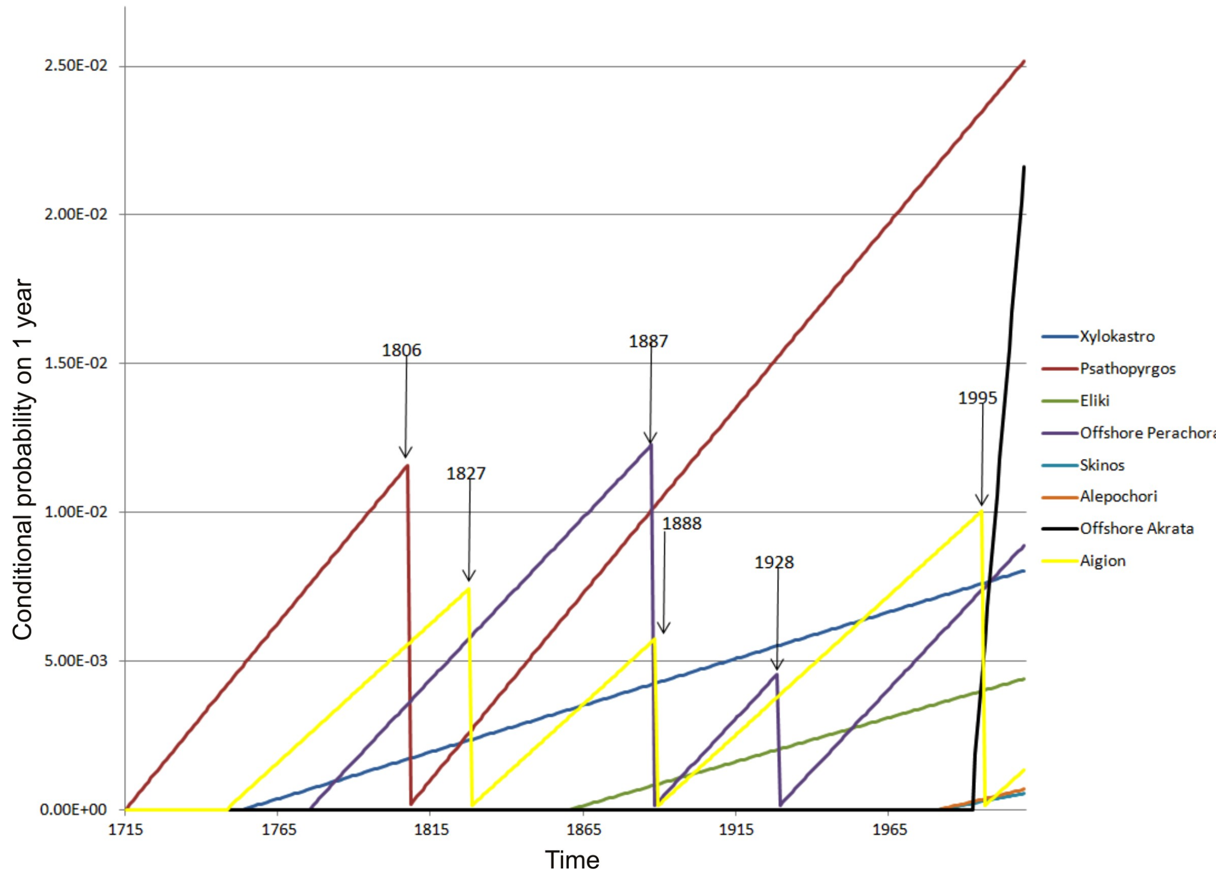
where γ is the shape parameter of the distribution, defined as the inverse of the coefficient of variation.

The probability for the occurrence of a new event in a given time window Δt, conditional to the occurrence that no events occurred before time t, is obtained from the density distribution of the inter event times:

$$\Pr\left[t < T \le t + \Delta t \mid T > t\right] = \frac{\Pr\left[t < T \le t + \Delta t\right]}{\Pr\left[t < T\right]} = \frac{\int_t^{t+\Delta t} f(u)\,du}{1 - \int_0^t f(u)\,du} \qquad (4)$$



Conditional probability on 1 year
2.00E-02
1.80E-02
1.60E-02
1.40E-02
1.20E-02
1.00E-02
8.00E-03
6.00E-03
4.00E-03
2.00E-03
0.00E+00
1715
1765
1815
1865
1915
1965
Time
1806
1827
1887
1888
1928
1995
Xylokastro
Psathopyrgos
Eliki
Offshore Perachora
Skinos
Alepochori
Offshore Akrata
Aigion



Conditional probability on 1 year
2.50E-02
2.00E-02
1.50E-02
1.00E-02
5.00E-03
0.00E+00
1715
1765
1815
1865
1915
1965
Time
1806
1827
1887
1888
1928
1995
Xylokastro
Psathopyrgos
Eliki
Offshore Perachora
Skinos
Alepochori
Offshore Akrata
Aigion

Effect of the stress transfer

We compute the stress tensor change due to slip on a rectangular fault on the surrounding elastic environment.
The Coulomb stress change is a linear combination of the shear and normal stress:

$$\Delta CFF = \Delta \tau + \mu' \cdot \Delta \sigma_n$$

The computation of ΔCFF requires the knowledge of the focal mechanism of the impending earthquake on the triggered fault.

The time elapsed since the previous earthquake is modified by a shift proportional to ΔCFF:

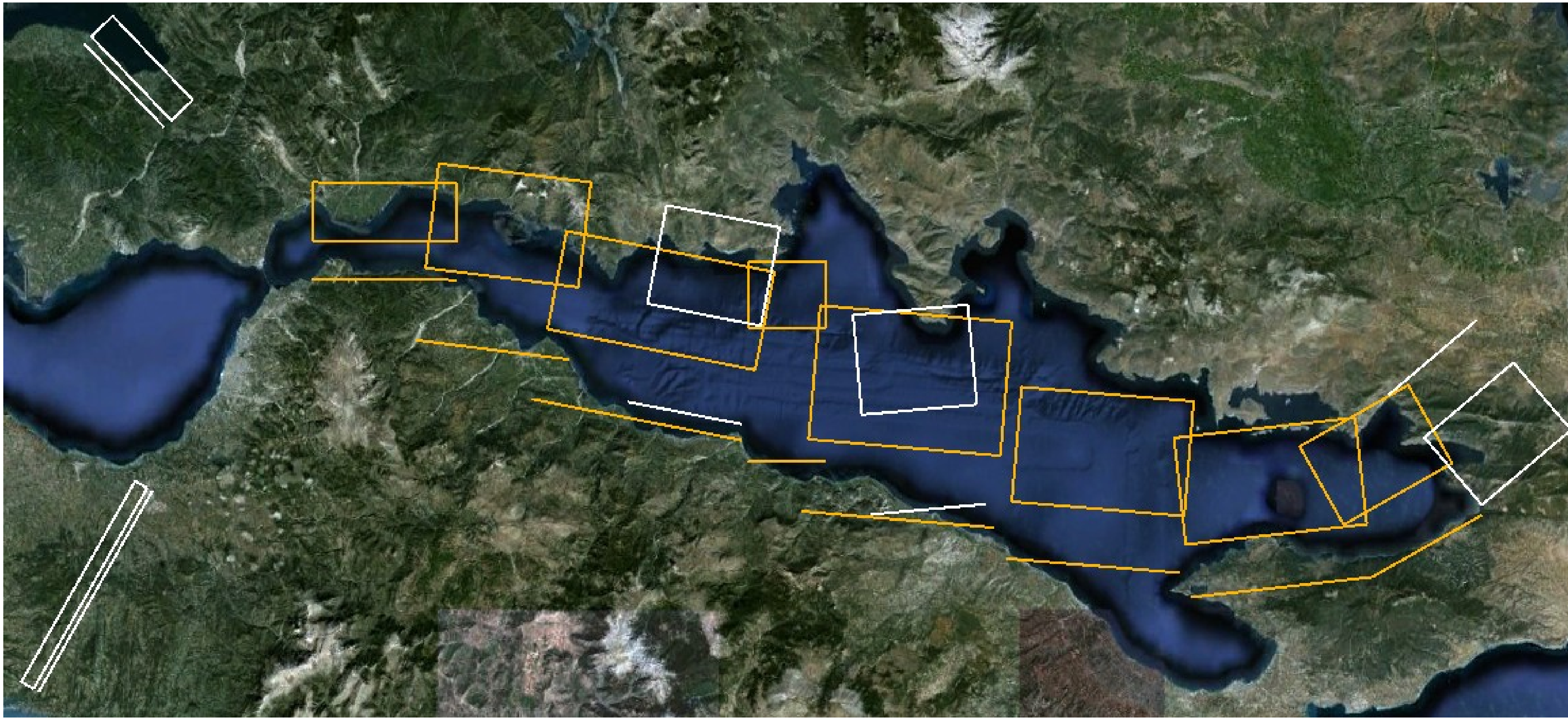
:

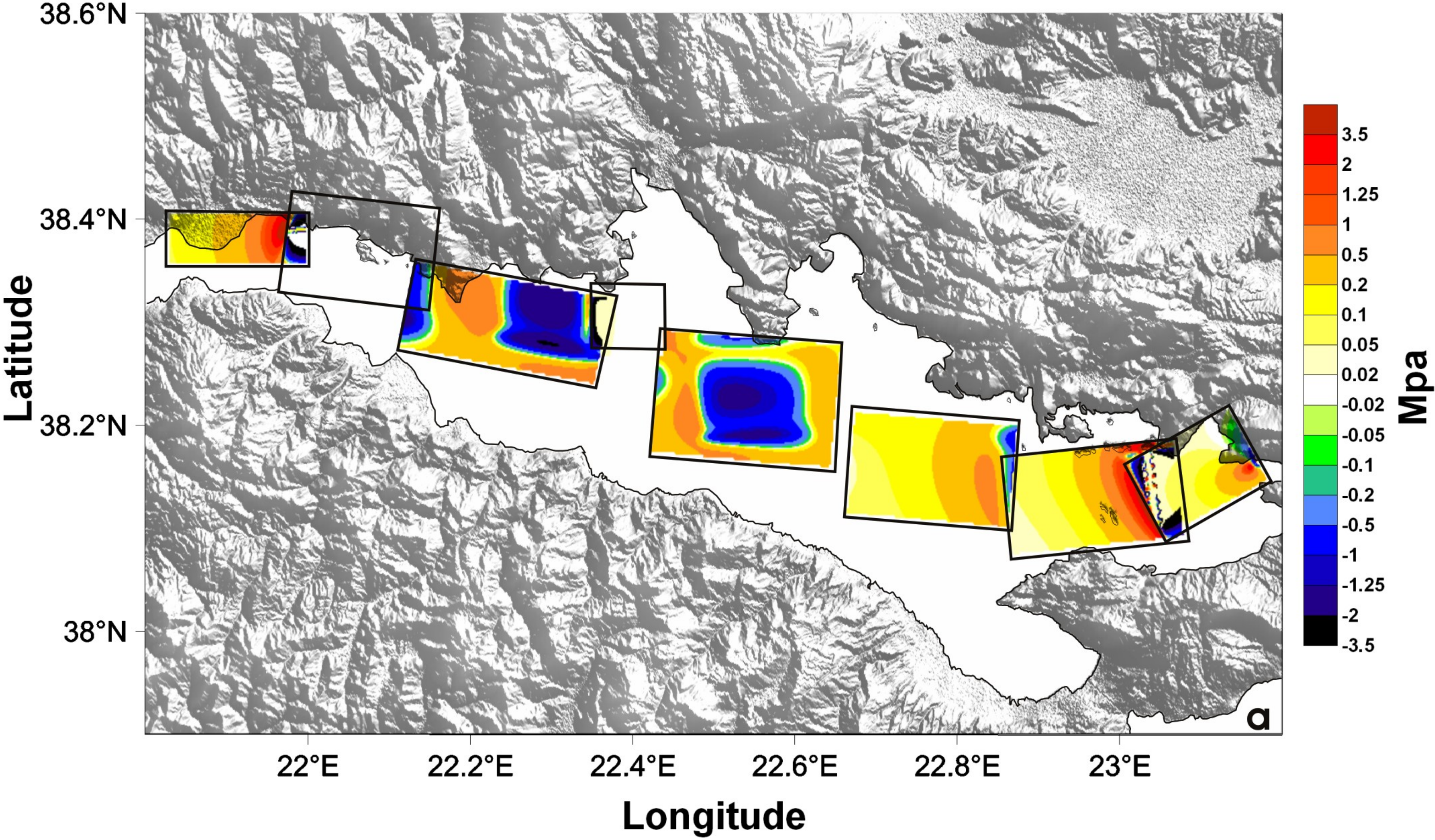
$$t' = t + \frac{\Delta CFF}{\dot{\tau}}$$

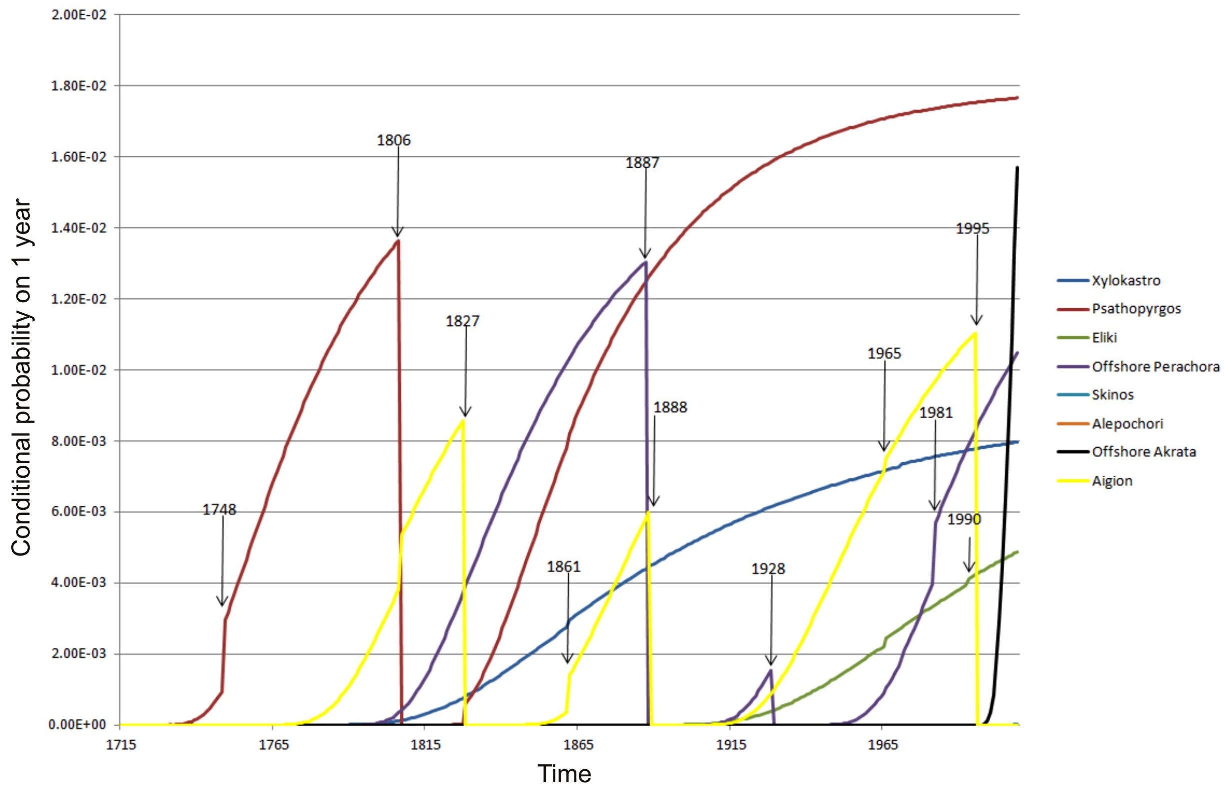
where $\dot{\tau}$ is the tectonic stressing rate.

Alternatively, the stress change can be equivalent to a modification of the expected recurrence time:

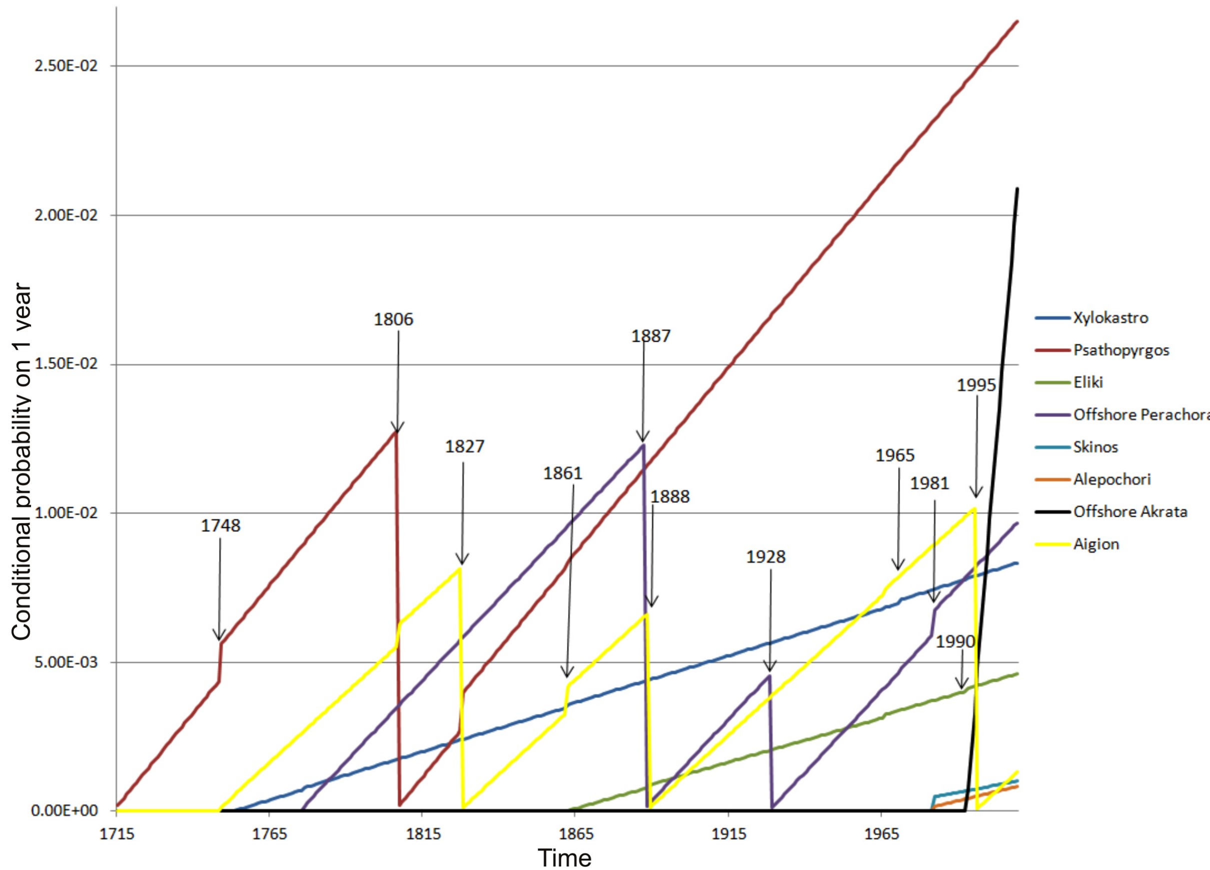
$$T_r' = T_r - \frac{\Delta CFF}{\dot{\tau}}$$




38.6°N
38.4°N
38.2°N
38°N
Latitude
22°E
22.2°E
22.4°E
22.6°E
22.8°E
23°E
Longitude
3.5
2
1.25
1
0.5
0.2
0.1
0.05
0.02
-0.02
-0.05
-0.1
-0.2
-0.5
-1
-1.25
-2
-3.5
Mpa
a



2.00E-02
1.80E-02
1.60E-02
1.40E-02
1.20E-02
1.00E-02
8.00E-03
6.00E-03
4.00E-03
2.00E-03
0.00E+00
1715
1765
1815
1865
1915
1965
Time
Conditional probability on 1 year
1748
1806
1827
1861
1887
1888
1928
1965
1981
1990
1995
Xylokastro
Psathopyrgos
Eliki
Offshore Perachora
Skinos
Alepochori
Offshore Akrata
Aigion



Conditional probability on 1 year
2.50E-02
2.00E-02
1.50E-02
1.00E-02
5.00E-03
0.00E+00
1715
1765
1815
1865
1915
1965
Time
1748
1806
1827
1861
1887
1888
1928
1965
1981
1990
1995
Xylokastro
Psathopyrgos
Eliki
Offshore Perachora
Skinos
Alepochori
Offshore Akrata
Aigion

Statistical evaluation.

In the previous section we have shown that the application of a renewal model to a sequence of characteristic earthquakes yields time-dependent probabilities for the occurrence of the next event.
These probabilities can be affected also by the interaction among different segments, due to the ***coseismic stress change*** on a particular fault segment.
In this section we deal with the problem of retrospectively evaluating the validity of the above-mentioned models, by comparing the forecasts with the historical information on real earthquakes.
To do so, we apply mathematical tools that have been already used in statistical seismology.
We distinguish, as is commonly done, between alarm–based forecasts, and probability-based forecasts.

Binary contingency table

	Observed	
Forecast	**Yes**	**No**
Yes	**a**	**b**
No	**d**	**c**

The meaning of the four entries is the following:

a, number of successful forecasts;

b, number of false alarms

c, number of cells without any forecast or any earthquake

d, number of missed alarms

The binary contingency table, once the entries **a, b, c** and **d** are filled with a suitably large number of observations, allows the computation of statistical indicators of the validity of the model. In this study we apply three of these indicators: the ***ROC diagram***, the ***R-score***, and the ***performance factor***.

The ***ROC*** (Relative Operating Characteristic) diagram is a plot in which the X–axis (false alarm rate) is defined as

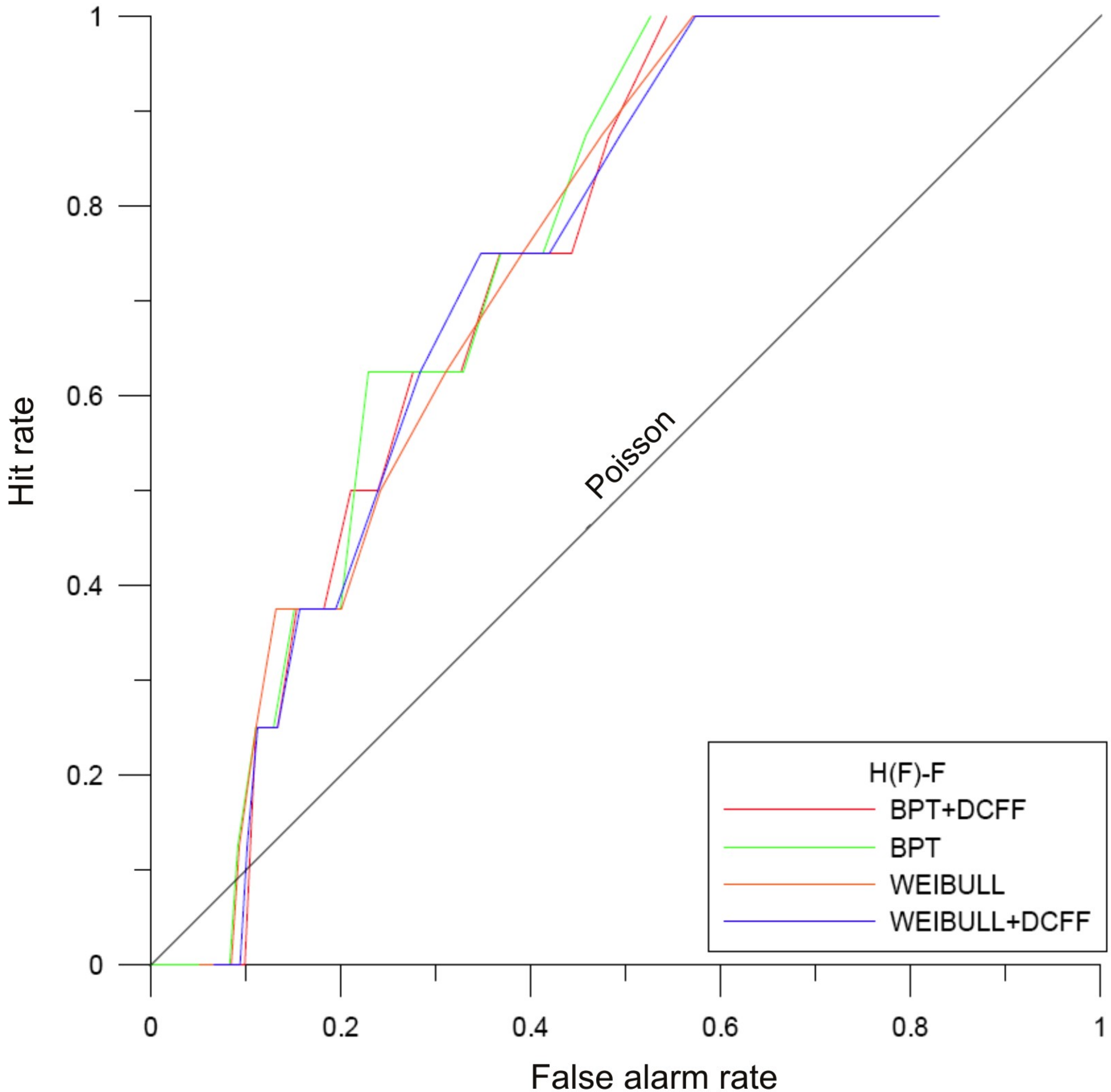
$$F = b/(b+c)$$

(the fraction of alarms issued where an event has not occurred)

and the Y–axis (Hit rate) is defined as

$$H = a/(a+d)$$

(the fraction of events that occur on an alarm cell).

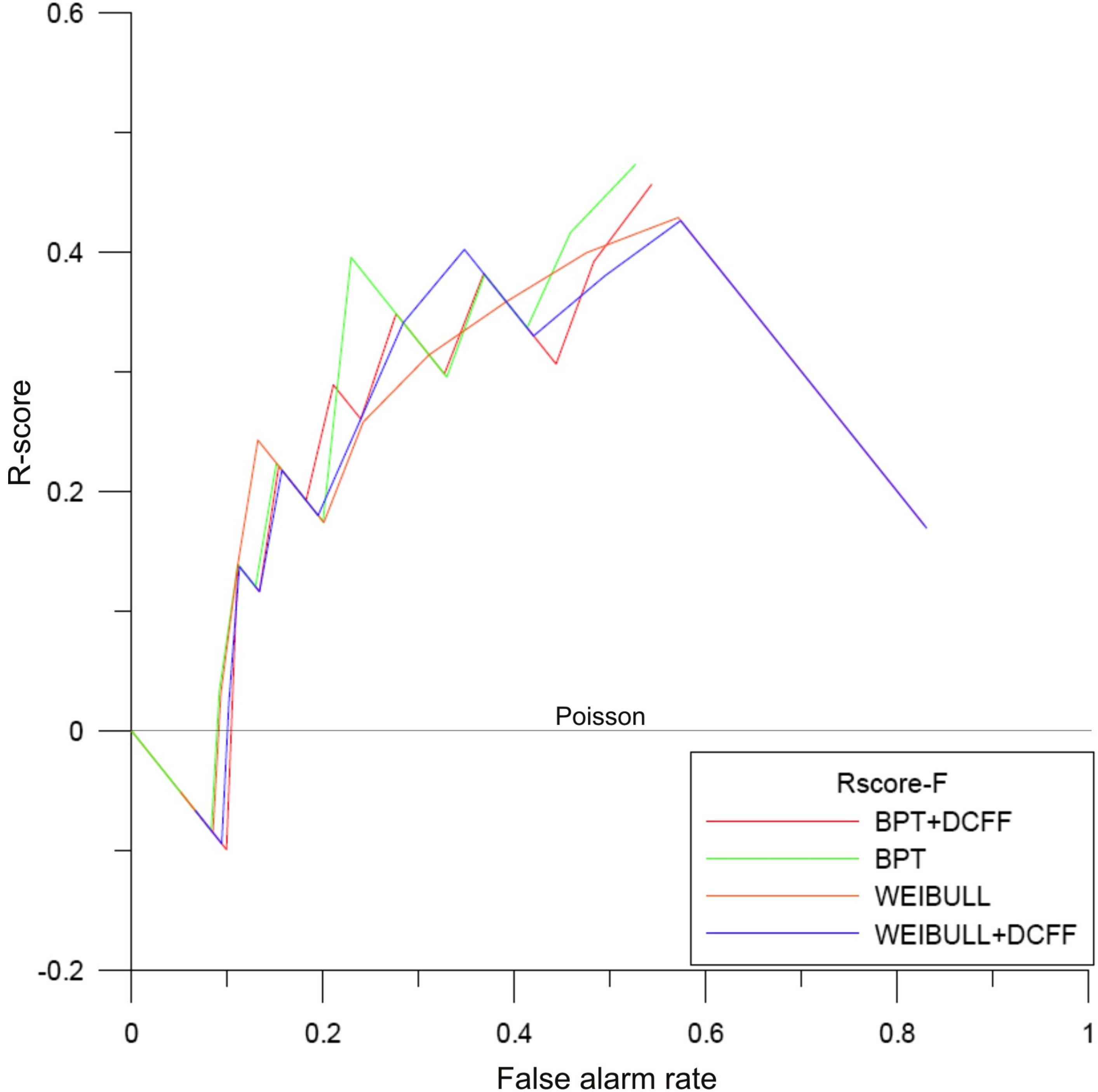


1
0.8
0.6
0.4
0.2
0
Hit rate
0
0.2
0.4
0.6
0.8
1
False alarm rate
Poisson
H(F)-F
BPT+DCFF
BPT
WEIBULL
WEIBULL+DCFF

The ***R–score*** is defined as the number of cells in which earthquakes are successfully predicted divided by the total number of cells containing alarms minus the number of failures to predict divided by the total number of cells without any alarms:

$$R = a \,/\, (a+b) - d \,/\, (c+d)$$

The expected behavior of the R–score for a plain time–independent Poisson model is a constant equal to zero. All the positive values of the R–score denote a forecast method that performs better than purely randomly given forecasts, as it is the case in our test, except for low threshold values (no events forecasted at all).



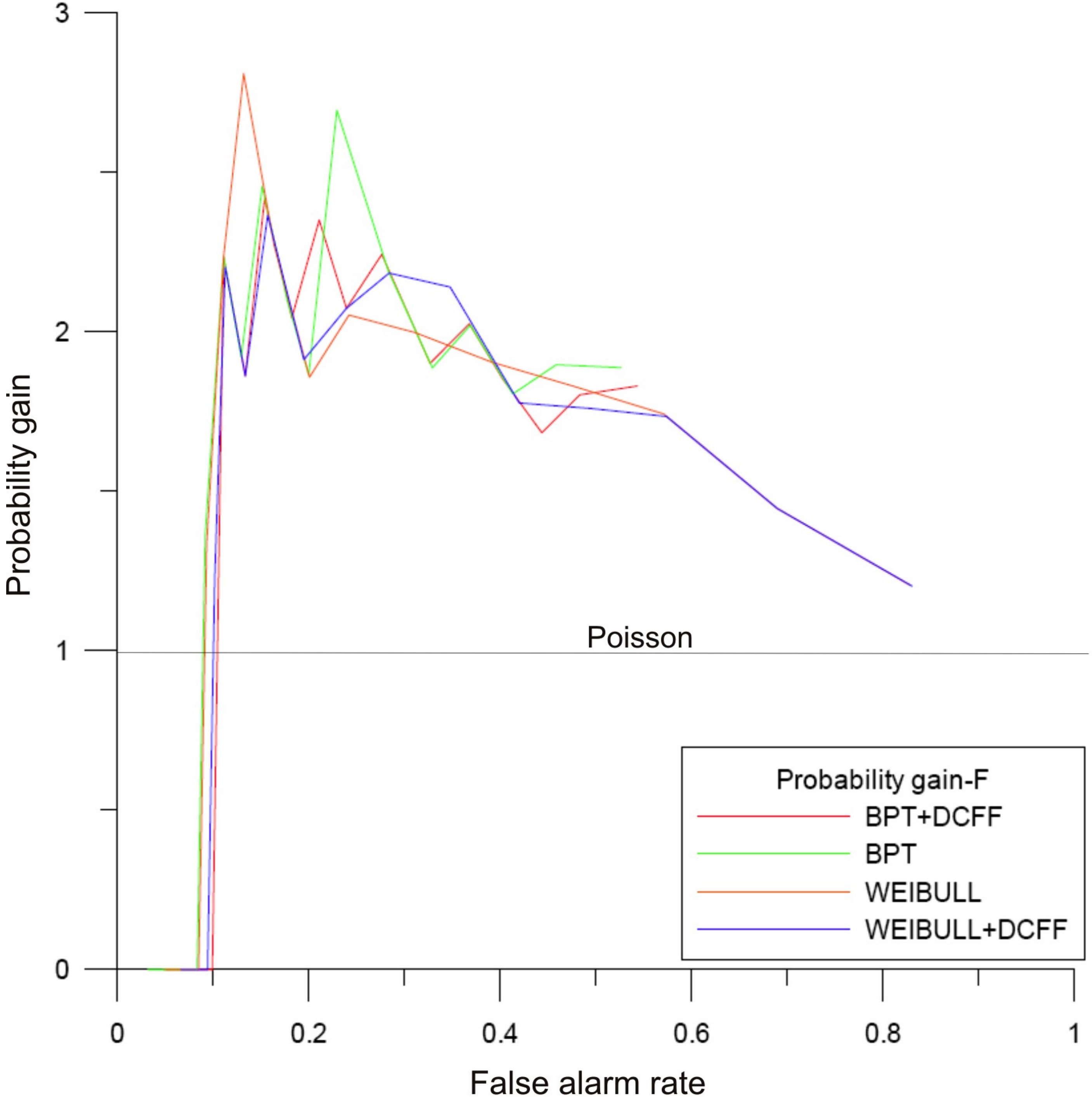
R-score
False alarm rate
Poisson
Rscore-F
BPT+DCFF
BPT
WEIBULL
WEIBULL+DCFF
0.6
0.4
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1

The ***probability gain*** is the ratio between the conditional probability (success rate) and the unconditional probability (average occurrence rate):

$$G = a\,/(a+d)\; e\,/(a+b) = H \cdot e\,/(a+b)$$

(where $e = a+b+c+d$, is the total number of geographic cells multiplied by the number of time bins)

Note that the expected probability gain for a plain time–independent Poisson model is a constant equal to 1. Again, our test achieves a performance better than a Poisson random forecast, except for low threshold values (no forecast events at all).



3
2
1
0
Probability gain
Poisson
0
0.2
0.4
0.6
0.8
1
False alarm rate
Probability gain-F
BPT+DCFF
BPT
WEIBULL
WEIBULL+DCFF

The log–likelihood of a binomial (occurrence or non occurrence) process under a given hypothesis is defined as

$$\log L = \sum_{i=1}^{P} \left[c_i \log(p_i) + (1 - c_i) \log(1 - p_i) \right] \quad (7)$$

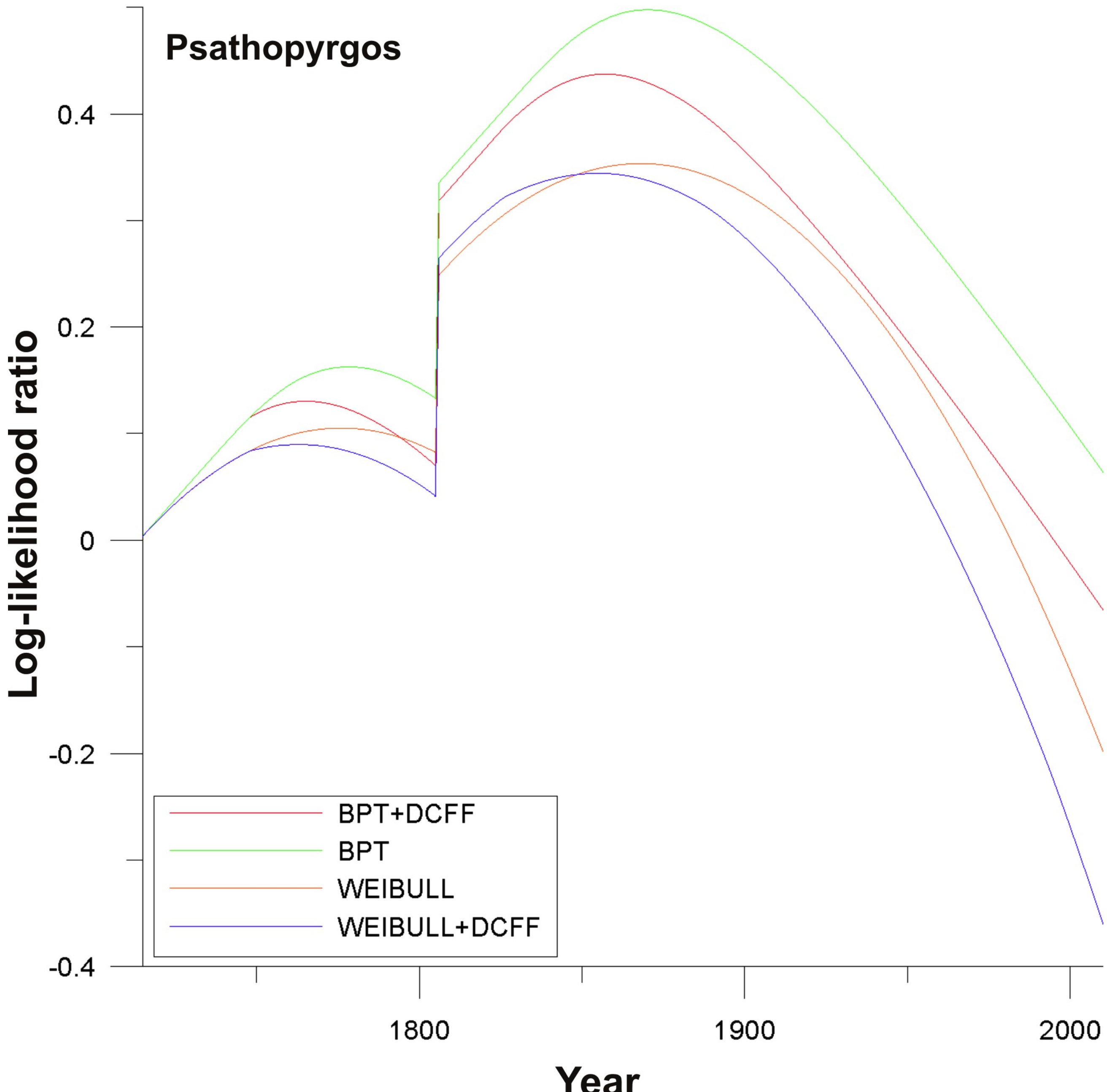
where: $\boldsymbol{p_i}$ is the probability associated with the *i*th cell in the space–time–magnitude volume, $\boldsymbol{c_i}$ is the binary value representing non-occurrence (0) or occurrence (1) of the event in the *i*th cell;

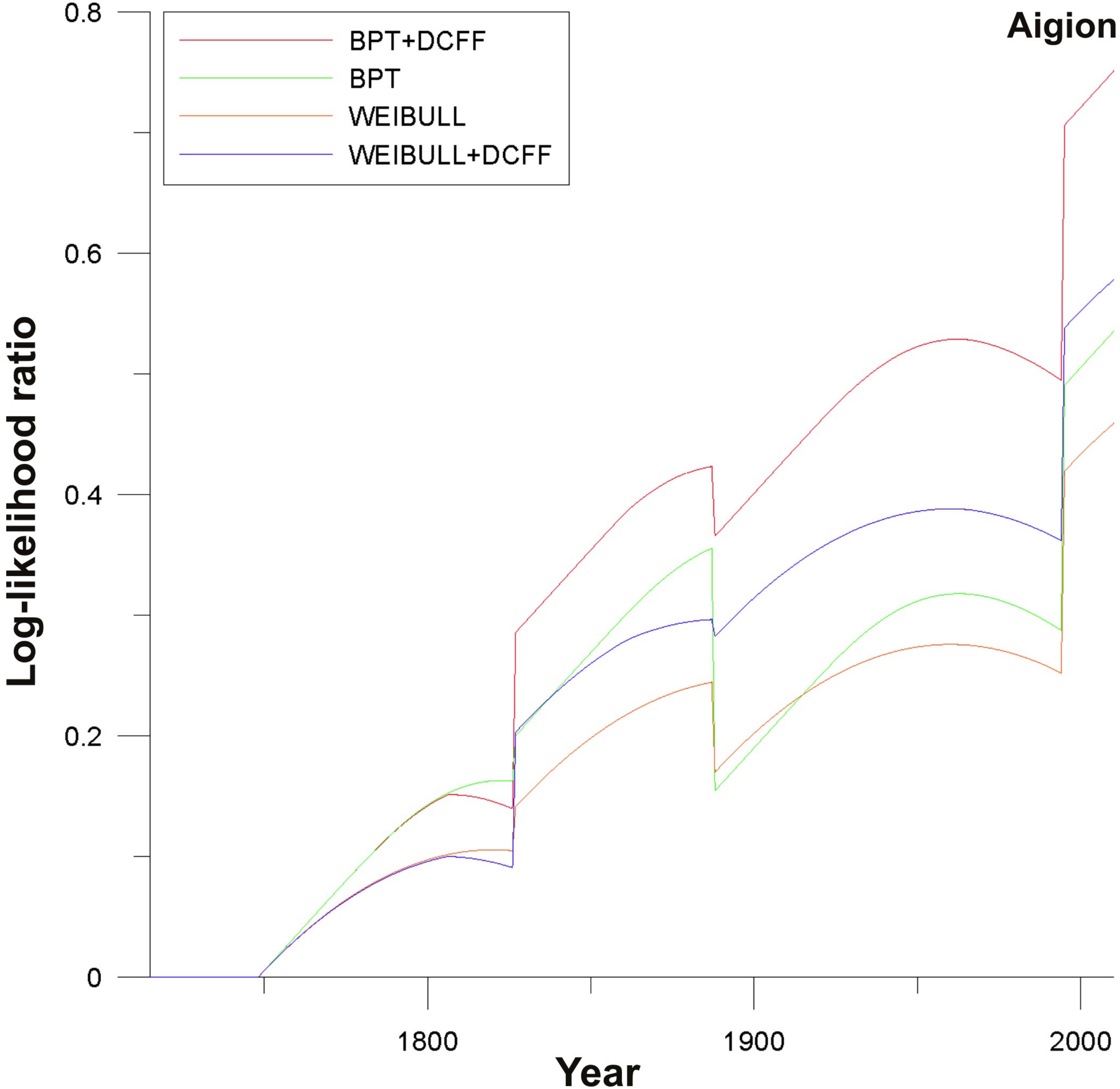
The log–likelihood ratio (Log R) is the difference between the log–likelihood computed under a model to be tested (L), and that computed for a reference model (L_0):

In our test the time–independent uniform Poisson model is taken as the reference model.

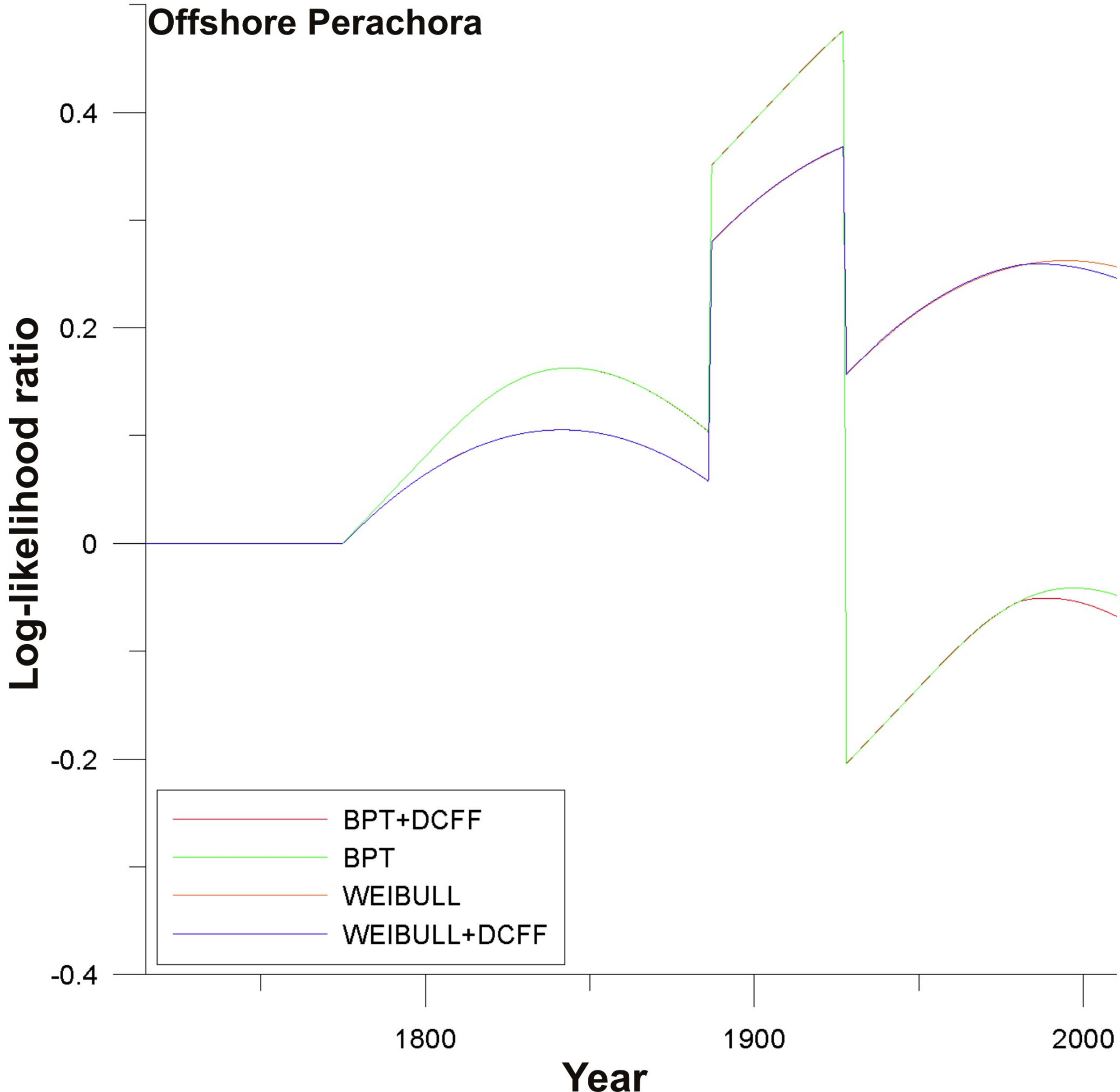
Plots of the log–likelihood ratio, computed under the four renewal models considered in this study (BPT, Weibull, with or without stress change effect), are shown for segments 1 (*Psathopyrgos*), 2 (*Aigion*) and 6 (*Offshore Perachora*), respectively.

Only segment 2 (*Aigion*) shows a stable positive trend of Log R; for the other two segments, the results show an alternation of positive and negative phases.


Psathopyrgos
Log-likelihood ratio
0.4
0.2
0
-0.2
-0.4
1800
1900
2000
Year
BPT+DCFF
BPT
WEIBULL
WEIBULL+DCFF



Aigion
BPT+DCFF
BPT
WEIBULL
WEIBULL+DCFF
Log-likelihood ratio
0.8
0.6
0.4
0.2
0
1800
1900
2000
Year


Offshore Perachora
Log-likelihood ratio
0.4
0.2
0
-0.2
-0.4
1800
1900
2000
Year
BPT+DCFF
BPT
WEIBULL
WEIBULL+DCFF