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Aftershock sequence analysis using a static fatigue approach

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Abstract. Four aftershock sequences that occurred in the area between the Friuli-Venezia Giulia region and Slovenia, from 1988 to 1998, are analyzed. The spatial patterns of the aftershocks are related to the main shock focal mechanisms. The computed focal mechanisms of major aftershocks evidence a complex slip faulting, in most cases with fault plane solution of similar type to that of the main shock, but with different plane orientation. The sequences are modelled with a log-linear relation between the released cumulative seismic moment and the time elapsed from the mainshock. The results support the hypothesis that the aftershocks energy decay is caused by a static fatigue process. Omori modelling of the sequences shows that the aftershock decay doesn't follow a smooth relaxation process. The occurrence rate of the aftershocks is characterized by sudden increases that are probably related to local stress concentration at some asperities in proximity of the main shock fault. The value of the exponent p is related to the heat-flow of the area.

1. Introduction

Aftershock hypocentres are usually clustered in space, suggesting the presence of multiple slip surfaces within or in proximity of the main fault zone. A characteristic feature is that the rate of the aftershocks decay is proportional to $1/t^p$, where t is the time after the mainshock, with p generally close to 1. Scholz (1968, 1972) explained the aftershocks as a delayed fracturing process caused by static fatigue. If a rock is subjected to stress, below its instantaneous breaking strength, the failure occurs after a time determined by the applied stress level. The static fatigue is caused by the slow growth of cracks favoured by the process of stress corrosion and can be modelled with an Arrhenius expression (Scholz, 1972). For Yamashita and Knopoff (1987) the occurrence of aftershocks is caused by stress inhomogeneities around the fault zone and it is

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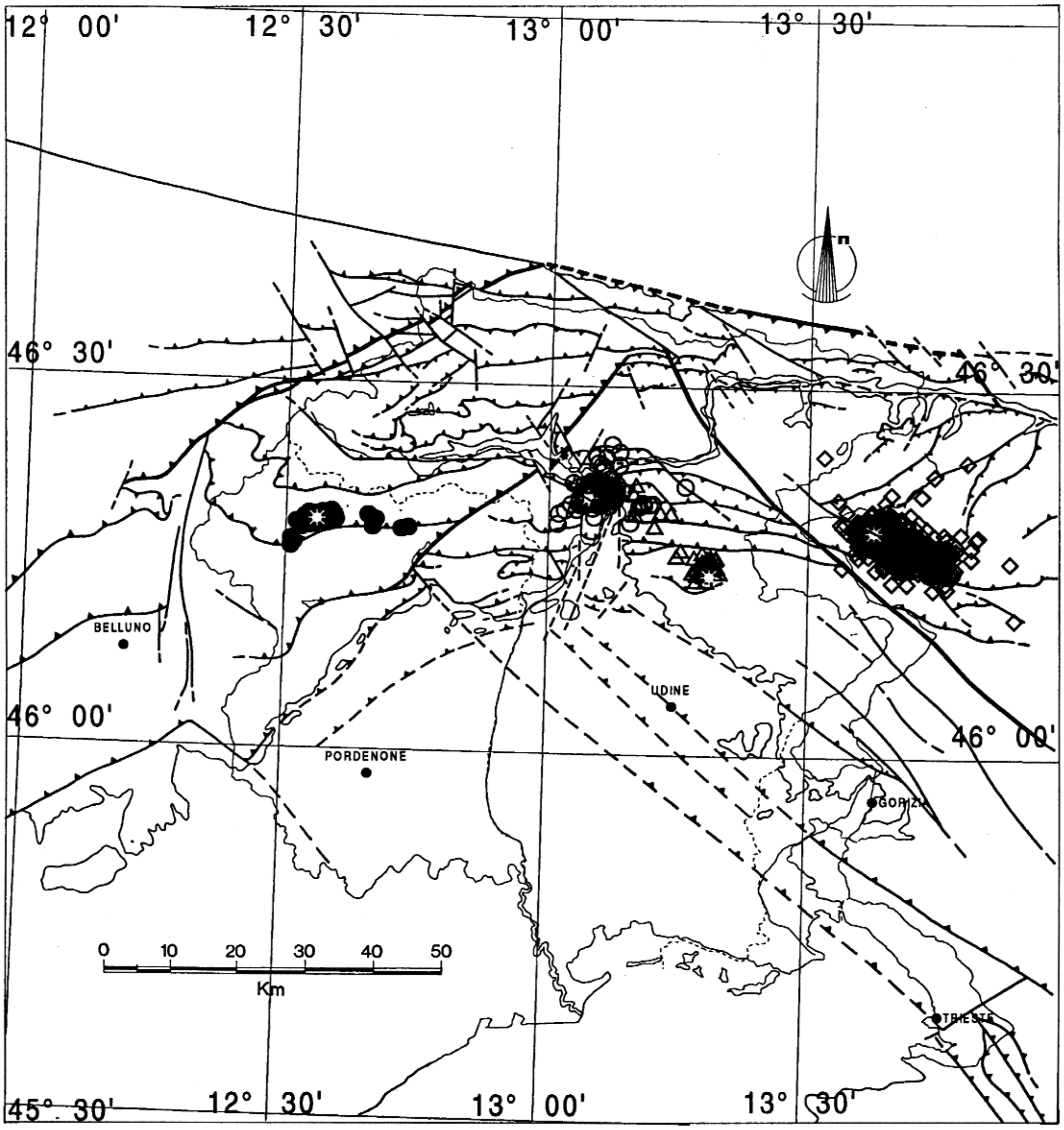

Fig. 1 - Tectonic map showing the locations of the analyzed earthquake sequences. Line: subvertical fault; saw-toothed line: thrust (modified from Venturini,1991). Open circles: BOO sequence - aftershocks following the February 1, 1988 main shock (M_L=4.2); triangles: LUS sequence - aftershocks following the October 5, 1991 main shock (M_L=3.9); full circles: CLA sequence - aftershocks following the April 13, 1996 main shock (M_L=4.3); diamonds: BOV sequence - aftershocks following the April 12, 1998 main shock (M_L=5.6); the main shock of each sequence is marked by an open asterisk.

favoured by stress corrosion cracking. Mendoza and Hartzell (1988) observed that the after-shocks pattern is caused by the redistribution of stress of main shock faulting and the earthquakes are triggered in the areas peripheral to the zone of maximum coseismic displacement. Dieterich (1994) formulates a model of aftershocks nucleation caused by a shear stress step due to the

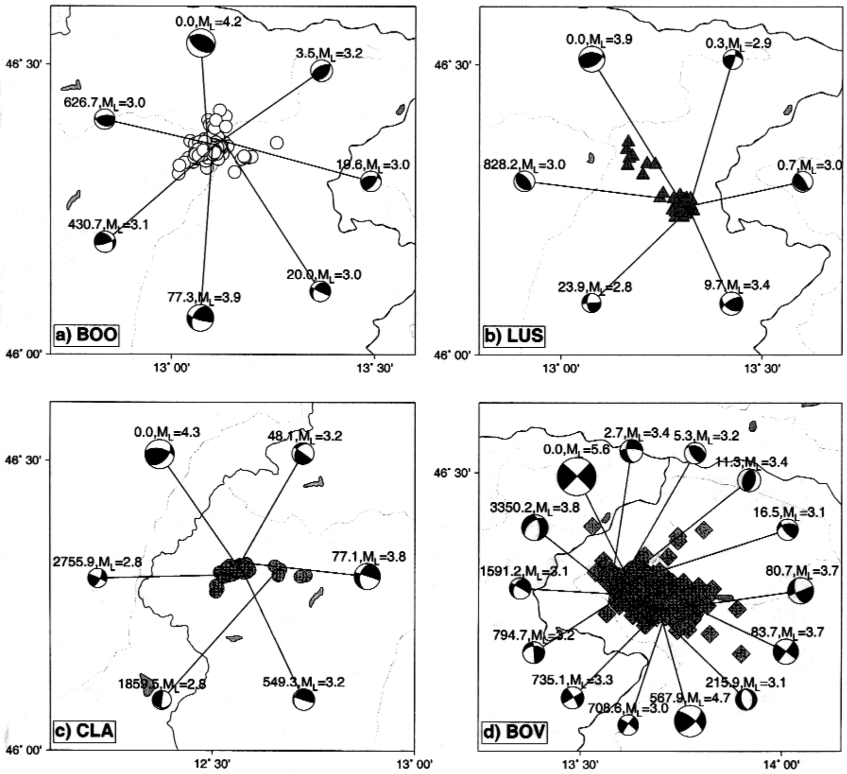

Fig. 2 - Map of earthquake sequences with fault plane solutions of the main shock and of the major aftershocks. The focal mechanisms are numbered according to their temporal occurence; elapsed time, in hours, from the main shock and the M_L are also shown. a) February 1, 1988 sequence (BOO sequence); b) October 5, 1991 sequence (LUS sequence); c) April 13, 1996 sequence (CLA sequence); d) April 12, 1998 sequence (BOV sequence).

dynamic rupture of the mainshock, with the rate of earthquake occurrence related to the stressing rate.

The rate of occurrence of four aftershock sequences that occurred in the area between Friuli-Venezia Giulia and Slovenia are analyzed together with the available focal mechanisms. The energy decay is investigated according to a static fatigue approach.

2. Aftershock sequences and focal mechanisms

Four aftershock sequences, recorded by the local seismic network of the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (Fig. 1), are analyzed. The events are located with the HYPO71 program (Lee and Lahr, 1975), the focal mechanisms solution of the main shocks and that of the stronger aftershocks (Fig. 2) have been computed with a program of Whitcomb (1973) based on first P-wave polarities. The aftershocks are selected inside a time window until the aftershock activity decreases to the level of background seismicity. We selected M_L 1.9 as the smallest local magnitude for the catalog completeness for all sequences.

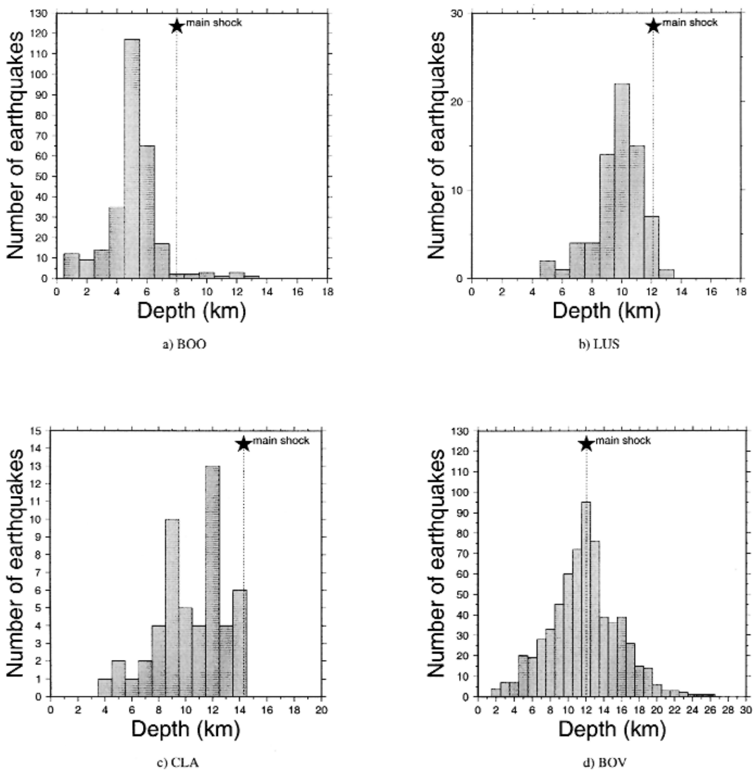

Fig. 3 - Depth distribution for each of the aftershock sequences under study. The depth of the main shock is marked by an asterisk.

1. The February 1, 1988 BOO sequence. The mainshock (M_L=4.2) is located at an 8 km depth, with a focal mechanism of thrust type with a negligible strike-slip component. The 286 aftershocks with M_L ranging from 1.5 to 3.9 are clustered in space and located mainly between a 4 and 7 km depth (Fig. 3a). All the available focal mechanisms of the strongest aftershocks show that thrusting is the dominant type of faulting, with fault planes differently oriented with respect to that of the main shock. After the magnitude cut-off for catalog completeness, the number of aftershocks retained is 159, with a time window of 2817 h starting from the main shock.
2. The October 5, 1991 LUS sequence. The mainshock (M_L=3.9) is located at a 12 km depth and is characterized by a thrust focal mechanism with a negligible strike-slip component. The focal depth of most of the 70 aftershocks (M_L ranging from 1.6 to 3.4) is between an 8 and 12 km depth (Fig. 3b) with a significant space cluster. The available focal mechanisms show thrusting motion and strike-slip motion with an inverse component. There is no clear relation between the main shock and the aftershock fault planes. The number of aftershocks retained for completeness of the catalog is 52, in a time window of 2710 h.
3. The April 13, 1996 CLA sequence. The focal mechanism of the main shock (M_L=4.3) shows thrusting with a strike-slip component with hypocentre located at nearly 14 km depth. The 91 aftershocks have a M_L ranging from 0.5 to 3.8. The located earthquakes are mainly distributed

between an 8 and 14 km depth (Fig. 3c). The space cluster is noticeable. The focal mechanisms of the strongest aftershocks are strike-slip and thrust with strike-slip components, with focal planes different from those of the mainshock. The aftershocks selected for the completeness of the catalog are 75 in a time window of 3019 h.

4. The April 12, 1998 BOV sequence. The mainshock (M_L=5.6) is located at a 12 km depth. The computed focal mechanism shows a pure strike-slip motion. The location of the aftershocks defines a rough NW-SE elongated ellipse around the plane of the main shock fault. The 652 aftershocks are mainly distributed between an 8 and 14 km depth (Fig. 3d), with local magnitude ranging from 1.4 to 4.7. The focal mechanisms available are of various types, even if strike-slip motion prevails, showing that the earthquakes occur on multiple slip surfaces. Some focal mechanisms are concordant with a continued slip on the main fault. The earthquakes selected for completeness of the catalog are 492, in a time window of 3334 h.

The aftershocks of the BOO, LUS and CLA sequences are spatially clustered over the main shock location. The main shocks are all characterized by a thrust focal mechanism. The aftershock clouds appear to be connected to upward stress propagation induced by the hangingwall deformation above the main shock faulting. The aftershock pattern of the BOV sequence occurs with different features. The NW-SE elongated aftershock zone and the quakes depth location (a roughly gaussian distribution around the main shock hypocenter) conform with main event strike-slip motion. A common aspect of the sequences examined is that the orientations of aftershock focal planes are in most cases, with the exception of some BOV aftershocks, different from that of the main shock. A plausible explanation is that the main shock significantly perturbs the local stress field and the aftershocks occur on faults around the main shock fault that are optimally oriented for failure. The change in stress caused by coseismic displacement of the main shock plus the regional stress tensor, control the orientation of the local stress tensor, and therefore, the orientation of the optimum slip planes, in accordance with King et al. (1994).

3. Analysis and discussion

The sequences are modelled by the Marcellini approach (1995 a, 1995 b), based on the empirical static fatigue relation of Zhurkov (1965). The aftershock initial stress conditions are so fixed: at the origin time of the mainshock, the stress in the fault zone is given by the superposition of the fracture stress (the static stress just before the event) and a shear stress step (the stress caused by the dynamic rupture effect). The aftershock decay model is expressed in the following form (Marcellini, 1997):

$$S(t_i) = d\sigma + \frac{RT}{\gamma} \cdot \ln t_i / t_0 \qquad (1)$$

where t_i is the time after the mainshock of the i-th aftershock, t_0 is set 1 arbitrarily, $S(t_i)$ is the cumulative stress drop, $d\sigma$ is the dynamic stress step, R the universal gas constant, T the absolute temperature and γ a constant. Zhurkov (1965) relates this parameter to the molecular structure

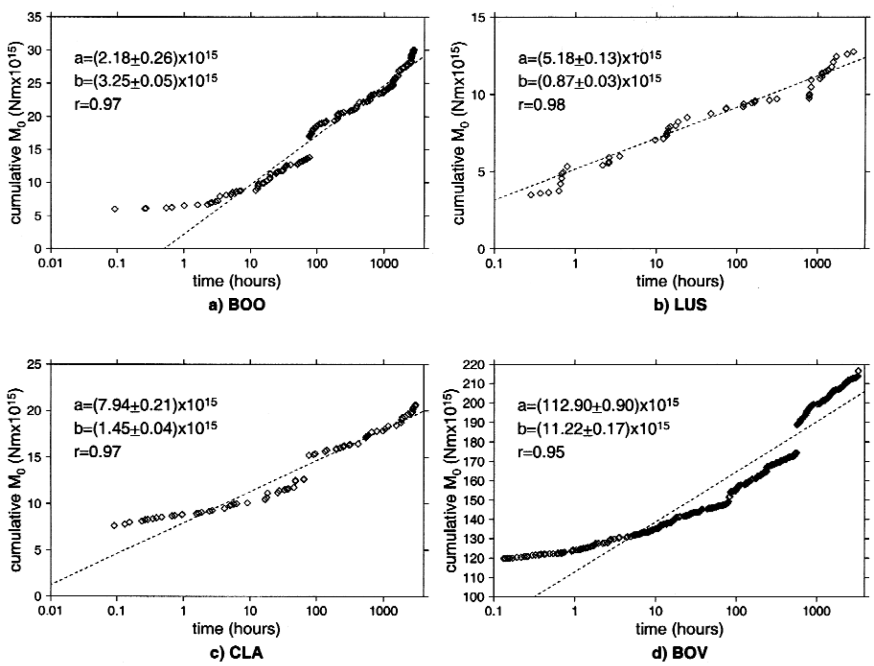

Fig. 4 - Fit (dashed line) of Marcellini's decay model (1995a, 1995b) to the analyzed earthquake sequences (diamonds). The cumulative seismic moment is expressed in N m. The parameters *a* and *b*, with standard deviation, obtained from the regression of Eq. (2) and the correlation coefficient *r* are shown.

disorientation in response to applied stress, using evidence from lab tests on several kinds of specimens.

Using $M_0 = \Delta\sigma\, V$ (Madariaga, 1979), where M_0 is the seismic moment, $\Delta\sigma$ the stress drop and V the focal volume, Eq. (1) becomes:

$$M_{0m} + \sum_{j=1}^{i} M_{0j} = a + b \cdot \ln t_i \tag{2}$$

where

$$a = V_i d\sigma, \;\; b = V_i \;\; RT/\gamma, \;\; V_i = V_0 + \sum_{j=i}^{i} V_j, \tag{3}$$

V_i cumulative focal volume, V_0 focal volume of mainshock, V_j focal volume of the *j*-th aftershock, M_{0m} seismic moment of the mainshock and M_{0j} seismic moment of the *j*-th aftershock.

The spatial variations of the stress are not considered in the present model. The relation of Madariaga (1979) gives the seismic moment as the product of the stress drop by the source volume associated to the rupture plane. Physically for Madariaga (1979) this volume is the region where large deformations, that are related to slip on plane faults and to general inelastic strain, occur. Following this approach, we consider the focal volume at time t as the volume affected by the overall deformation due to slip on a series of faults, that, as shown by the focal mechanisms, are often not coplanar with the main shock faulting.

The dynamic stress induced by the mainshock, causes a redistribution of stress in the volume surrounding the fault zone. Delayed fractures (aftershocks) occur by static fatigue on asperities in the neighbourhood of the main fault, once the fracture stress is reached. The asperities are small unbroken patches on the main fault plane and local patches near the end of the rupture, where large stress concentrations result from dynamic rupture. The effect of the main shock shear stress step results in a steady increase of the stress intensity factor on each asperity, where the crack grows quasi-statically up to failure, with a time delay depending on the initial value of the stress intensity factor. Aftershock i occurs at time t_i with stress drop $\Delta\sigma_i$, followed by another aftershock at time $t_i+\Delta t_i$ and so on, until the stress concentration is relaxed. The static fatigue modelling of aftershock sequences implies that the induced mainshock stress change is uniform in the cumulative focal volume.

Seismic moments were derived from M_L using the Marcellini (1995a) relation: $\log M_0=11.87+0.93M_L$. The aftershock sequences are modelled by Eq. (2), with least square regression analysis. Fig. 4 shows the modelled sequences together with the parameters obtained from regression.

Fig. 4 shows that a great number of aftershocks occurs in the hours immediately following the main shock. A favoured explanation is that the asperities, located on or near the main shock fault, experience large stress close to the stress state of the main shock and therefore break in a short time. As mentioned before, the log-linear relation between the cumulative seismic moment and time after the mainshock is tied to the condition of uniform mainshock stress change. So the quality of the fit is an indicator of the stress distribution in the focal volume. The better the fit the more the distribution of stress on the asperities is uniform. In the investigated cases the fit of the model to the aftershock sequences seems good (correlation coefficient r between 0.94 and 0.98, see Fig. 4), in comparison also to the results of Marcellini (1997).

A close inspection of Fig. 4 evidences some steps in the cumulative seismic moment release with time and in some cases not regular elapsed time of asperities breaking. Our favoured explanation is that these departures from the fit are caused by stress concentrations, i.e. not uniform conditions of stress in the focal volume as would be expected by the static fatigue approach. Scholz (1972) pointed out that the scatter in the fracture time is characteristic of static fatigue experiments and is probably due to fluctuations in the strength of the rock volume.

Eq. (3) states that the constant a is directly related to the dynamic stress step $d\sigma$, but we cannot check the validity of this relation because direct estimations of $d\sigma$ are not available. The values of the constant b (Fig. 4) seem to be influenced more by the cumulative focal volume, since γ is not significantly different from one earthquake to another (Marcellini, 1997) and the temperature T is very likely the same (Cataldi et al., 1995) for all the analyzed sequences.

All sequences are analyzed with the Utsu's (1961) modified Omori law, that describes the

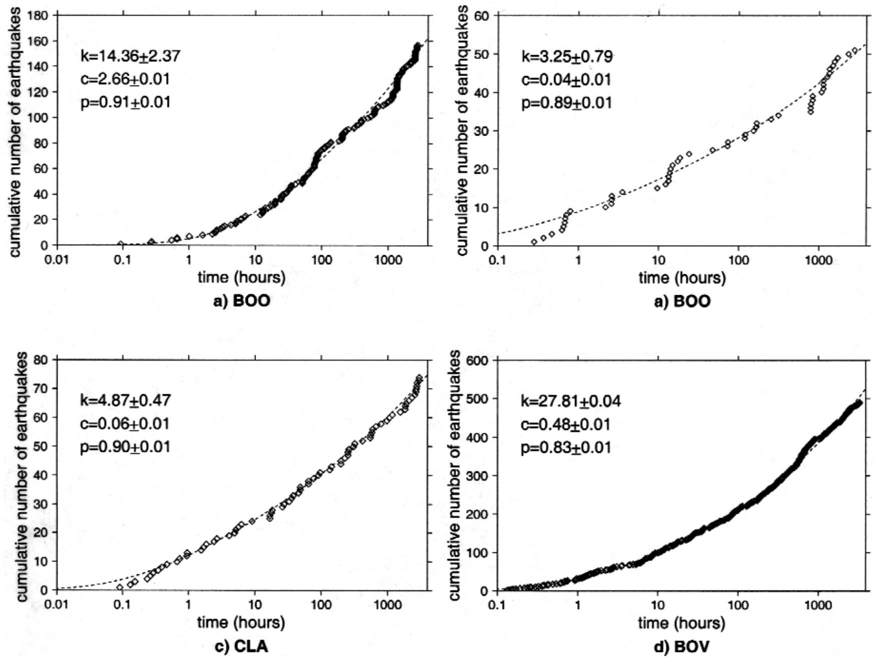

Fig. 5 - Occurrence rate of the aftershock sequences modelled according to Utsu's formulation (1961). Diamonds: events; dashed line: fit. The parameters *k*, *c* and *p*, with standard deviation, obtained from the regression of Eq. (4) are shown.

rate of occurence of the aftershocks as a function of time after the mainshock:

$$n(t) = k(t+c)^{-p} \tag{4}$$

where $n(t)$ is the number of events per unit t; k, c and p are constants. p is related to the decay of aftershocks and for Utsu et al. (1995) the p values of well documented aftershock sequences vary from 0.6 to 1.55. and   are related respectively to the total number of events and to the rate of activity in the earliest part of the sequence (Kisslinger and Jones, 1991).

The modelled sequences and the results of the regression are shown in Fig. 5. All regressions exhibit a low value of p. Kisslinger and Jones (1991) found a direct correlation of p values with surface heat flow. Since the aftershocks are a process of relaxing stress clustering and the stress relaxation is a thermally influenced process, the relaxation time and, hence, the decay of the aftershocks are directly related to the temperature in the crust. For Kisslinger and Jones (1991) high p values, that means a rapid decay of aftershocks, occur where the heat flow is high, while low p values are related to low heat flow. The low value of p obtained, ranging from 0.83 to 0.91, are consistent with the above observation since all the sequences are located in an area characterized by relatively low values of heat flow: 50-60 mWm^{-2} (Cataldi et al.,1995).

The direct correlation of p and temperature T has been emphasized by Marcellini (1995a), by substituting Omori's law in its simplest form $-n(t)=kt^{-p}$ in Eq. (1):

$$p = \frac{\ln k - \ln n(t)}{(S(t_i) - d\sigma)_\gamma} RT \tag{5}$$

The inverse dependence of p from the difference between the cumulative stress drop and the dynamic stress step $S(t)-d\sigma$ should be noted.

The fit to Omori's relation (Fig. 5) shows that the aftershock sequences are not characterized by a smooth relation, but changes in the occurrence rate are present. In detail, sudden increases in the event rate are recognizable, directly related to the sharp discontinuities (increases in seismic moment release) of the cumulative seismic moment versus time (Fig. 4). For Das and Scholz (1981) the implicit assumption of Omori's relation is that the stress relaxation occurs with a gradual decrease of the event rate, involving a random distribution of the stress intensity factor of the asperities. So, the departure from a smooth fitting to Omori's law, for the analyzed sequences, implies different stress concentration on the asperities in the focal volume that results also from the static fatigue modelling. Further support to this argument comes from Dieterich (1994) who proposed a model where aftershocks are caused by the steplike change of stress induced by the mainshock, deriving expressions for the seismicity rate as a function of time after the stress step. Dieterich (1994) showed that the aftershock decay gives p=1.0 if stress change is uniform over the volume affected by the sequence. If non-uniform stress change is considered, the model predicts $p \approx 0.8$ for aftershock decay, a similar value to that obtained in the present study.

According to Correig et al. (1997), the sudden increase in the occurrence rate of aftershocks could be explained by high stress concentration at asperities: a "leading" aftershock would initiate the failure of the asperity that would proceed with an avalanche series of events.

4. Conclusions

The log-linear relation of the seismic moment release versus time, after mainshock, favours the hypothesis that the aftershock decay is caused by a static fatigue process. The relation implies an uniform mainshock stress change. The better the fit, the more the mainshock stress change is uniform in the aftershock volume. Departures in the fit, such as steps in the temporal seismic moment distribution, are related to stress concentration on some asperities in the volume surrounding the main fault. Stress concentration is very likely the cause of sudden changes in the occurrence rate of the aftershocks and this is reflected in departures from Omori's law. The induced stresses in the aftershocks volume relaxes at a rate that depends on the rheological properties of the main fault zone materials. Since the aftershock activity is characterized by a sharp decay in higher temperature zones where the stress relaxation is faster and vice versa, the low value of the p exponent of Omori's relation obtained for the analyzed sequences is presumably related to the low heat-flow of the area.

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