Revision of the theoretical and observational grounds of the seismic hazard estimates at a national scale

Coordinator: Paolo Gasperini

Introduction

We would like to point out that this re-proposed project received the present year funds only around the half of January 2003. For this reason this report will reflect activities formally carried out in a time period definitely shorter than one year. In particular, for the peculiar nature of the collaboration with the private research company SGA, the planned activities in the ambit of Task 1 are still at a very early stage and will be presented here in a preliminary form. We thus reserve ourselves to complete the reporting at a successive time. On the contrary the activities concerning the other research lines were pursued almost exactly according to the initial program, due to the voluntary effort of the contributors, although with some difficulties.
The objectives of the project, as also described in the re-proposition proposal, have been resized with relation to the referees' comments and to the amount of assigned funds. The corresponding activities affects only 4 of the tasks initially proposed. This strongly reduced the unitariness and coherency of the project that originally was thought to have, as final product, the revision of hazard estimates at national scale.
We tried however to develop a proposal that, starting from the activities that the Evaluation Commission have judged new and innovative, was able to give results directly usable by other GNDT project. In this ambit, as also suggested by the Commission, we tried to integrate our project with the one coordinated by A. Amato through information exchanges, in order to avoid superposition or duplication of objectives. For this reason some researches we proposed have been thought to give products that can be easily used by anyone. Among the others we want to mention the "Boxer" code to analyze macroseismic data and the database of Earthquake Mechanism of Mediterranean Area (EMMA). These are tools designed for a free usage by Italian and foreigner investigators and for which we also prepared a reference manual.
In the following we synthetically report, for each of the active tasks, the planned activities, the expected results in the two years (second and third) of the re-proposition and those effectively achieved in the second year.

Task 1 HISTORICAL SEISMIC CATALOG (Responsible: Gasperini, Participants: Albarello, Bernardini, Camassi, Castelli, Ercolani, Lolli, Vannucci e SGA Working Group)

The planned activities concern.

i) Improvement of Boxer code by the introduction of the bilinear attenuation law (Gasperini, 2001).
ii) Development of new methods to compute the epicenter for offshore earthquakes.

iii) Development of robust techniques to estimate the depth of the source from macroseismic data.

iv) Application of the Fuzzy Sets algorithm for intensity estimates to some strong Italian earthquakes.

Expected results for the second year.

- New release of Boxer code for the computation of the location, the magnitude and the orientation of the source of historical earthquakes from macroseismic data using the bilinear attenuation law.
- Application of the Fuzzy sets algorithm to compute the intensity field of the 1930 Irpinia earthquake.

Expected results for the third year.

- New release of Boxer code allowing the location of offshore epicenters and the computation of depth.
- Application of the Fuzzy sets algorithm to other strong Italian earthquakes.

Results achieved in the second year:

We implemented a new "experimental" version of the Boxer code using the attenuation law proposed by Gasperini (2001). This was tested on Ligurian earthquakes of July 19, 1963 and some earthquakes of the Middle East.

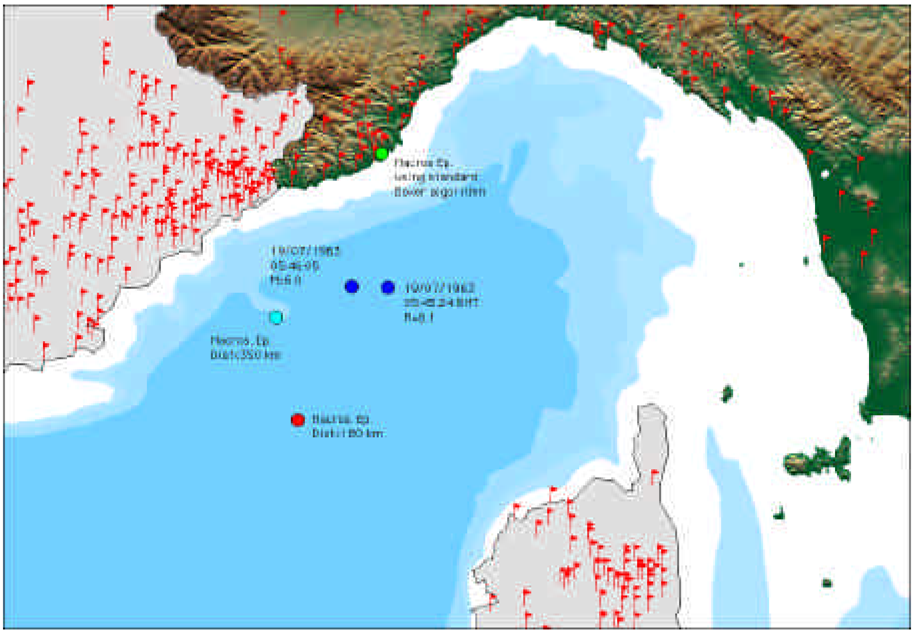

Figure 1. Macroseismic field of Ligurian earthquakes of July 17, 1963. The instrumental epicenters (ISS data) of the two main shocks, occurred at a minute one from the other, are indicated with dark blue circles. The macroseismic epicenter (regarding the effects induced by both shocks) computed by the previous version of Boxer code (3.2) as the barycentre of localities with maximum intensity (VI) is indicated in green. With light blue and red circles we reported instead the epicenters computed with the new version of Boxer code (4.0) using two different approaches: the first one using all data within a radius of 350 km, the second one the maximum distance is reduced to 180 and are only included localities where the expected intensity is larger or equal to IV (see Gasperini, 2001). The moment magnitude is 6.1 and the epicentral intensity (theoretical) is IX. It was not possible instead to evaluate the orientation of the source due to the lack of data in the epicentral area.

In Fig. 1 we can see how the modified algorithm, different from the one previously used by Boxer code (version 3.2), is able to correctly locate the earthquake in the sea. Although the correspondence with the instrumental epicenters is not particularly good, the result appears promising for future developments of the method.

By the technique developed by Ferrari et al. (1995) and Vannucci et al (2000), making use of *Fuzzy Sets*, we encoded and elaborated the data of observed effects for the July 23 1930 Irpinia earthquake, to obtain objective and reproducible estimates of the intensities. The comparison with other events previously studied through this method (S.Sofia 1918, Mugello 1919 e Garfagnana 1920) indicates a typology of information rather different. In fact if we use the empirical membership functions deduced from the other events ("invertite") we obtain macroseismic fields very different from the one obtained by the membership function deduced from the event itself ("proprie") as well as from the very similar one evaluated by a macroseismic "expert". This discrepancy is particular evident comparing the results of the application of the Boxer code on the different macroseismic fields (Fig. 2).

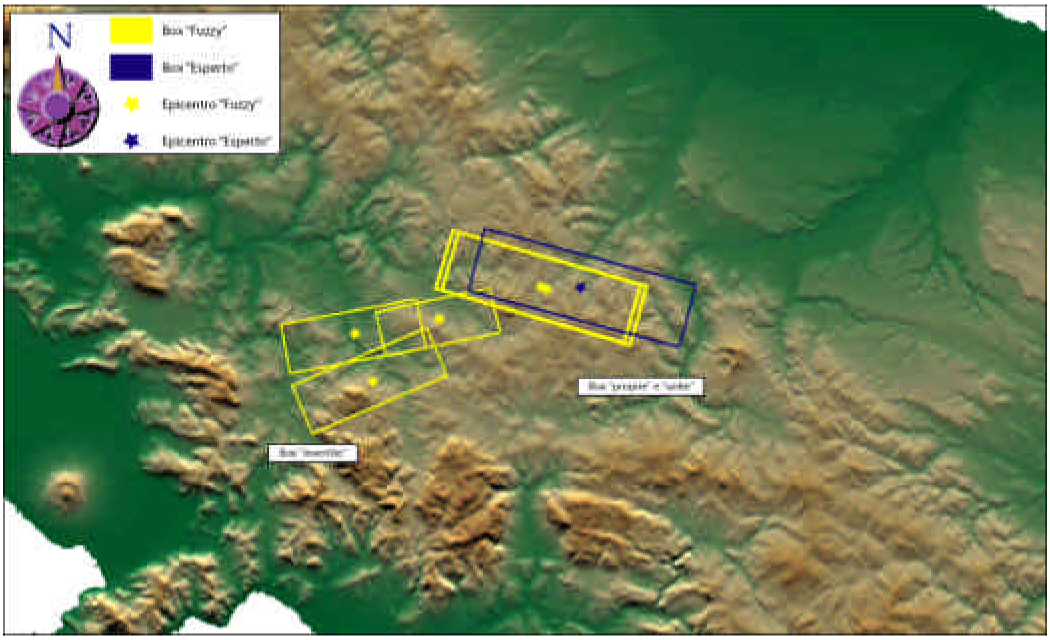

Figure 2. Application of the Boxer code (version 3.2) to the macroseismic fields of the July 23, 1930 Irpinia earthquake, as resulting from the Fuzzy algorithm estimates (in yellow) and from the estimates made by a macroseismic "expert" (in dark blue). The "invertite" boxes concern elaboration made using Fuzzy membership functions deduced from the data of other earthquakes (S.Sofia, 1918, Mugello, 1919 and Garfagnana, 1920). The "proprie" and "unite" boxes refer instead to the evaluations made using membership functions deduced from the 1930 earthquake itself and from the union of the data of all earthquakes respectively.

Task 6C, INTENSITY TOMOGRAPHY AND SITE EFFECTS (Responsible: Gasperini, Collaborators: Albarello, Bernardini, Camassi, D'Amico, Ercolani, Lolli, Mucciarelli, Vannucci)

The planned activities concern.

i) The detailed comparison of locality empirical residual with the lithological and topographical characteristics of sites in order to verify whether they are actually linked to specific local properties of the sites rather than to the uncertainties in the determination of intensity.

ii) Introduction of the seismic source spatial orientation in the bilinear attenuation equation in order to make more realistic and precise the computation of distances. This can be done both using the Boxer technique (Gasperini *et al.*, 1999) or computing, simultaneously to the tomographic inversion, the orientation of sources that minimize the equation residuals.

iii) Extension of the intensity dataset by the inclusion of the new data coming from the INGV macroseismic Bulletin of years 1993 to 1997.

iv) Continuation of the study (Boccaletti et at., 2001) on the lateral variations of intensity felt in the historical center of Florence on occasion of the 1895, Impruneta earthquakes and comparison with results of 1D simulation of ground motion and with soil amplification measures

Expected results for the second year.

- Integrated macroseismic database including the data from the INGV macroseismic bulletin for all the events with Imax>V.
- Preliminary tomographic inversion using the updated database.
- Introduction of the spatial extension of the sources in attenuation computations.
- Study of the lateral variations of the intensity in Florence for the earthquakes of 1895 compared with 1D simulations of ground motion.

Expected results for the third year.

- Database of the lithological and topographical characteristics of the localities having felt reports for more than 10 different earthquakes, basing on data used for the new tomographic inversion.
- Definitive tomographic inversion using the updated methods.
- Comparison of the lateral variations of the intensity in Florence with measures of soil amplification.
- Study of the lateral variation of intensity for other historical centers.

Results achieved in the second year.

We prepared a preliminary version of the macroseismic database, integrating the data coming from DOM (Monachesi and Stucchi, 1997) and CFTI(Boschi et al. 1995, 1997, 2000) on the basis of the choice made in the CPTI (CPTIWG, 1999), with data from the INGV Macroseismic Bulletin of events with Imax>V from 1993 to 1996. We also substituted the data coming from the Version 2 of CFTI (used by CPTI) with those of version 3 (Boschi et al., 2000) also adding the earthquakes that were not present in the previous version. The database now includes in all 61638 intensity data (of which 7102 added) relative to 2622 earthquakes (of which 142 added). We also approached the reordering and standardization of the catalog of localities that have intensity data. This was including initially 26450 localities, due to the different encoding of DOM CFTI and INGV Bulletin. After the reorganization the distinct localities are only 12267, although further tests and controls are necessary to eliminate possible further duplications.

On the basis of such integrated dataset, we made a new tomographic inversion of macroseismic intensity attenuation. With respect to the previous one (Carletti e Gasperini, 2003) presently in course of revision on an international journal, the database was extended, besides the data after 1992, even to ones, previously excluded, from 1600 to 1800. The total number of macroseismic observation used thus augmented from 19997 to 25864, with a relative improvement of about 30%. The inversion results (Fig. 3) are very similar to ones obtained previously and only slightly extend the covered area. The main improvement concerns instead the definition of locality residuals that can be used to evaluate site effects. The number of usable localities (with 8 intensity estimates at least) almost duplicates going from 285 to 559. The reason of such a large increase can be attributed to the larger frequency of localities that are selected by the INGV for sending the macroseismic questionnaires.

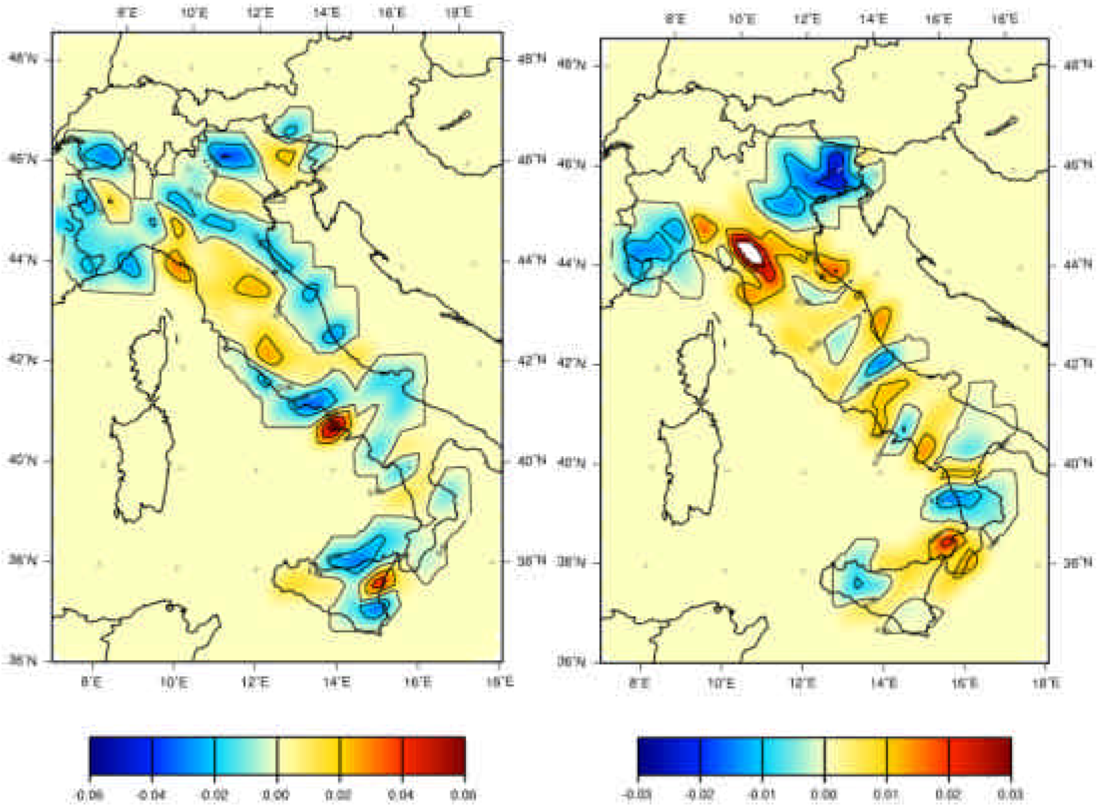

Figure 3. Results of tomographic inversion of seismic intensity attenuation for the new integrated dataset. On the left the differences with respect to average for the slope of the first trait (distance<45 km) of the bilinear attenuation model (Gasperini, 2001). On the right the same representation for the second trait (from 45 to 180 km). The areas in red are characterized by attenuation larger than average, while the blue ones by attenuation lower than average.

Just on the basis of the list of locality empirical residuals obtained by tomographic inversion, we faced up an analysis to characterize the sites from the point of view of the surface lithology and topography. Using the available geological maps (mainly obtained through the internet server managed by the Siena University), we classified 149 localities among those for which we computed an average residual using more than 10 macroseismic observations. We used a slightly modified version of the classification schema prepared by the Rovelli (INGV) group participating to the Amato GNDT Project.

Basing on such schema the surface geology is divided in A = Consolidated Lithoid character, B = Consolidated Semilithoid character, C = Unconsolidated (thickness<20m), D=Unconsolidated (thickness>20m).

The unconsolidated classes are further subdivided on the basis of the substratum: a=Lithoid character, b=Semilithoid character, c=Mixed character, d=unknown.

Finally, on the basis of the topography, the sites are evaluated in relation to the location of the majority of the buildings. The categories are: Coast, Crest, Plain, Valley, Slope.

In practice some of these classes resulted difficult (when not impossible) to evaluate on the basis of the cartography only. In particular it was never possible to infer the presence of layers thinner than 20 m and thus the C class resulted empty. However this investigation, that is presently at still a preliminary stage, allowed to identify al least two quite clear situations. These regards the combination of class A (Consolidated lithoid) in Plain, that significantly attenuate with respect to average (about 0.4 intensity degrees), and class B (consolidated semilithoid) in Valley that significantly amplify (about 0.2 intensity degrees). Further refinements are in course relatively to the extension of the number of classified localities and to the study of the time behavior of the residual for given localities.

Figure 4. Map of seismic zonation of the urban area of Florence in terms of EMS92 intensity, based on the analysis of effect on buildings of earthquakes of may-june 1895. The sites where we measured spectral rates (HVSR) are indicated with blue stars. A magenta star indicates where S waves velocity measurements are also made (some of the investigated point are external to the figure).

In the ambit of a seismic micro-zonation analysis of the city Florence we had carried out in the first year of the project, we made measures of background noise spectral rates in 15 sites located within the urban area as well as S-waves velocity profiles in 7 of these sites. The results of these investigations, that are still in course of elaboration (Albarello et al. 2003), will be compared with the lateral variation of EMS92 intensity deduced for the 1895 earthquakes (Fig. 4) and will also be used to constrain 1D simulations of ground motion.

Task 5 STATISTICS OF SEISMIC SOURCES AND CATALOG COMPLETENESS (Responsible: Marzocchi, Collaborators: Albarello, Dal Forno, D'Amico, Faenza, Gasperini, Lolli, Mucciarelli, Sandri, Selva, Vannucci)

The aim of this Task is to analyze the available seismological data (seismic catalogs, focal mechanisms, macroseismic fields, etc.) and to design specific experiments to verify the various hypotheses and theories on earthquake occurrence that has been proposed in the literature, as well as the ones that could issue from the research itself. We intend to study the modalities of the earthquake occurrence

i) in space (seismogenic model)
ii) in time (statistical occurrence models)
iii) in energy (scaling law)
iv) in ground motion amplitude at site (attenuation law and local effects)

Expected results for the second year.
None (not planned)

Expected results for the third year.

- Spatial seismic occurrence model relative to both the historical (long time-scale) and instrumental (short time-scale) seismicity.
- Statistical time occurrence model and its calibration on instrumental data.
- Verification of the magnitude scaling law for the instrumental catalog.
- Verification of the seismic attenuation law currently in use.
- Statistical model for the time series of the intensity felt at the site.

Results achieved in the second year.
We analyzed the spatio-temporal distribution of large earthquakes by a new non-parametric multivariate model. The method presents several advantages compared to other more traditional approaches. In particular, it allows to test straightforwardly a variety of hypothesis, such as any kind of time dependence (i.e., seismic gap,cluster, and Poisson hypothesis). Moreover, it may account for tectonics/physics parameters that can potentially influence the spatio-temporal variability, and to test their relative importance. The method has been applied to the Italian seismicity of the last four centuries (CPTIWG, 1999). The results show that large earthquakes in Italy tend to cluster; the instantaneous probability of occurrence is higher immediately after an event and decreases until to reach, in few years, a constant value. The results also indicate that the clustering is independent of the magnitudes of the earthquakes. A map of the probability of occurrence for the next large earthquakes in Italy in the next

10 years was provided (Fig. 5). This work is currently submitted to an international journal (Faenza and Marzocchi, 2003).

We also continued the activities in the field of the statistical modeling of earthquake occurrence properties. A first paper (Lolli and Gasperini, 2003a) regarding the forecast of seismic aftershocks in Italy, making use of the Reasenberg and Jones (1989) model is currently in press. Other two studies are at an advanced state of preparation. They regards the validation (Lolli e Gasperini, 2003b) of the results of the first paper by the comparison with the data from 1997 to 2002, recently made available at the INGV web site and the evolution of the aftershock occurrence model Gasperini e Lolli, 2003).

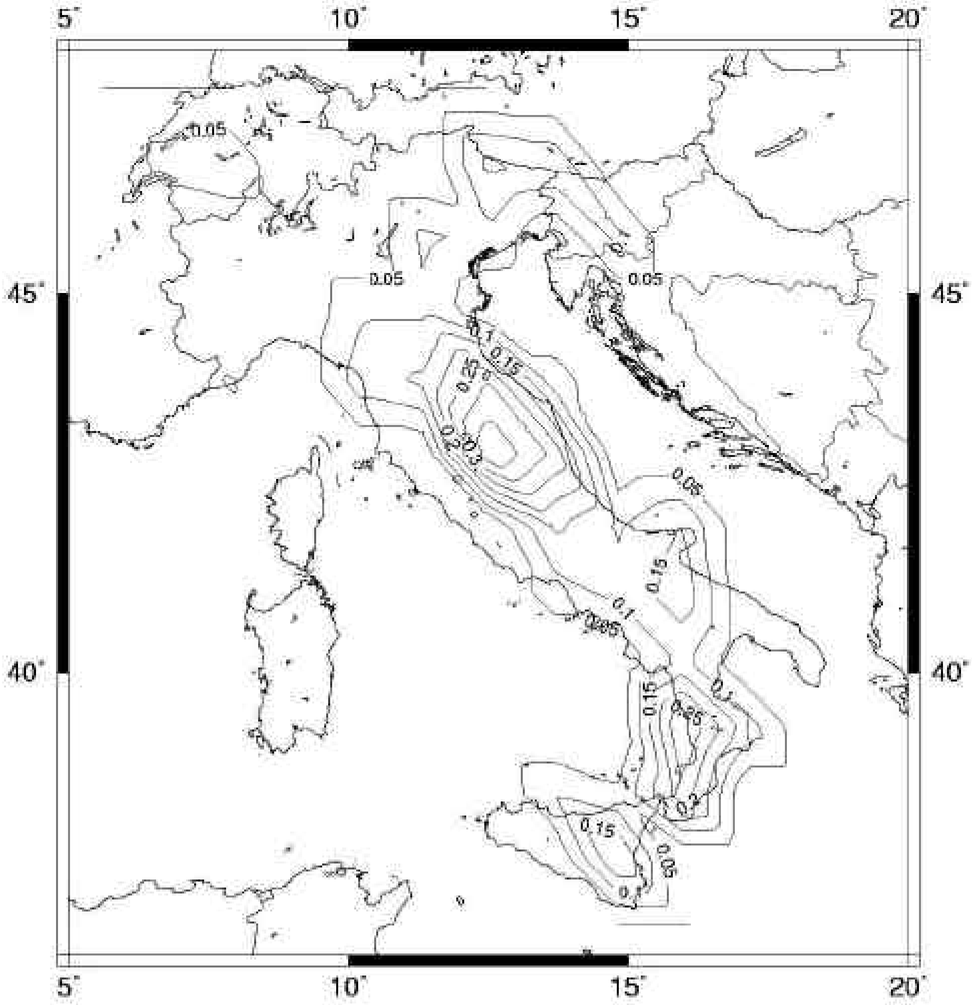

Figure 5. Map of the probability of occurrence for the next large earthquake in Italy in the next 10 years.

The comparison between the aftershocks average properties for the two datasets (Fig. 6) shows a good agreement for the time decay rate while the absolute rates result about twice after 1996 with respect to the period before. This discrepancy could be due to a residual calibration bias among the magnitude estimates in the two

periods. We also observed that at significant fraction of the sequences occurred after 1996 (like for example the Umbria-Marche one of 1997-1998) shows a “swarm” behavior with many shocks with similar energy rather than the classical mainshock-aftershock behavior. In these cases the model used until now is clearly inadequate.
To overcome this limit we tackled the problem of the formulation of a new occurrence model, introducing the epidemic principle (ETAS, Ogata, 1988) according to which every shock of the sequence is on its turn a source of further aftershocks. In parallel we studied the role of the parameters of the Reasenberg e Jones (1989) model by a correlation analysis among the values estimated in different regions of the World (California, New Zealand, Italy). The model we proposed as the most suitable to represent the time behavior of the shocks rate even for complex sequences is the following:

$$l(t) = 10^{-bM_{min}} \left[m_0 + \sum_{t_i=1}^{L(t)} \frac{10^{a_1 + b_1 M_{0_i}}}{(t - t_i + c)^p \int_{t_i}^{T} (t - t_i + c)^{-p} dt} \right]$$

where the parameters appearing in the summations (a_1, p, c, b_1 e b) are not correlated among each other and thus can be considered as representative of specific physical properties. Parameter m_0 is the background seismicity rate, while c is a time shift that slow down the decay in the first hours after the shock. Parameters a_1 e b_1 are the index of the productivity independent of and depending on the mainshock magnitude respectively. Finally $L(t)$ is the number of generating events preceding the time t. The parameters are estimated maximizing, by non-linear multiparameter optimization techniques, the log-likelihood function of the process:

$$l(p,c,a_1,b_1,m_0) = 10^{-bM_{min}} \left(\begin{array}{l} \ln\left(\prod_{j=1}^{N} \left(m_0 + \sum_{i=1}^{L(t)} \frac{10^{a_1 + b_1 M_{0_i}}}{(t_j - t_i + c)^p \int_{t_i}^{T} (t - t_i + c)^{-p} dt} \right) \right) + \\ - m_0 T - \sum_{i=1}^{L(t)} 10^{a_1 + b_1 M_{0_i}} \end{array} \right)$$

The first results of the application of this model to Italian sequences show a significant improvement of the fit (Fig. 7) with respect to the simple Reasenberg and Jones (1989) model.

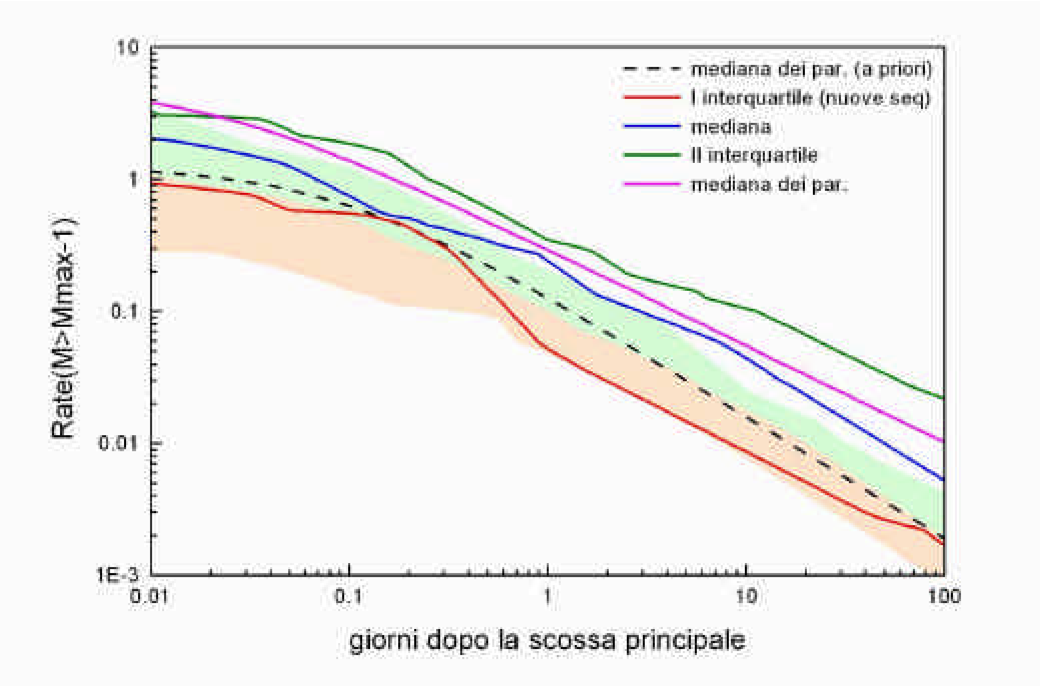

Figure 6. Comparison between the modeled aftershocks rates for sequences from 1997 to 2002 with M>Mmax-1 and those predicted on the basis of parameters estimated by Lolli e Gasperini (2003a) using sequences occurred between 1960 and 1996. The colored bands in light orange and green indicate, for the sequences from 1960 to 1996, the intervals between the first interquartile and the median and between the median and the third interquartile of the distribution of rates. The dashed line shows the value predicted by the model using the medians of parameters.

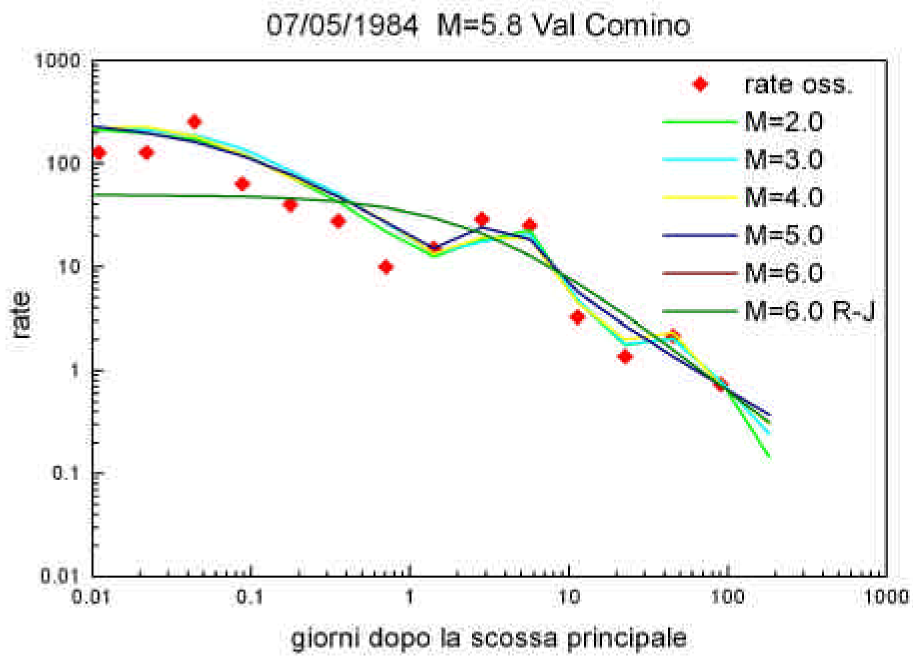

Figure 7. Comparison between rates observed (red dots) and expected (lines) on the basis of ETAS model, for different minimum magnitude thresholds for the generation of subsequences up to the maximum (M-6.0) corresponding to the Reasenberg e Jones (1989) model.

Task 7 FOCAL MECHANISMS (Responsible: Gasperini, Collaborators: Dal Forno, Lolli, Morelli, Pondrelli, Vannucci)

The activities mainly concern the development and the updating of the database of first motion mechanism of the Mediterranean area (Vannucci and Gasperini, 2002; Gasperini and Vannucci, 2002) and the computation of regional CMT solutions (Pondrelli et al., 2002).

- i) Insertion in the database of further mechanisms coming from other published papers.
- ii) Improvements of the database management software, including some new procedures in the MS-ACCESS application like that the plot of the mechanism and the in-line checking of inserted mechanisms.
- iii) Availability on the web of a reduced version of the first motion solution database.
- iv) Computation of new RCMT mechanisms.
- v) Analysis of cumulative moment tensor (Kostrov, 1974) and of compatibility of stress directions (Gephart & Forsyth, 1984) for various zones of the Mediterranean area.

Expected results for the second year.

- New preliminary *release* of the database of Earthquake Mechanisms of the Mediterranean Area (EMMA)

Expected results for the third year.

- First public *release* of the database of Earthquake Mechanisms of the Mediterranean Area (EMMA)

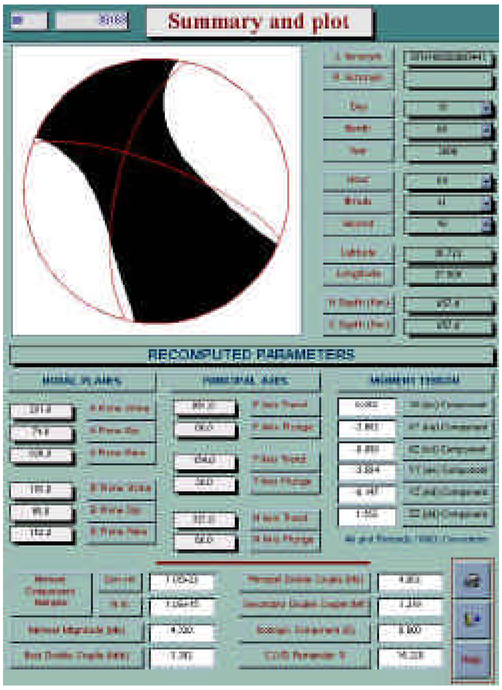

Figure 8. Summary an plot mask of the database of Earthquake Mechanisms of Mediterranean Area (EMMA). (Vannucci e Gasperini, 2003).

Results achieved in the second year.
We have verified that more than 40% of the fault plane solutions published in the literature contains inaccuracies, misprints and in some cases true computation errors. In many cases we found the focal planes or the deformation axis not perpendicular or inconsistent among each other. The database, based on MS-ACCESS platform, allows to select the mechanisms (in all about 5000 excluding the CMT catalogs), to examine their parameters and in the last version even to display the "beach-ball" plot (Fig. 8). A paper (Vannucci e Gasperini, 2003) is currently in press on an international journal.
To make the necessary tests before inserting new mechanisms in the database, we wrote a package of Fortran subroutines allowing to make the principal computations related to focal mechanisms (axes from planew and viceversa, a plane form the other one, planes and axes from moment tensor and viceversa). We carefully verified all procedures, by comparing their computations with data reported by Harvard CMT catalog. The coincidence was found to be within reasonable tolerances (3 degrees) for more than 99% of the mechanisms. Only for less than 1% we observed larger discrepancies, however addressable in all cases to the limited number of significant digits given by the CMT catalog. This paper also is currently in press (Gasperini e Vannucci, 2003).

Conclusion

The distinctive trait of most of the researches proposed by our project is the focussing on the analysis of macroseismic data. These are a set of information completely independent of the instrumental ones that can represent for these last a useful control dataset.
An particularly significant example in this sense is represented by the tomographic inversion of seismic intensity attenuation. It gives in fact the possibility to "calibrate" the instrumental attenuation investigation made in some areas of the Italian territory (*i.e.* in the ambit of Amato Project) with a globally homogeneous result. An accessory product of such work is the list of locality empirical residuals. This allows to verify, on a very large database of localities (more than 500), the site effects estimates made by several GNDT projects, basing on both theoretical/geological (simulations of ground motion) and experimental methods (absolute amplification or spectral rates measures).
Just in the field of site effects, the detailed zonation of the urban area of Florence represents a unique occasion to directly compare the 1D modeling techniques and instrumental measures with the distribution of effects really observed in the city historical center after an earthquake (the shocks of May-June, 1895).
Finally, in the ambit of the study of the seismic sources statistics we faced on some fundamental problems for the development of new hazard model that appear instead somehow neglected by other GNDT projects. Our interest in this case id particularly focussed at the spatio-temporal clustering properties of earthquakes that usually are almost ignored by current hazard models. In many cases in fact the aftershocks are even removed from catalogs while the experience of recent Italian seismic sequences (Umbria-Marche, Campobasso) clearly evidenced that aftershocks can

induce further damages and a significant extension of the area requiring emergency services

We also showed that the earthquakes time-space clustering is not confined to the first times after the main shock and to the area initially struck but even at spatio-temporal scales of the order of years and hundreds of km. On the other hand it was already shown in the literature that simple recurrence models, even those adopted by hazard estimates in deeply studied areas (California, Japan), are not suitable to represent the real occurrence of earthquakes (Kagan and Jackson, 1991, 1995, Mulargia and Gasperini, 1995).

In this research field an essential condition is represented by the availability of a homogeneous seismic catalog as most complete as possible. This is the reason why, even if this kind of studies had not been considered relevant by the Commission, some propaedeutical activities on this problem will be carried out anyhow, at least until the revision of historical and instrumental databases by the Amato Project will be completed.

Notwithstanding the difficulties due to the retarded activation of the funding with respect to other projects, most of the first year objectives of this project have been achieved an in some cases even exceeded.

In most cases our results correspond to significant improvements of the knowledge of some phenomena that are of interest for hazard estimates (attenuation and site effects properties, lateral variation of site effects in urban centers, statistical properties of eartquakes) as well as of the tools required to infer such estimates (Boxer code, instrumental catalog, focal mechanisms database, macroseismic database). The continuation of the project according to the established program should allow in the third year to further improve both.

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