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Compilation of a recent seismicity data base of the greater Alpine region from several seismological networks and preliminary 3D tomographic results

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Abstract
Local earthquake data collected by seven national and regional seismic networks have been compiled into a travel time catalog of 32 341 earthquakes for the period 1980 to 1995 in South-Central Europe. As a prerequisite, a complete and corrected station list (master station list) has been prepared according to updated information provided by every network. By simultaneous inversion of some 600 well-locatable events we obtained one-dimensional (1D) velocity propagation models for each network. Consequently, these velocity models with appropriate station corrections have been used to obtain high-quality hypocenter locations for events inside and among the station networks. For better control, merging of phase data from several networks was performed as an iterative process where at each iteration two data sets of neighbouring networks or groups of networks were merged. Particular care was taken to detect and correctly identify phase data from events common to data sets from two different networks. In case of reports of the same phase data from more than one network, the phase data from the network owning and servicing the station were used according to the master station list. The merging yielded a data set of 278 007 *P* and 191 074 *S*-wave travel time observations from 32 341 events in the greater Alpine region. Restrictive selection (number of *P*-wave observations > 7; gap < 160 degrees) yielded a data set of about 10 000 events with a total of more than 128 000 *P* and 87 000 *S*-wave observations well suited for local earthquake seismic tomography study. Preliminary tomographic results for South-Central Europe clearly show the topography of the crust-mantle boundary in the greater Alpine region and outline the 3D structure of the seismic Ivrea body.

Key words *seismic catalogue – tomography – Ivrea body*

1. Introduction

Seismicity maps and seismic data banks are prerequisites to apply 3D seismic tomography, to study seismotectonic processes, and to assess seismic hazard.

Several national, regional, and local seismological networks, in a few cases since the 1960's, monitor local seismic activity in the greater Alpine region encompassing Northern Italy, Switzerland, Austria, and parts of France and Germany. The long recording period of some permanent networks in combination with several temporal seismic station networks result in a comparatively large data set for an

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Mailing address: Dr. Stefano Solarino, Dister, Dipartimento di Scienze della Terra, Viale Benedetto XV, 5, 16132 Genova, Italy; e-mail: peter@dister.unige.it area of moderate seismic activity if the data of all networks are merged.

From a theoretical point of view, merging travel time data from neighbouring seismic station networks is a simple and straightforward procedure. In practice, however, different ways of recording (including differences in the electronics) and of treating the data (including the attribute of observation weights) may not only result in different time bases but may also lead to misinterpretation of phase data that appear similar but actually may be systematically different, or *vice versa*. Phase identification and event locations depend on the velocity models used for location procedure and vary greatly among the seismological networks.

Due to irregular station distribution and to different processing and storage policies, earthquake catalogues of individual seismological networks show significant variations in their completeness. Last but not least, phase data recorded by two seismological services from an event outside either station network are often hard to identify as such, since they normally are reported as belonging to two different hypocenters.

In this study we designed and applied a procedure to compile a clean and as complete-as-possible phase data set for the greater Alpine region using the catalogues of seven independent seismological networks (SED Zürich, Dister Genoa, Sismalp Grenoble, EOPG Strasbourg, TU Karlsruhe, ING Rome, OGS Trieste). Obviously, some deficiencies in the original data sets may never be resolved. With reference to the proposed use of the merged data for tomographic and seismotectonic studies, we set the highest priority to cleanness. In any case of conflicting data or if a recognized error in one of the original catalogues could not be recovered, then this particular event data was deleted. The resulting merged data set, therefore, is not complete to the lowest possible magnitude but it will contain fewer large errors and be almost free of blunders.

By inversion of 600 well-locatable events selected from this data set, a Minimum 1D model for the greater Alpine region was obtained. With this model the 32 341 events were relocated with more or less uniform precision. In addition, the Minimum 1D model for the greater Alpine region served as initial reference model (Kissling *et al.*, 1994) for 3D tomography. 44 317 P-wave travel times of 2150 selected events were inverted to obtain a 3D tomographic image of the western part of the Po plain and the inner parts of the Western Alps encompassing the Ivrea body.

2. Seismic stations in the greater Alpine region

Political considerations play an important role in the decision-making process when establishing a seismological service for a region. These considerations in conjunction with the fact that the greater Alpine region is shared by several nations and politically independent regions has led to a comparatively high station density with respect to the moderate level of seismic activity. On the other hand, the little coordination that was possible among neighbouring seismic networks during the installation of their permanent and temporary stations resulted in a non-uniform station distribution and in potential naming conflicts that needed to be accounted for in the merging process. For this purpose, we compiled a complete station list with all permanent and temporary stations that were continuously operative during the period 1977 to 1995.

Aside from their own seismic stations, most networks also list information about some stations of neighbouring networks. Often, this information is outdated, incomplete, or otherwise incorrect. Based on the assumption that the group maintaining a seismic station knows its coordinates best, we first compiled a list showing all these permanent and currently maintained stations where the owner is known. Then we identified the owners of all other stations and asked each seismological service to cross-check the coordinates and names of these stations attributed as their own. In a following step, the station names used by seismological services for stations outside their own network were correlated with the corresponding station names reported by the owners. For this correlation we referred to the various published catalogues and strongly depended on the help of the network operators. This process yielded a master station list for the greater Alpine area (including Western France and the Pyrenees) containing 585 station locations with a total of 796 names. For convenience, the owner's name was preferred over the names used by other networks unless a potential naming conflict in the combined station list results. In these few cases the station names were modified by adding a fourth character. The master station list also contains reports from 70 seismic stations that were identified as problematic, since some of their station parameters could not be verified or corrected. Most of these stations were temporary stations where the original reports have been lost. The information about these stations is marked as unreliable and is listed in a separate part of the master station list. These stations were rejected from the final combined station list. The phase data from all stations where ownership and/or coordinates remain unclear was ignored in the subsequent merging process.

Of the 585 final reliable stations in the master station list, about 15% needed corrections in their original coordinates, with many of these corrections significantly large (up to 1°) to potentially cause problems in any application. When adding the stations identified as unreliable and rejected from the final station list, a total of 25% of all stations reported by the participating networks contained errors in their original station parameters (mostly coordinates) or could not be verified. Since not all coordinate errors were of significant magnitude and since not all stations were used in the phase data, this number denotes an upper bound of erroneous data contained in the seismic phase data catalogues. In our experience with seismic tomography application, however, a much smaller percentage than 25% of systematic errors in phase data may seriously affect the results (Kissling, 1988). The tedious work of verifying the information in the station lists provided by participating networks (Kruse, 1995; Handl, 1995), therefore, was not only justified but required by the planned use of the phase data for seismic tomography.

Figure 1 shows the location of the reliable checked stations of the compiled master list

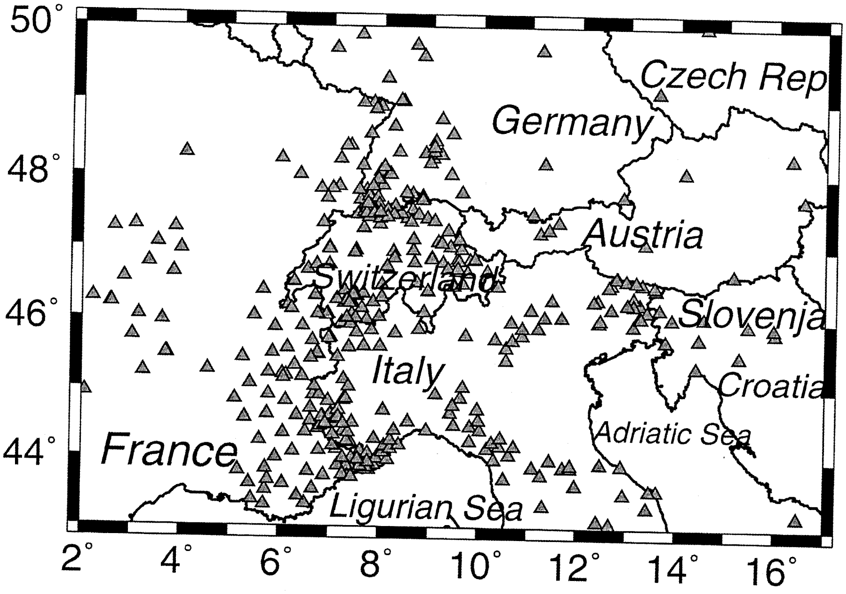

Fig. 1. Station distribution in the greater Alpine region (43°-50°, 2°-17°) for the period 1977 to 1995. Note that not all stations were operative simultaneously. Rather, the station distribution varied greatly with time.

only for the greater Alpine region (43°-50°, 2°-17°). The coverage, although reflecting the main tectonic features of South-Central Europe, is almost homogeneous with the exception of the Austrian part of the Eastern Alps.

3. Merging procedure for phase data from different networks

The merging process was designed to account for three main characteristics of the various data sets. They cover different areas variable over time, different and sometimes overlapping time periods, and often contain particular phase data exchanged with – and partly modified from – other networks. As a general rule, when merging we preferred and made use of only those observations provided by the owner of a station, the only exception being the readings exchanged with networks not participating in this merging process for the greater Alpine area. In these cases the reporting network was considered the owner. As a consequence, some data were lost when the time periods reported by the participating seismological networks did not overlap completely as is the case in this merging (see below). This procedure, however, obeys the principle of preferring smaller higher quality data sets over larger data sets that might contain more errors and blunders. By using only «original» data (phase data read by the owner of the station), modifications, made almost routinely by operators when including foreign phase data to improve earthquake location, were neglected.

Often such modifications in arrival time and/or observation weight were applied to the phase data directly without consulting with the original time signal. The changes in foreign phase data were motivated by the aim of locating hypocenters outside each network with small r.m.s. error values while using their own standard velocity model and phase identification which vary greatly among the seven seismological networks in the Alpine region. Modified phase data reported by a network other than the owner of the station were, therefore, generally less reliable than the original readings.

For better control, the phase data from several networks were merged as an iterative process where at each iteration two data sets were merged. Each iteration consisted of six steps (see also fig. 2): calculation of Minimum 1D models (1), relocation of events followed by time sorting of events (2); detection and listing of events common to both data sets (3); merging phase data for common events (4); relocation of common events (5); compilation of merged data set (6).

Velocity models and appropriate station delays for routine earthquake location are tuned to the specific high-priority aims of the individual network. For the Alpine region, these models and the corresponding routine phase identification vary greatly, leading to difficulties when searching for phase data that belong to common events reported by different networks. For better identification of such phase data and to consistently locate and to better recognize events between two station networks, Minimum 1D models (Kissling, 1988) were calculated for each individual network and phase data set. Minimum 1D models with appropriate station corrections were calculated as a result for the coupled hypocenter-velocity model problem using up to 600 well-locatable events selected from the original data sets (Kissling *et al.*, 1994). Minimum 1D models for Switzerland and for the Cuneo area (North-Western Italy) have previously been proposed by Kradolfer (1989) and Kissling *et al.* (1995), respectively.

Relocation of all data with the Minimum 1D velocity model and appropriate station corrections calculated in step 1 guarantee more or less uniform hypocenter location precision, uniform phase identification, and equal data format (archive type format with header containing hypocenter information followed by phase lines containing original phase readings and calculated residuals). Subsequently, these data sets were sorted according to event origin time and data from the so-called «sequences» of events (events with origin times of less than 15 s apart from each other) were separated in special files. This definition of a sequence is wider

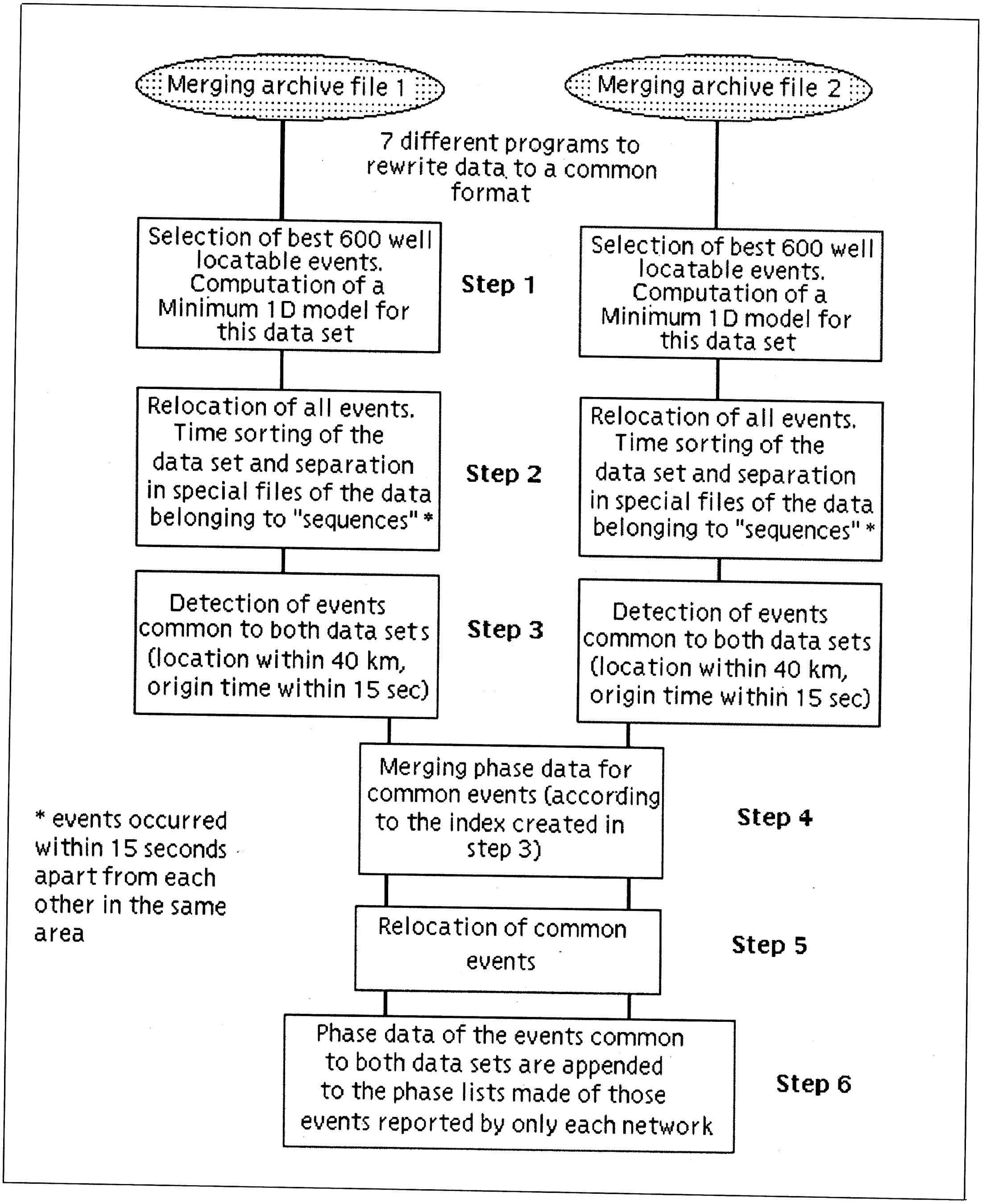

Fig. 2. Flow chart showing the process of merging archive travel time data from different seismological networks.

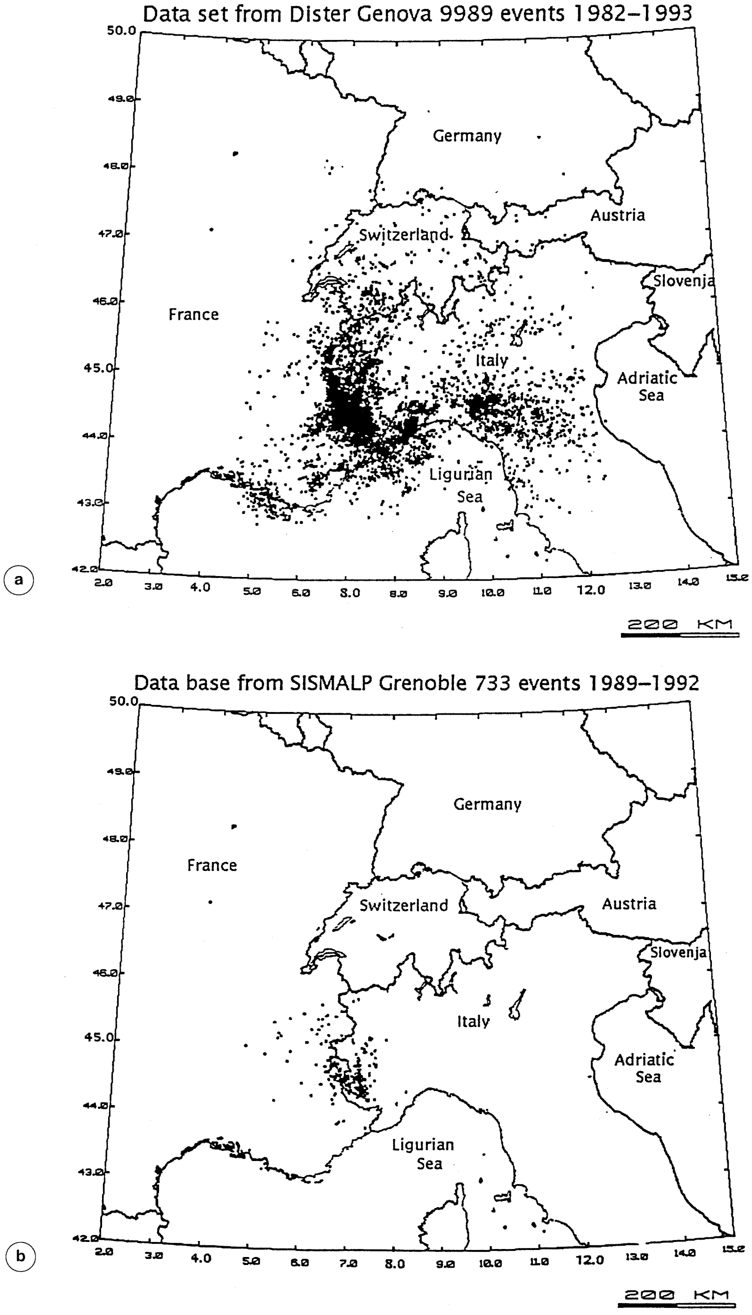

Fig. 3a,b. a) Epicenter location map of 9989 events which occurred in the period 1982 through 1993 provided by Dister Genoa. b) Epicenter location map of 733 events which occurred in the period 1989 through 1992 provided by Sismalp Grenoble.

than that commonly used for earthquake sequences since its principal aim was to simplify the merging process.

Two phase lists reported by two networks were primarily identified as belonging to the same event by comparing origin times and hypocenter locations. For this recognition process to work well routinely, reliable hypocenter locations obtained by Minimum 1D models were a prerequisite (see step 1). We chose a time window of 15 s and a maximum distance of 40 km between the hypocenters as a spatial window to check for doublets. Two hypocenters within the same time and space window were identified as belonging to the same event and were added to a list of events common to both data sets.

Once the list of events common to both data sets was compiled, the merging of phase data (4) was simple except for these – rather numerous – cases of conflicting data. Most common were differences in observation weight, station name or type of phase (*e.g.*, P_g and P_n) and sometimes in values of arrival times. For these cases we had to refer to the master station list. We preferred to use phase data of the network that owns and maintains the particular station over second or third-party reports that might have been modified without checking with the original seismogram. All conflicting phase data were stored in a special file for additional checking by hand.

Relocation of the «common» events (5) with an appropriate Minimum 1D model provided an additional check on the merged phase data. In the final step (6) of the merging cycle, the phase data of the events common to both data sets were appended to the phase list made

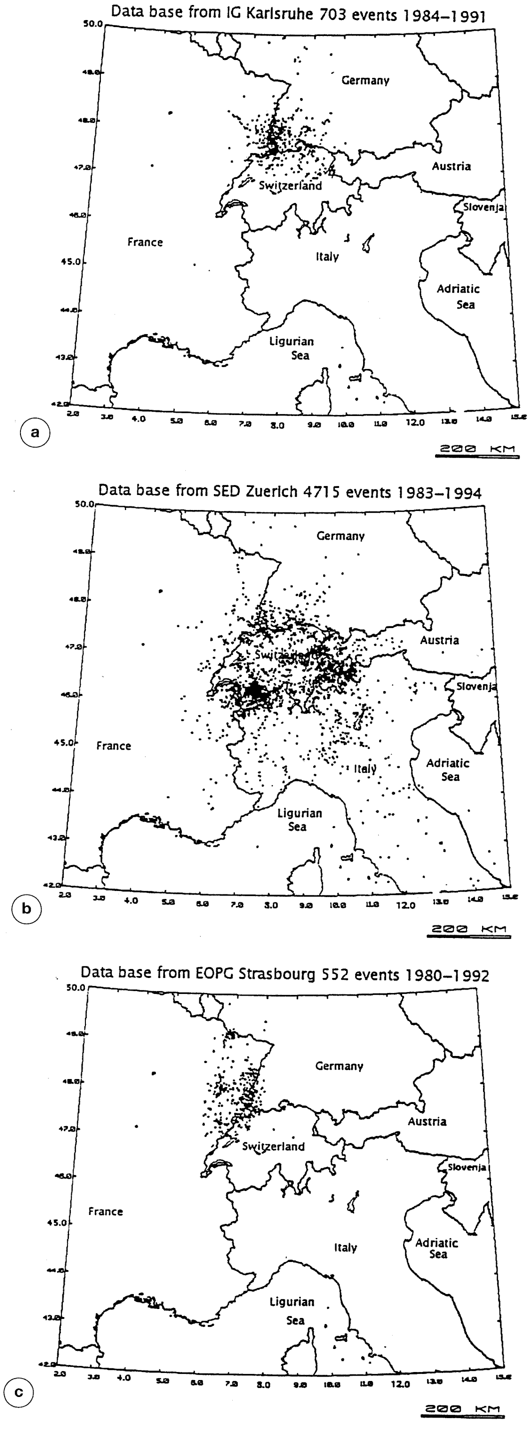

Fig. 4a-c. a) Epicenter location map of 703 events which occurred in the period 1984 through 1991 provided by IG Karlsruhe. b) Epicenter location map of 4715 events which occurred in the period 1983 through 1994 provided by SED Zürich. c) Epicenter location map of 552 events which occurred in the period 1980 through 1992 provided by EOPG Strasbourg.

of those events reported by only one of the networks.

After completion of one cycle (steps 1 through 6), the resulting data set could be merged with the phase data archive from an additional network. As first iteration, the data set from Dister, Genoa (fig. 3a; 9989 events from the period 1982 through 1993) was merged with the phase data provided by Sismalp, Grenoble (fig. 3b) containing 733 events from the period 1989 through 1992. In a second iteration the data set from the period 1984 through 1991 (703 events) by IG, Karlsruhe (fig. 4a) was merged with the 4715 events (fig. 4b; period 1983 through 1994) by SED, Zürich. A third iteration combined the newly formed Zürich-Karlsruhe data set with the 552 events for the period 1980 through 1992 provided by EOPG, Strasbourg (fig. 4c), followed by the fourth iteration combining the two data sets resulting from the first and third iteration. This merging resulted in a data set for the Western Alpine region combining the data provided by Grenoble, Genoa, Zürich, Karlsruhe and Strasbourg (called GGZKS). In the fifth iteration the GGZKS data were merged with the 11 175 events (north of latitude 43 degrees) for the period 1982 through 1995 provided by ING, Rome (fig. 5a). Finally, during the sixth iteration the result of iteration five was merged with a data set (fig. 5b) consisting of 9543 events for the period 1977 through 1994 provided by OGS (Udine and Trieste).

The final merged data set (fig. 6) consisted of 278 007 *P* and 191 074 *S*-wave observations of 32 341 events recorded over a period of 18 years (with strongly variable station configuration!). Note that data were provided by all networks only during the period 1989 through 1991.

4. Seismicity map 1980 to 1995 of the Alpine-Northern Apennine region

The merged data set of 32 341 events (fig. 6) was relocated using a Minimum 1D model for the whole region and Minimum 1D models for the subregions. On the basis of the magnitude reports by the catalogues of Dister (Genoa) for 9989 events, SED (Zürich) for 4715 events, and ING (Rome) for 11 175 events, we estimated our merged data set to be complete for earthquakes of magnitude 2.5 and larger. During much of the time period (1977 to 1995) covered by our merged data set, only few participating networks were operative or these networks did not report their observations to us for other reasons. Hence, a significant number of events in the merged data set remain poorly locatable. Distribution of epicenters (fig. 7) for the 17 000 *ca.* well-locatable events (more than 5 *P* observations, gap smaller than 240 degrees), however, shows a distribution similar to the one for the complete merged data set.

5. Preliminary seismic tomographic image of the Ivrea body

Recently, Solarino (1994) and Solarino *et al.* (1996) investigated the gross and deep features of North-Western Italy by means of tomographic inversion of teleseismic data.

Within this sector of the Alps lies the so-called Ivrea body, a complex of high-density, high-velocity and high-magnetic susceptibility rocks of lower crustal and possible upper mantle origin. The knowledge of the precise shape of the Ivrea body and of its relation to the surrounding structure is fundamental to the understanding of its role in late Alpine orogeny (Menard and Thouvenot, 1987).

Due to wave lengths of the order of 10 km and more, teleseismic tomography cannot resolve details of the 3D crustal structure but provides only a blurred image of an elongated and narrow structure like the Ivrea body. Thus, for a detailed modeling of the subsurface geometry of the body, a high-resolution 3D seismic method such as seismic tomography with local earthquakes is required. In a preliminary attempt to define and image a detailed Ivrea body, we applied the methodology developed by Kissling (1988) to a high-quality data set consisting of 44 317 *P*-wave observations from 2150 events (fig. 8) selected from the above mentioned 17 000 *ca.* well-locatable events. Selection criteria for this 2150 events were

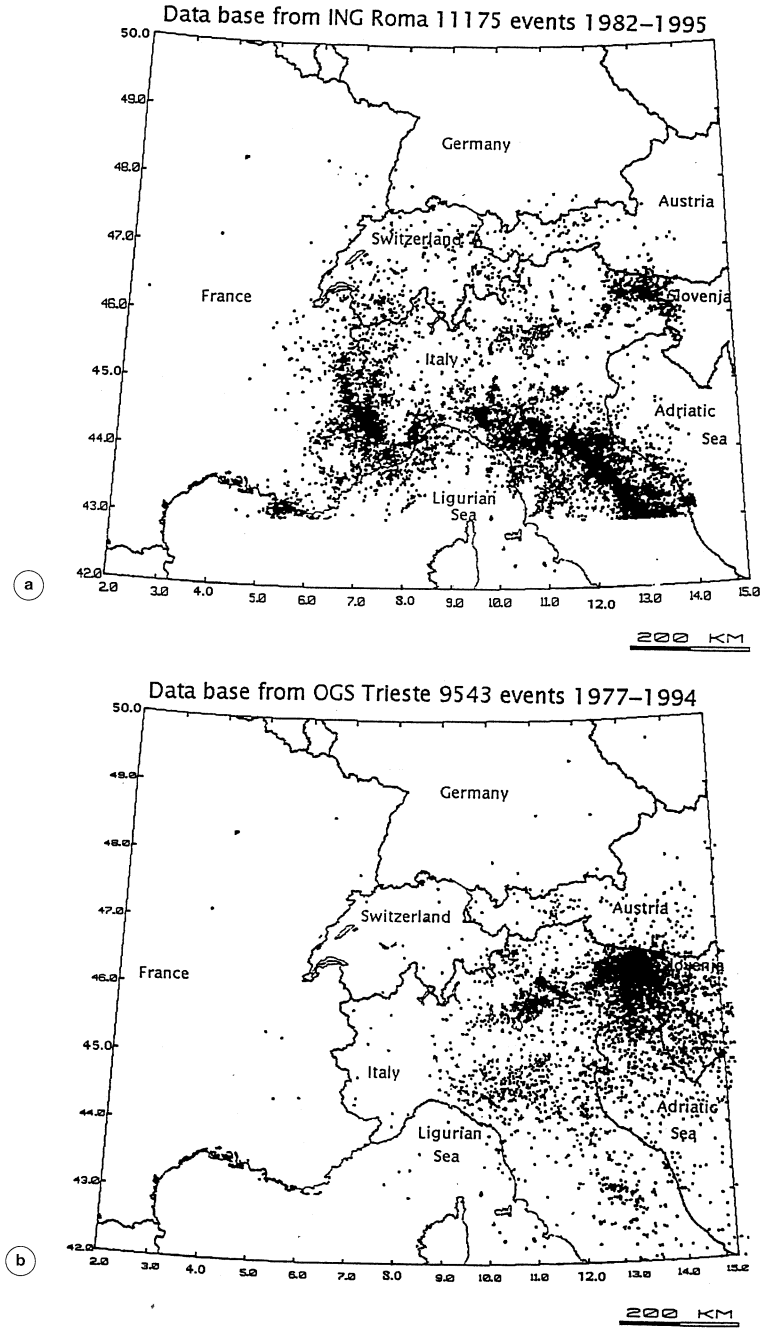

Fig. 5a,b. Epicenter location map of 11 175 events (north of latitude 43 degrees) which occurred in the period 1982 through 1995 provided by ING Rome. b) Epicenter location map of 9543 events which occurred in the period 1977 through 1994 provided by OGS Udine.

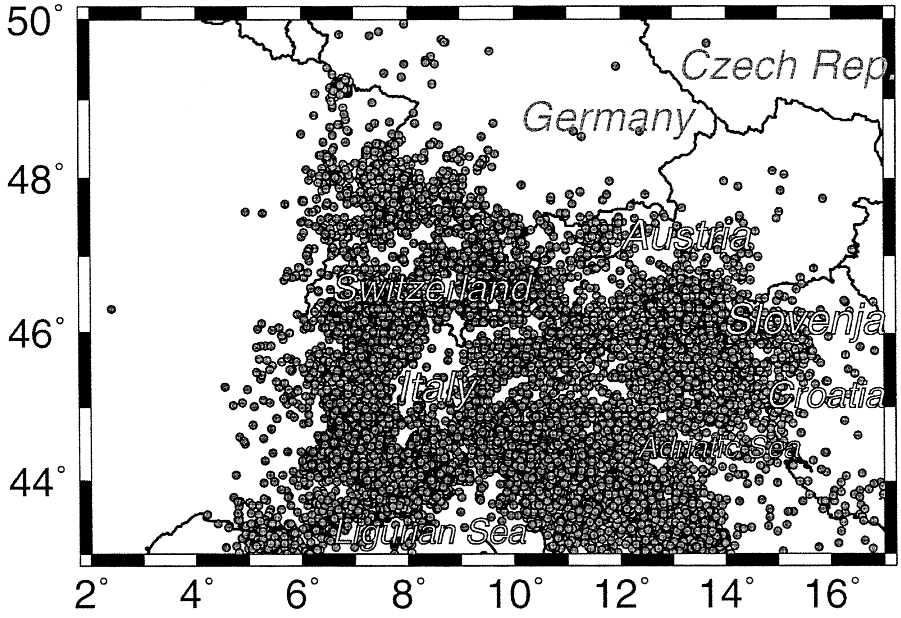

Fig. 6. Epicenter location map of merged data set consisting of 32 341 events recorded from 1977 to 1995 by any of the seven participating seismological networks. Note that data were provided by all networks only during the period 1989 through 1991.

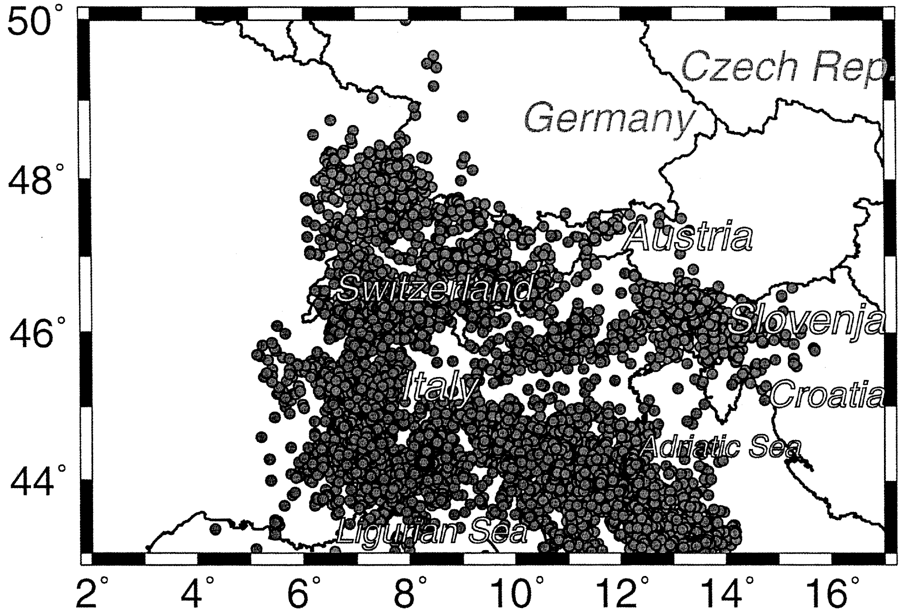

Fig. 7. Epicenter location map of the 17 034 well-locatable events.

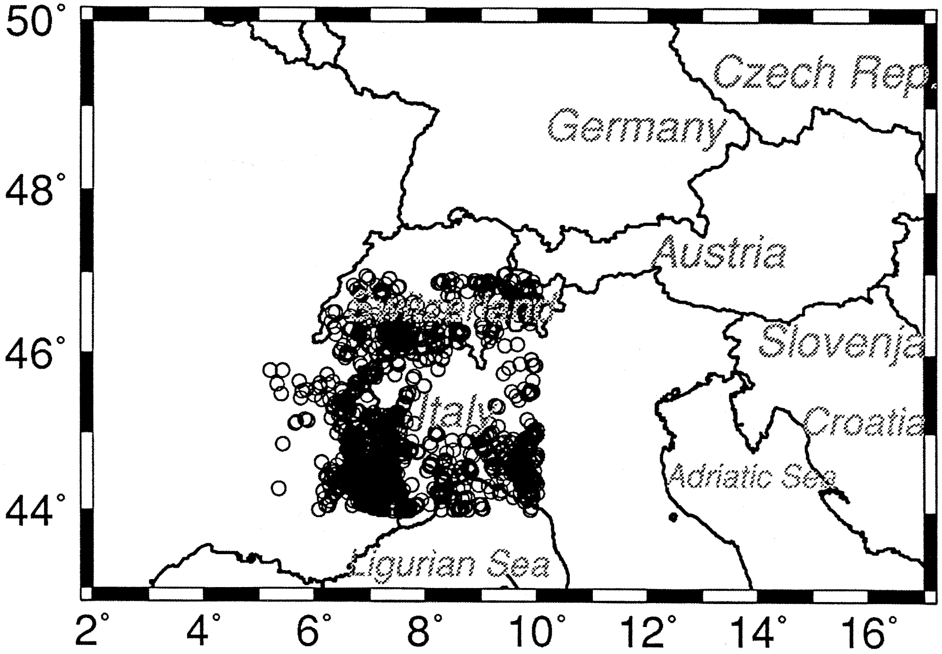

Fig. 8. Epicenters location map of 2150 events selected for preliminary seismic tomography study.

quality requirements (minimal number of 12 *P* observations per event, gap smaller than 180 degrees) and geographical considerations to obtain maximum resolution in the target area. Use of all available observations even from stations outside the tomography study area better constrained the location part of the coupled hypocenter-velocity problem and, hence, better illuminated the area under study.

Non-linear tomographic inversion was performed by iterating over few full-matrix inversions (by Cholesky decomposition, see Kissling, 1988) after separation of the hypocenter and velocity model parameters. Figure 9 shows the preliminary tomographic results obtained after two iterations. The results clearly outline the geometry of the Moho through beneath the Alps and the shape of the high-velocity Ivrea body. The extent and shape of the low-velocity Alpine crustal root, the high-velocity anomaly along the southern rim of the model corresponding to upper mantle material reaching depths as shallow as 25 km beneath Liguria, and – adjacent to the North – the low-velocity anomaly representing the Adriatic Moho descending to depths greater than 50 km, all document a Moho topography in accordance with results obtained independently by controlled-source seismology (Kissling, 1993). This excellent correspondance of one part of the tomographic results with *a priori* known structure suggests that the equally well-resolved Ivrea body was reliably imaged.

Three tomographic cross sections (fig. 10) nearly perpendicular to the strike of the gravity anomaly related to the Ivrea body show the steeply dipping layer of high-velocity rocks partly overlying lower crustal material associated with the Western Alpine crustal root. This is in general agreement with previously proposed models of the Ivrea body mainly based on gravity models (Kissling, 1984; Menard and Thouvenot, 1987).

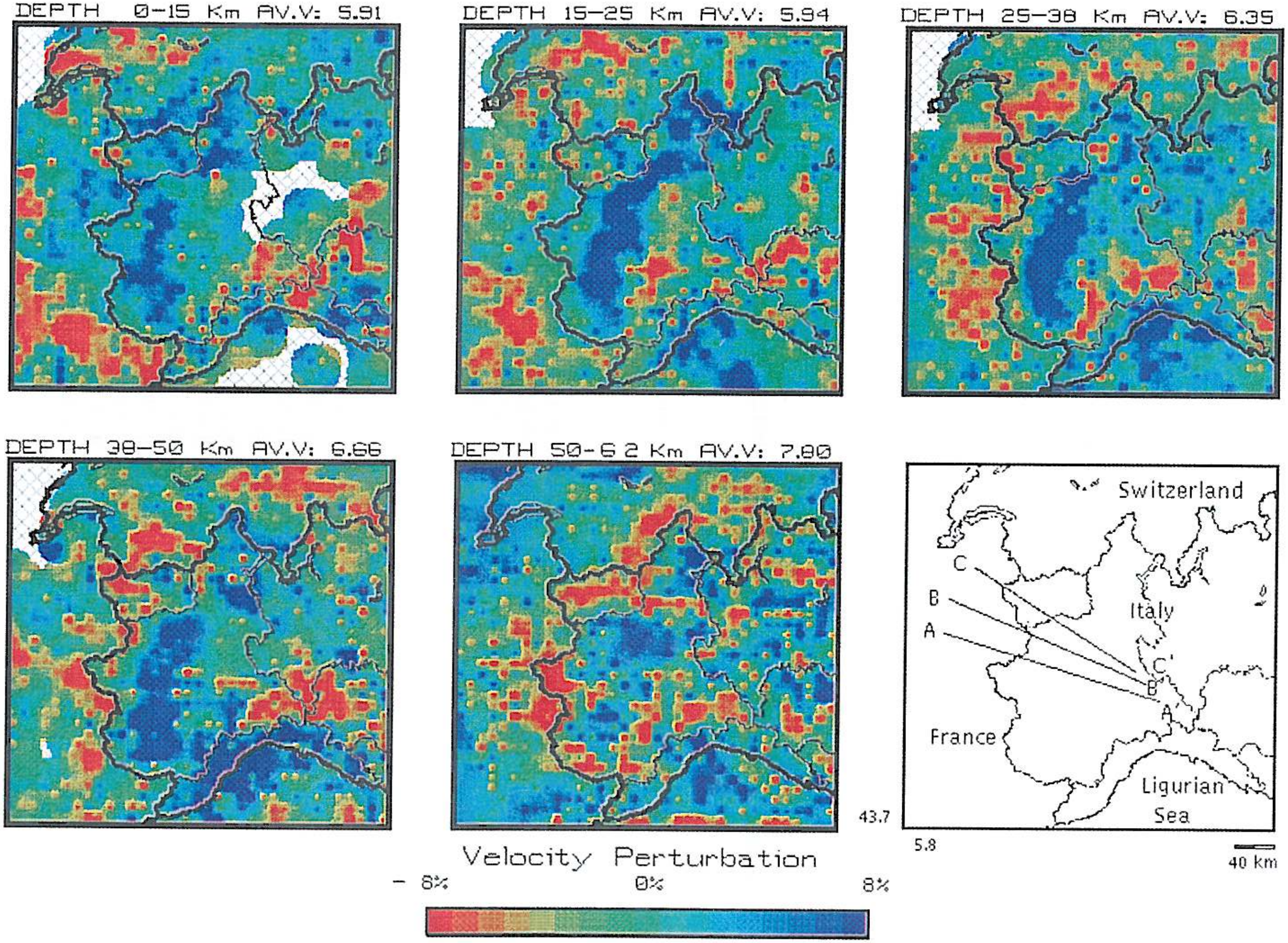

Fig. 9. Preliminary 3D *P*-wave velocity field in NW Italy and adjacent regions derived by non-linear inversion of local earthquake data. Five horizontal cross-sections (layers) are shown from top (upper left corner) to bottom of the model (lower centre), representing layers at 15 km, 25 km, 38 km, 50 km, and 62 km depth, respectively. Blue color denotes areas of higher, red color regions of lower-than-average velocities. In the right lower corner, a map shows the directions of the vertical cross-sections AA′, BB′, CC′ of fig. 10.

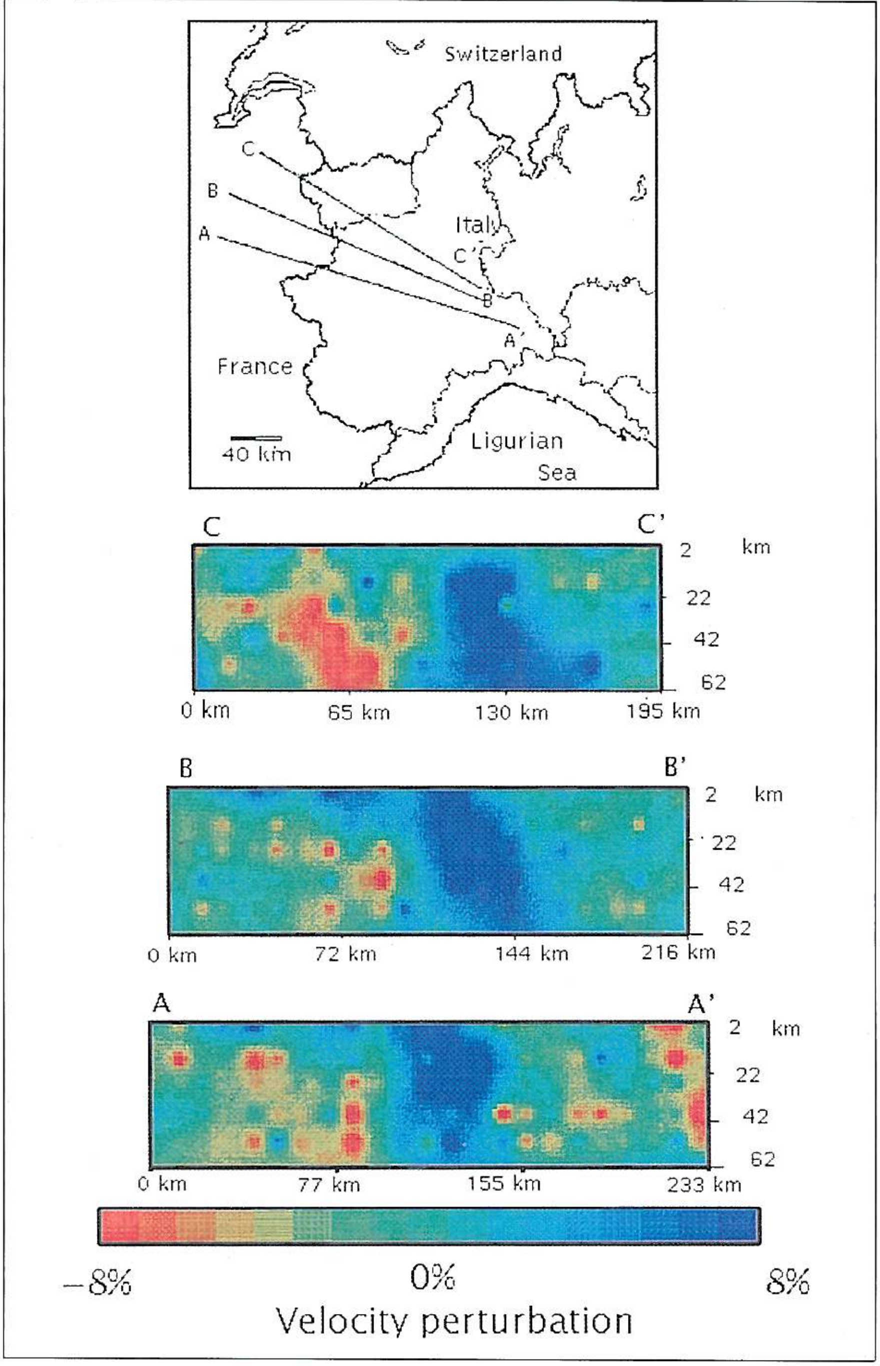

Fig. 10. Vertical cross-sections AA′, BB′, CC′.

6. Conclusions

The use of only few observations from stations outside a network may greatly improve the location precision of events near the edge of a network and certainly such additional data provide the means to precisely locate those local events that are far from the array but still close and strong enough to be recorded by many stations. Therefore, most seismological networks nowadays often use data from stations outside their own networks for their routine work. With the repeated changes of the station configuration common to all seismic networks, however, such sporadic use of «foreign» data bears the potential for introducing systematic errors into the solution rather than improving it. As we realized during compilation of the complete and clean master station list, published and currently used station information for all seismological networks did contain at least a few problems and inconsistencies that may have led to gross errors. Last but not least, such errors will almost certainly not be detected by single event locations!

There is no reason to assume that in any other region there will be fewer problems with a station list than in any one of the seven participating networks. Our experience demonstrates that better care must be taken to ascertain correct recording of all modifications to the station array. Station parameters obviously need to be routinely checked and they need to be reported to all neighbouring networks that sometimes use foreign phase readings.

By merging of phase data from neighbouring seismological networks not only may we find and subsequently reduce a number of errors in the data but, in addition, we can improve the quality of the merged data (reduction in gap, increase in the number of observations) and the areal coverage, in particular in the area between the two networks. We thus conclude that merging of seismic phase data (arrival times for first *P* and *S*-wave arrivals) leads to high-quality local earthquake data sets well-suited for seismic tomography. With regard to other uses, such as fault plane solutions, however, additional checks on station parameters are necessary.

Acknowledgements

Aside from releases to the media, routine seismological service work is rarely appreciated by the public or by research seismologists. Without the dedication of the people who do their routine work as well as possible, much of the data that we merged would never have been collected and stored. We thank the members of the seven seismological networks for the efforts that went into their data banks. We are indebted to G. Poupinet (Grenoble) for taking the initiative to share routine seismological data under the sole condition that seismic tomography studies should result. We are grateful to G. Bressan for his cooperation.

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