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Earthquakes in Switzerland and surrounding regions during 2002

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Key words: Earthquakes, focal mechanisms, moment tensors, Switzerland

ABSTRACT

This report of the Swiss Seismological Service summarizes the seismic activity in Switzerland and surrounding regions during 2002. During this period, 546 earthquakes and 137 quarry blasts were detected and located in the region under consideration. The increase in the total number of recorded events relative to previous years is restricted to low magnitudes. It is due to the lower detection threshold of the new station network and to the occurrence of six earthquake swarms, which alone account for 39 % of the total seismic activity in 2002. In fact, with 27 events with $M_L \geq 2.5$, the seismic activity in the year 2002 was close to the average over the last 28 years. The strongest event, with $M_L = 3.8$ and intensity $I_0 =$ V, occurred near Santa Maria Maggiore, between Valle Vigezzo and Valgrande, just beyond the border with Italy. As in previous years, most of the seismic activity during 2002 was concentrated in the Valais, the southeastern part of Graubünden and in the adjacent regions of northern Italy.

ZUSAMMENFASSUNG

Dieser Bericht des Schweizerischen Erdbebendienstes stellt eine Zusammenfassung der im Vorjahr in der Schweiz und Umgebung aufgetretenen Erdbeben dar. Im Jahr 2002 wurden im erwähnten Gebiet 546 Erdbeben sowie 137 Sprengungen erfasst und lokalisiert. Die Zunahme der Anzahl registrierter Ereignisse verglichen mit früheren Jahren beschränkt sich auf die kleinen Magnituden. Sie ist zurück zu führen auf die erhöhte Detektionsempfindlichkeit des neuen Stationsnetzes und auf das Auftreten von sechs Erdbebenschwärmen, die allein für 39 % der gesamten seismischen Aktivität im Jahr 2002 aufkommen. Tatsächlich war die seismische Aktivität mit 27 Beben mit Magnituden $M_L \geq 2.5$ nahezu durchschnittlich. Das stärkste Beben erreichte eine Magnitude $M_L = 3.8$ und eine Intensität $I_0 =$ V; das Epizentrum befand sich bei Santa Maria Maggiore, zwischen Valle Vigezzo und Valgrande, jenseits der Grenze zu Italien. Wie schon in früheren Jahren ereigneten sich die meisten Beben im Jahr 2002 vor allem im Wallis, im südöstlichen Teil von Graubünden und in den angrenzenden Gebieten von Norditalien.

RESUME

Le présent rapport du Service Sismologique Suisse résume l'activité sismique en Suisse et les régions limitrophes au cours de l'année écoulée. En 2002, 546 tremblements de terre et 137 tirs de carrière furent détectés et localisés. L'accroissement du nombre total de détections comparé aux années antérieures concerne principalement les faibles magnitudes et s'explique par la sensibilité accrue des nouvelles stations du réseau sismique ainsi que par l'occurence de six séquences sismiques responsables de 39 % de l'activité de l'année 2002. Avec 27 événements de magnitude $M_L \geq 2.5$, l'activité sismique de l'année 2002 est proche de l'activité moyenne observée ces 28 dernières années. L'événement le plus significatif, d'une magnitude $M_L = 3.8$ et d'une intensité $I_0 =$ V, s'est produit près de Santa Maria Maggiore, entre Valle Vigezzo et Valgrande, en Italie à proximité de la frontière suisse. Comme les années précédentes, l'activité sismique s'est prinicipalement concentrée dans le Valais, dans la partie sud-est des Grisons et dans les régions proches du Nord de l'Italie.

Introduction

Past earthquake activity in and around Switzerland has been documented in an uninterrupted series of annual reports from 1879 until 1963 *(Jahresberichte des Schweizerischen Erdbebendienstes)*. Three additional annual reports have been published for the years 1972-1974. These reports together with historical records of earthquakes dating back to the 13th century have been summarized by Pavoni (1977) and provided the basis for the first seismic hazard map of Switzerland (Sägesser & Mayer-Rosa 1978). With the advent of routine data processing by computer, the wealth of data acquired by the nationwide seismograph network has been regularly documented in bulletins with detailed lists of all recorded events *(Monthly Bul-*

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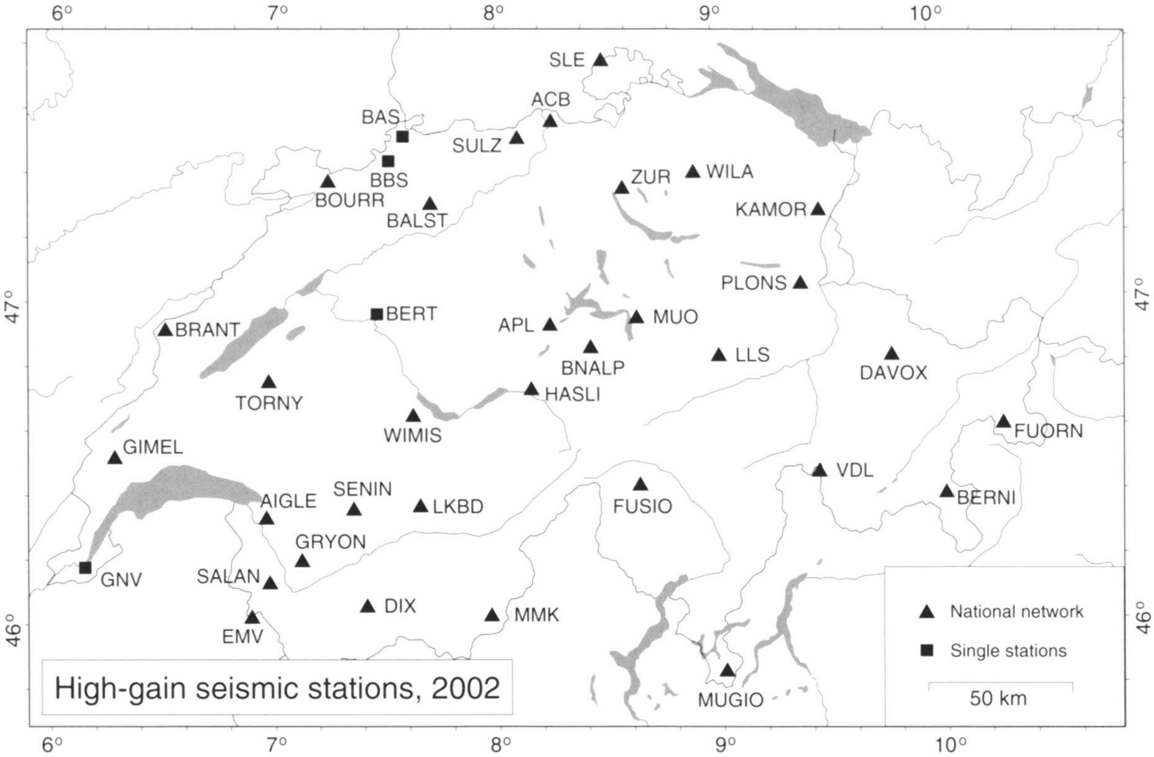


Fig. 1. Seismograph stations in Switzerland operational at the end of 2002.

letin of the Swiss Seismological Service). Since 1996, annual reports summarizing the seismic activity in Switzerland and surrounding regions have been published in the present form (Baer et al. 1997, 1999, 2001; Deichmann et al. 1998, 2000a, 2002). Recently, in the process of reassessing the seismic hazard in Switzerland, a new uniform earthquake catalog covering both the historical and instrumental periods has been compiled (Fäh et al. 2003). The data in the new Earthquake Catalog of Switzerland (ECOS) are available on line (http://histserver.ethz.ch). In addition, numerous studies covering different aspects of the recent seismicity of Switzerland have been published in the scientific literature (for an overview and additional references see, e.g. Pavoni 1984; Deichmann 1990; Deichmann & Baer 1990; Pavoni & Roth 1990; Deichmann, 1992; Rüttener, 1995; Rüttener at al., 1996; Pavoni et al., 1997; Deichmann et al. 2000b).

Seismic stations in operation during 2002

The Swiss Seismological Service operates two separate nationwide seismic networks, a high-gain seismometer network and a low-gain accelerograph network. The former is designed to continuously monitor the ongoing earthquake activity down to magnitudes well below the human perception threshold (Baer 1990), whereas the latter is principally aimed at engineering concerns and thus only records so-called strong motions (Smit 1998). The observations presented here are based mainly on the high-sensitivity monitoring network. The data that has been collected during 2002 by the strong-motion network is documented separately (Wyss 2003).

Beginning in 1998, the configuration of the national high-gain network has undergone a transformation from a short-period analog telemetry system to a digital high-dynamic-range network equipped almost entirely with broad-band STS-2 sensors. For a detailed description of the new data acquisition system, see Baer et al. (2001). By the end of 2001, the installation of the new network was almost completed and the two systems were operating in parallel. After the new system had demonstrated its reliability, the old network, except for the stations ACB and APL, was decommissioned in February 2002 (Table 1 and Fig. 1). In the course of the year 2002, four additional sites have been equipped with the new instruments (BRANT, GRYON, MUGIO and SENIN), thus increasing the total number of digital stations to 29 (BB and EB in Table 1). Moreover, the two preliminary sites CHDAV and MELS, that were in operation earlier (Deichmann et al. 2002), were replaced by stations DAVOX and PLONS. An additional three-component short-period seismometer with an analog telemetry link has been installed near Leukerbad, 3 km south of the existing site (LKBD), to monitor the local microseismic activity in the context of the construction of the new railway tunnel through the Lötschberg.

Tab. 1. Seismograph stations operational at the end of 2002. Instrument types: SP = 1 - 2 seconds, EB = 5 seconds, BB = broad band, 1 = vertical component only, 3 = vertical and horizontal components.

National high-gain network recorded in Zürich

Code	Station name	Type	Remarks
ACB	Acheberg, AG	SP-3	analog telem.
AIGLE	Aigle, VD	BB-3	
APL	Alpnach, OW	SP-3	analog telem.
BALST	Balsthal, SO	BB-3	
BERNI	Bernina, GR	BB-3	
BNALP	Bannalpsee, NW	BB-3	
BOURR	Bourrignon, JU	BB-3	
BRANT	Les Verrières, NE	BB-3	
DAVOX	Davos, GR	BB-3	
DIX	Grande Dixence, VS	BB-3	
EMV	Vieux Emosson, VS	BB-3	
FUORN	Ofenpass, GR	BB-3	
FUSIO	Fusio, TI	BB-3	
GIMEL	Gimel, VD	BB-3	
GRYON	Gryon, VS	EB-3	
HASLI	Hasliberg, BE	BB-3	
KAMOR	Kamor, SG	BB-3	
LKBD	Leukerbad, VS	EB-3	
LLS	Linth-Limmern, GL	BB-3	
PLONS	Mels, SG	BB-3	
MMK	Mattmark, VS	BB-3	
MUO	Muotathal, SZ	BB-3	
SALAN	Lac de Salanfe, VS	EB-3	
SENIN	Senin, VS	BB-3	
SLE	Schleitheim, SH	BB-3	
SULZ	Cheisacher, AG	BB-3	
TORNY	Torny, FR	BB-3	
VDL	Valle di Lei, GR	BB-3	
WILA	Wil, SG	BB-3	
WIMIS	Wimmis, BE	BB-3	
ZUR	Zürich-Degenried, ZH	BB-3	

Single stations

Code	Station name	Type	Remarks
BAS	Basel, BS	SP-3	digital (LED)
BBS	Basel-Blauen, BL	SP-1	telemetry (LED)
BERT	Bern, BE	SP-3	paper records
GNV	Geneva, GE	SP-1	paper records

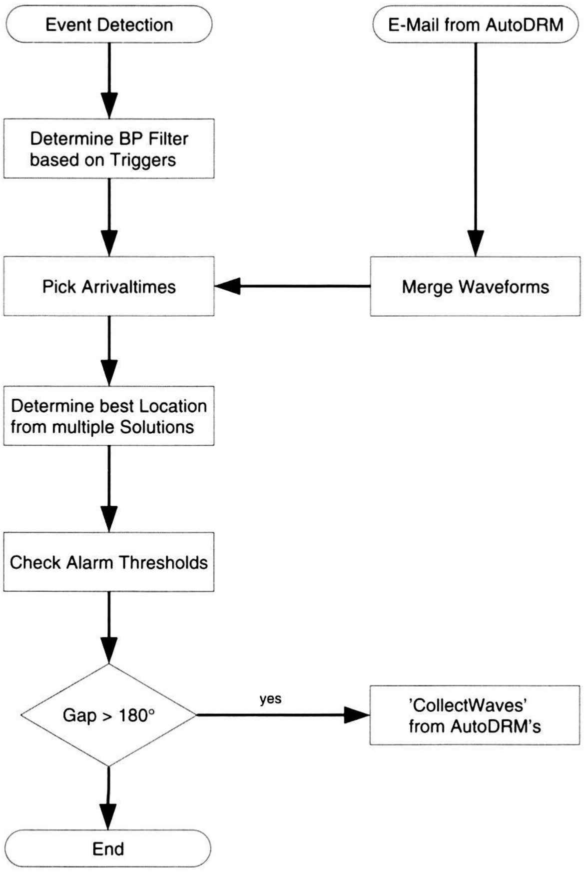


Fig. 2. Diagram illustrating the automatic data processing system.

Data from foreign networks

For detailed studies of selected earthquakes and for constraining the location and the focal mechanisms of earthquakes situated on the periphery or outside the Swiss station networks, we use additional data obtained from the Erdbebendienst des Landesamtes für Geologie, Rohstoffe und Bergbau Baden Württemberg in Freiburg (LED), from the Zentralanstalt für Meteorologie und Geodynamik in Vienna, from the SISMALP array operated by the Laboratoire de Géophysique Interne et Tectonophysique, Observatoire de Grenoble, from the Laboratoire de Détection et Géophysique in Bruyères-le-Châtel, from the RENASS array operated by the Ecole et Observatoire des Sciences de la Terre in Strasbourg, from the Istituto Nazionale di Geofisica e Vulcanologìa in Rome and from the Istituto di Geofisica, Università di Genova.

To improve the reliability of automatic locations for events at the periphery or outside of Switzerland we have implemented an automatic system for retrieving foreign data. Many station and network operators make their waveforms available through AutoDRM, an e-mail based data transfer system (Kradolfer 1996). Recently a Java program, CollectWaves (http://www.seismo.ethz.ch/collectwaves), has been developed, which allows to send e-mail requests to data centers based on preliminary hypocenter coordinates and origin time. CollectWaves can request all available data, all data within a distance range, all data within an azimuth range or data required to achieve the best azimuthal station coverage. The last option is implemented in the automatic location procedure of the Swiss Seismological Service. If the preliminary location for an earthquake returns a distance less than 35° and an azimuth range with no observations (*gap*) larger than 180°, CollectWaves is activated and determines which stations with data available in near real-time could decrease the *gap*. As soon as the request-

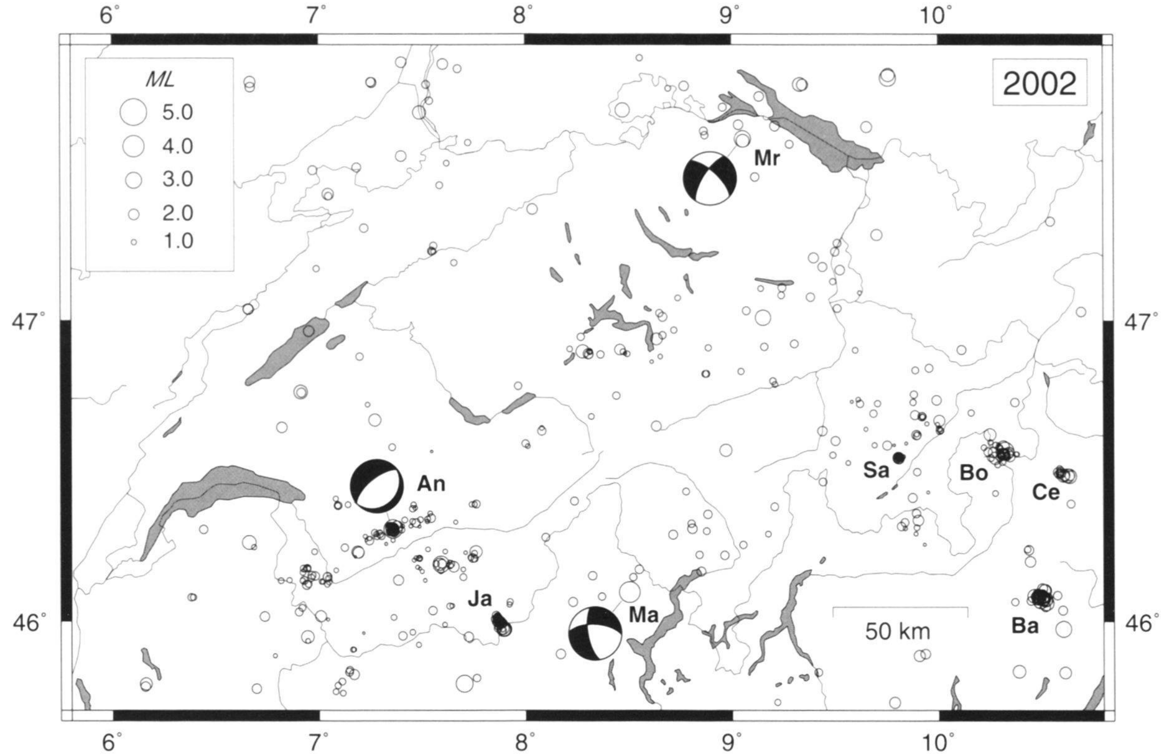


Fig. 3. Epicenters and focal mechanisms of earthquakes recorded by the Swiss Seismological Service during 2002. Epicenters of earthquakes mentioned in the text are Anzère (An), Val Baone (Ba), Bormio (Bo), M. Cevedale (Ce), Cima di Jazzi (Ja), Märstetten (Mr), Samedan (Sa), S. Maria Maggiore (Ma).

ed data arrive by e-mail, they are merged into the existing waveform file and the automatic location procedure is repeated with the new data (Fig. 2).

Data analysis

Preliminary hypocenter locations are determined on the basis of an automatic arrival time picker (Baer & Kradolfer 1987), but final arrival times and locations are subsequently reviewed by a seismologist. Locations are calculated either with a modified version of the widely used HYPO-71 algorithm originally developed by Lee & Lahr (1972) or with a grid search algorithm, that can use any Earth model for which travel times of seismic waves can be computed. The seismic velocity models consist of three horizontal crustal layers with constant velocities overlying a mantle half-space. The models in a simplified way account for differences between the near-surface geology in the Alps and foreland as well as for the large depth variation of the crust-mantle boundary. In addition, calculated travel times are corrected for differences in station elevation.

Routinely determined focal depths are reliable only if the epicenters are located inside the station network and if at least one station lies within an epicentral distance that is less than 1.5 times the focal depth. In the case of selected events, in particular those for which we constructed focal mechanisms, focal depths were checked by 2-D ray-trace modeling of the travel-time differences between the direct ray (Pg) and the reflection from the Moho (PmP) or between the Pg and the ray refracted in the upper mantle (Pn) (e.g. Deichmann 1987; Deichmann & Rybach 1989). The crustal velocities used for the ray-trace models are obtained from tomographic and seismic refraction studies (e.g. Maurer & Ansorge 1992; Maurer & Kradolfer 1996; Pfister 1990; Roth et al. 1992; Yan & Mechie 1989; Ye et al. 1995) and the Moho topography is based on the results of Waldhauser (1996) and Waldhauser et al. (1998), thus accounting realistically for the crustal heterogeneity. The same ray-tracing technique is also employed to identify correctly first arrivals and to estimate take-off angles of the rays at the source, which are used for constructing the focal mechanisms based on first-motion polarities (e.g. Eva et al. 1998; Deichmann et al. 2000b).

The newly installed broadband stations allow the use of state-of-the-art waveform modeling techniques to study the source parameters of some larger earthquakes in Switzerland. We invert complete three-component waveforms recorded at local to regional distances for the seismic moment tensor by minimizing the least squares misfit between observed and syn-

Tab. 2. Earthquakes with $M_L \geq 2.5$. The focal depths of the earthquakes for which focal mechanisms have been calculated are based on 2-D ray-tracing or on additional data from foreign networks.

Date & Time UTC	Lat. [°N]	Lon. [°E]	X / Y [km]	Depth [km]	Mag. [M_L]	Q	Location
2002.01.10 19:27:25	47.594	9.055	721/273	25	3.1	A	Märstetten, TG
2002.01.18 11:14:54	46.563	10.316	820/161	7	3.4	B	Bormio, I
2002.01.20 03:56:40	46.071	10.518	838/107	10	2.5	C	Val Baone, I
2002.01.20 04:09:49	46.074	10.520	838/107	10	2.6	C	Val Baone, I
2002.01.20 11:17:04	46.069	10.495	836/106	10	2.9	C	Val Baone, I
2002.01.20 17:24:13	46.061	10.524	839/106	10	2.7	C	Val Baone, I
2002.01.25 16:19:39	46.085	10.465	834/108	10	2.6	C	Val Baone, I
2002.03.20 14:44:13	46.191	7.592	612/115	7	3.1	B	Zinal, VS
2002.03.31 19:39:27	46.898	8.280	664/194	3	2.5	A	Kerns, OW
2002.04.21 17:57:15	45.790	7.703	620/ 71	4	3.2	C	Val d'Ayas, I
2002.04.24 13:03:31	46.308	7.357	594/128	3	2.5	B	Anzère, VS
2002.04.28 09:06:45	46.264	6.662	540/124	3	2.6	B	Le Biot, F
2002.04.29 15:14:09	46.102	8.457	679/106	21	3.8	B	S.Maria Magg., I
2002.05.10 19:55:02	47.009	9.152	730/208	5	2.9	B	Engi, GL
2002.05.17 07:19:39	47.688	8.474	678/282	24	2.7	A	Hallau, SH
2002.05.31 16:50:33	46.322	7.359	594/130	5	3.5	A	Anzère, VS
2002.06.17 01:50:31	46.764	6.913	560/179	6	2.6	A	Granges, VD
2002.07.06 14:09:55	47.792	9.759	774/296	27	3.1	C	Waldburg, D
2002.07.07 12:27:25	47.802	9.760	774/297	25	2.5	C	Waldburg, D
2002.07.09 03:21:21	47.771	9.333	742/293	20	2.6	C	Markdorf, D
2002.08.12 22:07:25	45.974	7.895	635/ 91	6	2.6	A	Cima di Jazzi, VS
2002.09.26 21:01:39	47.680	7.491	604/281	11	2.5	C	Rheingraben, F
2002.09.29 08:10:45	45.972	7.892	635/ 91	5	2.6	A	Cima di Jazzi, VS
2002.10.25 23:34:48	45.974	10.605	845/ 96	12	3.0	D	V.Giudicarie, I
2002.12.09 22:41:55	45.973	7.897	635/ 91	6	2.7	A	Cima di Jazzi, VS
2002.12.29 18:21:14	46.499	10.621	844/155	18	2.6	B	M.Cevedale, I
2002.12.29 22:54:51	46.500	10.621	844/155	18	2.7	B	M.Cevedale, I

thetic seismograms. Strike, dip, rake, and seismic moment follow directly from the moment tensor formulation. Earthquake depth is found by repeating the inversion for several trial depths. The inversion is performed at relatively low frequencies; thus, a simple one-dimensional velocity-depth model is sufficient to calculate synthetic discrete wavenumber seismograms (Bouchon 1982) for all stations. The model consists of a 35 km thick continental crust with an average ratio between the P- and S-wave velocities of 1.73. Using three-component data and low-frequency waveforms provides robust and stable source parameter estimates; moderate changes in the crustal model affect the moment tensor solutions only slightly. We refer to Nabelek & Xia (1995) and Braunmiller et al. (1995) for a more detailed description of the method and to Deichmann et al., 2000a for an illustration of the application to a local earthquake in Switzerland. The complete set of moment tensors calculated by the Swiss Seismological Service, including plots of all waveform fits, is available on line (http://seismo.ethz.ch/info/mt.html).

Tab. 3. Criteria and location uncertainty corresponding to the quality rating (Q) of the hypocentral parameters in Table 2. GAP = largest angle between epicenter and two adjacent stations; DM = minimum epicentral distance; H = horizontal location; Z = focal depth.

Rating	Criteria		Uncertainty	
Q	GAP (degrees)	DM (km)	H (km)	Z (km)
A	≤ 180	$\leq 1.5 \times Z$	≤ 2	≤ 3
B	≤ 200	≤ 25	≤ 5	≤ 10
C	≤ 270	≤ 60	≤ 10	> 10
D	> 270	> 60	> 10	> 10

During the transition time from the short-period to the broad-band network, magnitudes were determined from the records of both systems. However, since February 2002, magnitude calculations are based almost entirely on seismograms from the new stations. The broad-band signals are digitally filtered to simulate the response of a Wood-Anderson seismograph, and M_L is then determined directly from the maximum amplitudes of the resulting horizontal seismograms. The attenuation with epicentral distance is accounted for by an empirically determined relation (Kradolfer & Mayer-Rosa, 1988). The final magnitude corresponds to the median value of all individual station magnitudes. Assuming a Wood-Anderson gain of 2800 and adding a correction of 0.1 to each station magnitude results in values for M_L that are consistent with M_L deter-

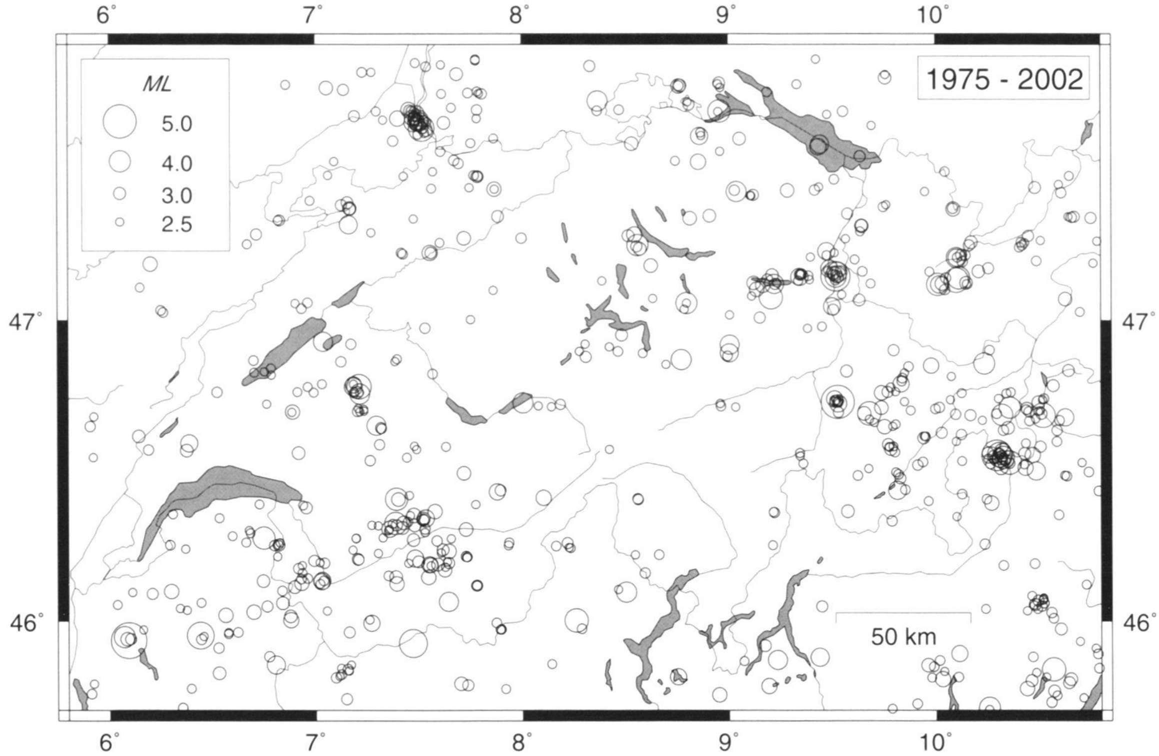


Fig. 4. Epicenters of earthquakes with Magnitudes $M_L \geq 2.5$, during the period 1975 — 2002.

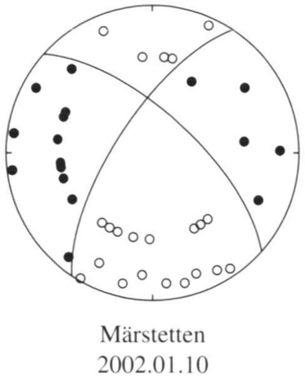


Fig. 5. Fault-plane solution based on first-motion polarities (lower hemisphere, equal area projection) for the Märstetten event. Solid circles correspond to compressive first motion (up) and empty circles to dilatational first motion (down).

mined previously from the vertical component short-period stations.

For the compilation of a unified earthquake catalog of Switzerland, that includes both historical and instrumental data (ECOS), it was decided to adopt moment magnitude M_w as a uniform estimate of earthquake size (Fäh et al. 2003). An analysis performed in this context showed that on average the M_L determined routinely by the Swiss Seismological Service is 0.2 magnitude units higher than M_w.

Seismic activity during 2002

Overview

During 2002, the Swiss Seismological Service detected and located 546 earthquakes in the region shown in Figure 3. Based on such criteria as the time of occurrence, the location, the signal character or on direct information, 137 additional seismic events were identified as quarry blasts.

Magnitude values of the events recorded in 2002 range between $M_L = 0.4$ and 3.8. The events with $M_L \geq 2.5$ and the criteria used to assign the quality rating for the given locations as well as the corresponding estimated location accuracy are listed in Tables 2 and 3. Where available, the epicentral coordinates and focal depths given in Table 2 are based on the results that include additional data from foreign networks and on 2-D ray-tracing. The locations of all earthquakes with $M_L \geq 2.5$ recorded in Switzerland and surroundings since 1975 are shown on the epicenter map in Figure 4.

In what follows, we present the highlights of the seismic activity observed during 2002.

Tab. 4. Focal mechanism parameters based on first-motion polarities (lines with M_L) and full-waveform inversion (lines with M_w).

Location	Date & Time [UTC]	Depth [km]	Mag.	Plane 1 Strike/Dip/Rake	Plane 2 Strike/Dip/Rake	P-Axis Az/Dip	T-Axis Az/Dip
Märstetten	2002.01.10 19:27	25	M_L 3.1	312/68/-158	213/70/-024	172/31	263/01
S.Maria Magg.	2002.04.29 15:14	21	M_w 3.5	170/68/-031	273/61/-154	129/37	223/04
Anzère	2002.05.31 16:50	5	M_L 3.5	046/24/-094	231/66/-088	145/69	319/21
		4	M_w 3.3	061/19/-073	223/72/-096	124/63	318/27

Significant earthquakes of 2002

Märstetten

The source of the earthquake, which occurred on Jan. 10th with magnitude M_L 3.1 and epicenter near the village of Märstetten, TG, was located in the lower crust at a depth of 25 km. It was followed a day later by an aftershock with M_L 2.4. The focal depth determination is based on records from stations in northern Switzerland and southern Germany (gap = 109° and D_{min} = 23 km) and is confirmed by ray-trace modelling of Pn phases. Earthquakes in the lower crust below the Molasse basin of northern Switzerland and southern Germany are not uncommon (e.g. Deichmann et al. 2000b). The well constrained fault plane solution based on first-motion polarities (Fig. 5) corresponds to a strike-slip mechanism with orientations of the P- and T-axes (Table 4) that are typical for earthquakes in northeastern Switzerland (Deichmann et al., 2000b; Kastrup, 2002).

Bormio

The M_L 3.4 event of Jan. 18th, together with 31 other weaker ones, represents continuing activity in the epicentral region of the M_L 4.9 Bormio earthquake of Dec. 29th, 1999. During 2002, most of this aftershock activity occurred in January and February. It gradually decreased over the subsequent months with the last event having occurred at the end of September. Thus the entire aftershock sequence of the 1999 Bormio event seems to have lasted for nearly 3 years.

Val Baone

In the second half of 2001, an earthquake swarm with epicenter in Val Baone near the Tonale Pass in northern Italy became active. During 2001, the Swiss high-gain network detected 42 events that are associated with this cluster; the strongest event reached M_L 3.0. This activity persisted at a high rate during January and February 2002 with an additional 36 events (Fig. 3). The strongest of these events with M_L 2.9 occurred on Jan. 20th (Table 2). After four more events with $M_L \leq 2.2$, that occurred between end of June and end of October, the activity in this cluster seems to have ceased. Given a minimum epicentral distance from the Swiss network of around 50 km and an azimuthal gap of about 300°, the epicentral locations shown in Figure 3 are poorly constrained. Judging from the similarity of the observed waveforms, the true epicenters are certainly more concentrated than the apparent scatter in Figure 3 would suggest.

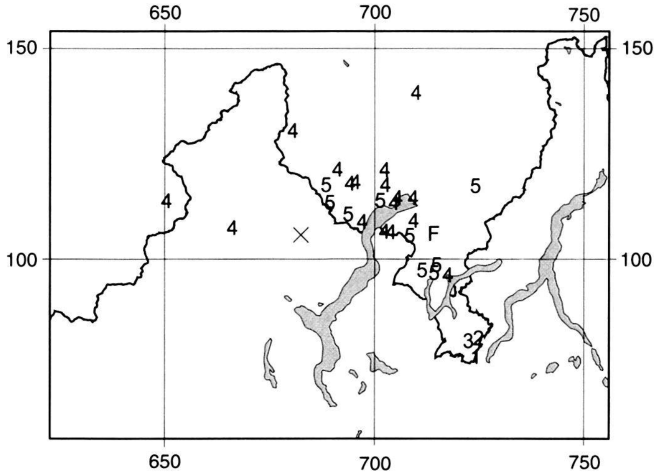


Fig. 6. Macroseismic observations of the S. Maria Maggiore event of 2002/04/29. Each value represents the macroseismic intensity (EMS-98) assigned to a single postal code zone. The X corresponds to the instrumental epicenter. The Swiss cartesian coordinate grid is labeled in km.

Santa Maria Maggiore

With M_L 3.8 and M_W 3.5, this event, which occurred on April 29th in the border region between Ticino and northern Italy, was the strongest event to have been recorded in 2002 in Switzerland and surrounding regions. It reached a maximum intensity of V and was felt all over southern Switzerland and the adjoining regions of northern Italy (Fig. 6). The epicenter was located about 5 km south of Santa Maria Maggiore between Val Vigezzo and Valgrande, Italy. This location situates the epicenter in the middle of the Ivrea Zone, which is characterized by outcropping mantle rocks with P-wave velocities in the range of 7-8 km/s. The 1-D velocity model used routinely for location is thus only a poor approximation of the real crustal structure in this region. To minimize the possible effects of lateral velocity variations on the location, we used stations out to an epicentral distance of only 50 km. Including also data from several Italian stations, this gave 5 P- and 4 S-

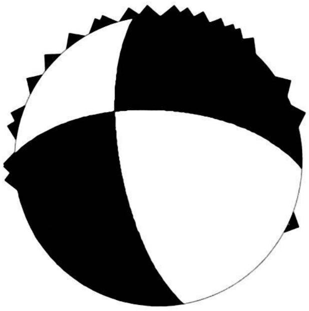


Fig. 7. Focal mechanism (lower hemisphere, equal area projection) for the event of S. Maria Maggiore, based on full-waveform moment tensor inversion. Triangles on the periphery of the stereo plots show the station locations.

arrivals with which to calculate the location. Despite a good azimuthal station distribution (gap = 120º), the remaining epicentral uncertainty is probably on the order of 5 km. Since the nearest station is about 35 km from the epicenter, the focal depth is even more poorly constrained and very sensitive to the assumed V_p/V_s velocity ratio. Thus we chose to fix the focal depth to 21 km, which gives the best wave-form fit in the moment tensor inversion. The moment tensor corresponds to a strike-slip mechanism with a strong normal faulting component and with P- and T-axes directed NW-SE and NE-SW (Fig. 7). Due to the difficulty of calculating correct take-off angles from a source located in such a complex geological structure as the Ivrea Zone, we did not attempt to construct a self-consistent fault plane solution from first motion polarities. However, within the uncertainties of the routinely calculated take-off angles, the moment tensor result matches the first motion polarities reasonably well.

Anzère

The M_L 3.5 earthquake that occurred on May 31st with epicenter 4 km NW of Anzère, VS, was the strongest event of an earthquake sequence that lasted for several months. Of the 35 detected and locatable events that were associated with this swarm, 3 occurred in January and February, 2 in October, and the remaining events occurred all between Apr. 24th and June 14th. Except for the main shock and three others with M_L between 2.1 and 2.5, magnitudes of the locatable events were all between M_L 0.5 and 1.8.

At several stations, the signals of the main shock are dominated by pronounced surface wave trains (e.g. station TORNY in Fig. 8), which at first sight would suggest that the source is located at a depth of only 1 or 2 km within the near-surface sedimentary cover. However, such a shallow source is at odds with the travel-time data. In fact, the hypocentral location is well constrained by station SENIN, at an epicentral distance of only 6 km, and by the P- and S-arrival times at two additional strong-motion stations (SAYF and SIOV) at distances of 5 and 9 km (Wyss 2003). The resulting focal depth of 4 to 6 km is corroborated by ray-trace modelling of PmP-Pg arrival-time differences at stations in northern Switzerland (5 km) and by the results of the moment tensor calculations (4 km).

The orientation of focal the mechanism of this event differs radically from anything observed so far in the northern Valais. It corresponds to a normal faulting mechanism on either a

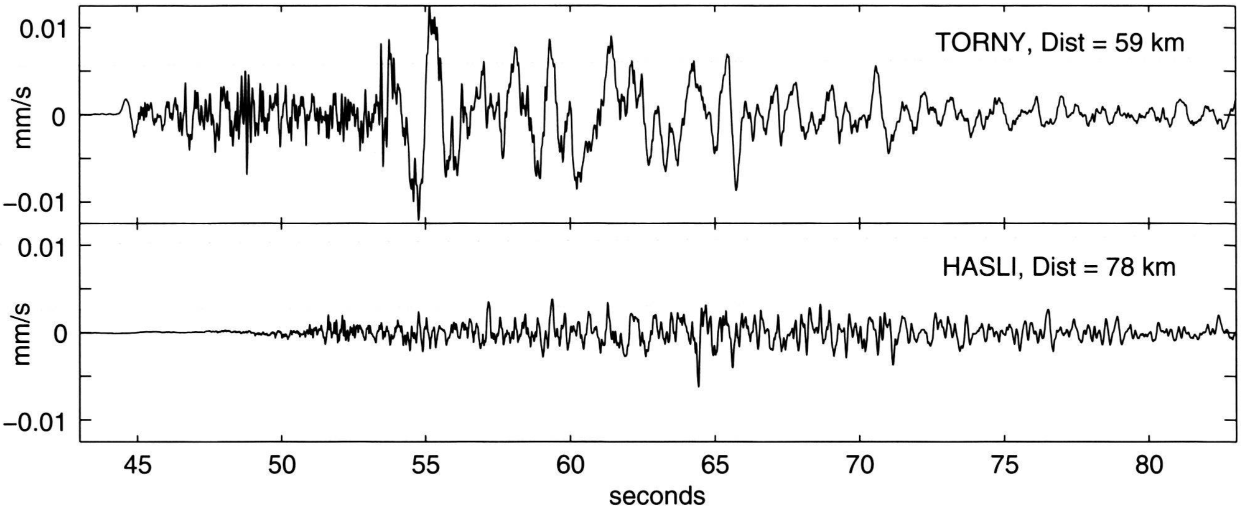
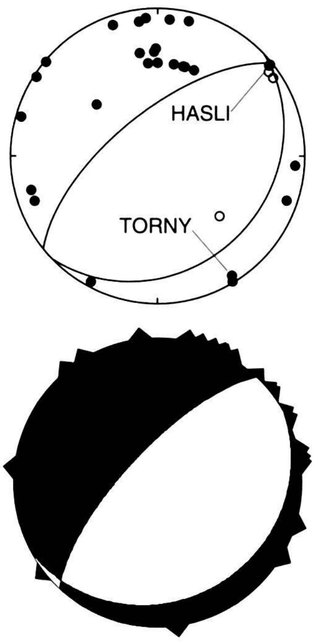


Fig. 8. Vertical component broad-band signals of the Anzère event recorded at stations TORNY and HASLI. Amplitudes at HASLI have been scaled to match the epicentral distance of TORNY by assuming a geometrical spreading dependence equal to 1/distance. Note the impulsive P- and S-arrivals as well as the pronounced surface wave train beyond 55 seconds at TORNY and, in contrast to this, the largely featureless low-amplitude signal consisting only of scattered waves at HASLI.



Anzère
2002.05.31

Fig. 9. Focal mechanism for the Anzère event, based on first-motion polarities and on full-waveform inversion. The labeled data points correspond to the two stations mentioned in the text.

steeply dipping or a flat lying fault plane that strikes in a NE-SW direction. The NW-SE trending extensional (T) axis is rotated by about 90° relative to the T-axes of most of the neighboring focal mechanisms (Maurer et al. 1997; Pavoni et al. 1997; Kastrup 2002). The mechanisms derived from the fault-plane solution based on first motion polarities and from the full wave-form moment tensor inversion are well constrained by data (Fig. 9), and the corresponding parameters agree with each other to within 10° (Table. 4). In particular, the null (B) axis and thus the strike of the nodal planes in the first-motion fault-plane solution are well constrained by the take-off direction of the ray to station HASLI. As shown in Figure 8, the signal recorded at this station lacks any recognizable onset of either a P- or S-wave. Such featureless signals consist only of scattered energy from waves leaving the source in directions other than the direct ray to the observer, which is consistent with the fact that a double-couple source does not radiate any energy in the direction of the null axis. When available, such signals are powerful constraints on the orientation of the focal mechanism.

The apparently discrepant orientation of the focal mechanism relative to the prevailing stress field (Kastrup 2002) can not be explained by questioning the reliability of the observations or by invoking possible near-surface stress heterogeneities affecting an unusually shallow source (i.e. the Anzère event occurring within a mechanically decoupled sedimentary layer and thus possibly responding to a different stress field). Given that the most robust feature of stress inversions performed on the basis of the hitherto observed focal mechanisms in the northern Valais is the NE-SW orientation and the nearly horizontal plunge of the least principal stress σ_3 (Kastrup 2002), a local perturbation of the stress field that would lead to a horizontal rotation of σ_3 of as much as 90° at a depth of 5 km within the Earth's crust is also highly unlikely. A possible explanation consistent with previous stress inversions (Kastrup, 2002) can however be found by observing that the orientation of the null axis matches almost exactly the orientation of σ_3 and that the possible orientations of σ_1 and σ_2 can take on any value within a vertical plane perpendicular to σ_3. In this case, slip on a pre-existing fault with an orientation as that of the Anzère event is possible and will be triggered not by the difference $\sigma_1 - \sigma_3$ but by $\sigma_1 - \sigma_2$. The permutability of the directions of σ_1 and σ_2 is favoured if their magnitudes are similar, implying that the fault, which was active during the earthquake sequence of Anzère, must have been particularly weak. Temporarily elevated fluid pressures on the fault would not only have the necessary weakening effect, but would also function as a trigger mechanism for the observed swarm-like occurrence of these events.

Cima di Jazzi

A particularly active earthquake sequence manifested itself during 2002 on the Swiss-Italian border between the valleys of Zermatt and Macugnaga. After 3 preliminary events ($M_L \leq 1.5$) in January and February, activity suddenly picked up again at the beginning of July, with 24 events detected during that month alone. It continued at a somewhat slower pace over subsequent months, reaching a total of 73 detected events by the end of the year. Three earthquakes reached magnitudes, M_L, of 2.6 and 2.7 (Table 2). The magnitudes of all other events were between 0.9 and 2.2. Preliminary locations scattered over a distance of 10 km, with an apparent distribution into two subclusters separated by an aseismic gap of about 3 km. It turned out that this was entirely an artifact of the location procedure and of the complicated crustal structure in this region. Rays leaving the hypocenters of these events towards the east and northeast are strongly affected by the Ivrea Body, with its high lateral velocity contrast relative to the surrounding crust. For this situation the one-dimensional velocity model used in our routine location procedure constitutes an inadequate simplification. In addition, the epicentral area lies at the periphery of the Swiss station network (*gap* > 180). As a consequence, locations that include arrivals at stations FUSIO and MUGIO (see Fig. 1) are systematically shifted to the SE by about 6 km relative to the locations of the generally weaker events based only on the three closest stations MMK, DIX and LKBD in the Valais. For four of the stronger events, we obtained data from the Italian stations Macugnaga (MCGN), Oropa (ORO) and Varese (VAI). The most stable and reliable locations, which are listed in Table 2, are based only on

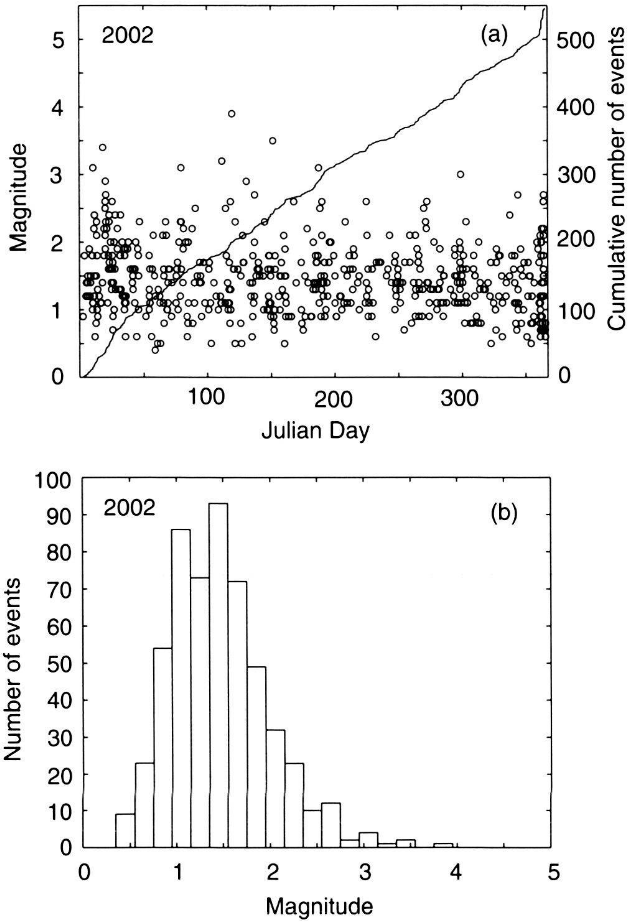


Fig. 10. Earthquake activity during 2002: magnitude of each event and cumulative number of events (a); histogram of magnitudes (b).

arrivals at stations MCGN, ORO, MMK, DIX and LKBD (Minimum epicentral distance, D_{min} = 7 km, *gap* = 118° and the root-mean-square of the travel-time residuals, *rms* = 0.10 - 0.14 s). The resulting travel-time residuals at the Italian station VAI (Varese) and at stations FUSIO and MUGIO, which were not used for calculating the locations, range between -0.82 and -1.37 s, which is at least qualitatively consistent with the expected effect of the high-velocity Ivrea Body. For the sake of consistency, all other events were located using only the three stations in the Valais, which for these events, results in a systematic shift of about 4 km to the NW relative to the locations based also on the Italian stations (Fig. 3).

Samedan

Beginning on December 27th, a sequence of microearthquakes (M_L = 0.6 - 2.2) became active north of Samedan in the Upper Engadine. By December 31st, the total number of detected earthquakes belonging to this cluster had reached 21, but most of the events occurred in two spurts of activity lasting one hour each in the early morning of December 27th (8 events) and 28th (7 events).

Monte Cevedale

The last earthquake sequence recorded in 2002 occurred over a time period of only five hours on the evening of Dec. 29th. Its epicenter was situated in northern Italy, 30 km SE of station FUORN, in the area of Monte Cevedale. A total of 12 detected events with M_L = 1.2 - 2.6 were associated with this cluster.

Discussion

Figure 4 shows the epicenters of the earthquakes with $M_L \geq 2.5$, which have been recorded in Switzerland and surrounding regions over the period of 1975 - 2002. The chosen magnitude threshold of 2.5 ensures that the data set is complete for the given period and that the number of unidentified quarry blasts and of badly mislocated epicenters is negligible. These events represent about 10% of the total number of events detected during that time period in the same area.

Compared to the period 1996-2001, when the number of recorded earthquakes ranged between 226 and 382 events/year, the year 2002 seems at first sight to have witnessed an unusually high seismic activity. However, averaged over the last 28 years, the earthquakes shown in Figure 4 are equivalent to about 25 events with $M_L \geq 2.5$ and about 8 events with $M_L \geq 3$ per year. With 27 events with $M_L \geq 2.5$ and 8 events reaching $M_L \geq 3$ (Table 2 and Fig. 10), the seismic activity in 2002 was thus about equal to the average over the last 28 years for earthquakes in these magnitude ranges. Consequently the observed activity increase is due only to the lower-magnitude events. This is caused by the lower detection threshold following the completion of the new broad-band network (Deichmann et al. 2002), and by the occurrence of an unusual number of earthquake swarms during 2002. In fact, 39 % of the total number of events were associated with the six earthquake sequences of Bormio, Val Baone, Anzère, Cima di Jazzi, Samedan and Monte Cevedale. Thus, the enhanced activity visible in the plot of the temporal evolution of seismicity (Fig. 10) at the beginning of the year is due to the Bormio and Val Baone events, while the sharp increase during the last days of the year reflects the sudden occurrence of the swarms of Samedan and Monte Cevedale.

Routinely calculated focal depths for the 546 earthquakes recorded in 2002 range between 1 and 30 km, but only 25 of these hypocenters are deeper than 15 km. As in the past (e.g. Deichmann et al. 2000a), almost all these deep sources are located in the lower crust beneath the Jura Mountains and Molasse Basin of northern Switzerland. Notable exceptions are the hypocenters of the Santa Maria Maggiore event at a depth of more than 20 km in the Ivrea Zone and of the Monte Cevedale sequence. However, the focal depths of the latter (15-20 km), determined from routine analysis only, are questionable and need to be confirmed by additional evidence.

Overall, as in previous years, most of the seismic activity during 2002 was concentrated in the Valais, the southeastern part of Graubünden and in the adjacent regions of northern Italy (Fig. 3).

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REFERENCES

Baer, M. 1990: The seismic station network of the Swiss Seismological Service. In: I. Workshop on: Mednet, the Broad-Band Seismic Network for the Mediterranean (Ed. by E. Boschi, D. Giardini and A. Morelli). Istituto Nazionale Geofisica, Roma, 345–350.

Baer, M. & Kradolfer, U. 1987: An automatic phase picker for local and teleseismic events. Bull. Seis. Soc. Am. 77, 1437–1445.

Baer, M., Deichmann, N., Fäh, D., Kradolfer, U., Mayer-Rosa, D., Rüttener, E., Schler, T., Sellami, S., & Smit, P. 1997: Earthquakes in Switzerland and surrounding regions during 1996. Eclogae geol. Helv. 90/3, 557–567.

Baer, M., Deichmann, N., Ballarin Dolfin, D., Bay, F., Delouis, B., Fäh, D., Giardini, D., Kastrup, U., Kind, F., Kradolfer, U., Künzle, W., Röthlisberger, S., Schler, T., Sellami, S., Smit, P., & Spühler, E. 1999: Earthquakes in Switzerland and surrounding regions during 1998. Eclogae Geol. Helv., 92/2, 265–273.

Baer, M., Deichmann, N., Braunmiller, J., Ballarin Dolfin, D., Bay, F., Bernardi, F., Delouis, B., Fäh, D., Gerstenberger, M., Giardini, D., Huber, S., Kastrup, U., Kind, F., Kradolfer, U., Maraini, S., Mattle, B., Schler, T., Salichon, J., Sellami, S., Steimen, S., Wiemer, S. 2001: Earthquakes in Switzerland and surrounding regions during 2000. Eclogae Geol. Helv., 94/2, 253–264.

Bouchon, M. 1982: The complete synthesis of seismic crustal phases at regional distances. J. Geophys. Res., 87, 1735–1741.

Braunmiller, J., Nabelek, J. L., Leitner, B. & Qamar, A. 1995: The 1993 Klamath Falls, Oregon, earthquake sequence: source mechanisms from regional data. Geophys. Res. Lett., 22, 105–108.

Deichmann, N. 1987: Focal depths of earthquakes in northern Switzerland. Annales Geophysicae 5B, 395–402.

Deichmann, N. 1990: Seismizität der Nordschweiz, 1987–1989, und Auswertung der Erdbebenserien von Günsberg, Läufelfingen und Zeglingen. Nagra Technischer Bericht, NTB 90–46, Nagra, Baden.

Deichmann, N. 1992: Recent seismicity of the northern Alpine foreland of Switzerland. Eclogae geol. Helv. 85/3, 701–705.

Deichmann, N. & Baer, M. 1990: Earthquake focal depths below the Alps and northern Alpine foreland of Switzerland. In: The European Geotraverse: Integrative Studies. (Ed. by R. Freeman, P. Giese and St. Mueller). European Science Foundation, Strasbourg, France, 277–288.

Deichmann, N. & Garcia-Fernandez 1992: Rupture geometry from high-precision relative hypocenter locations of microearthquake clusters. Geophys. J. Int. 110, 501–517.

Deichmann, N. & Rybach, L. 1989: Earthquakes and temperatures in the lower crust below the northern Alpine foreland of Switzerland. In: Properties and Processes of the Lower Crust. (Ed. by R. F. Mereu St. Mueller and D. Fountain). Am. Geophys. Union, Geophysical Monograph 51, IUGG Vol. 6, 197–213.

Deichmann, N., Baer, M., Ballarin Dolfin, D., Fäh, D., Flück, P., Kastrup, U., Kradolfer, U., Künzle, W., Mayer-Rosa, D., Röthlisberger, S., Schler, T., Sellami, S., Smit, P., & Giardini, D. 1998: Earthquakes in Switzerland and surrounding regions during 1997. Eclogae geol. Helv. 91/2, 237–246.

Deichmann, N., Baer, M., Braunmiller, J., Ballarin Dolfin, D., Bay, F., Delouis, B., Fäh, D., Giardini, D., Kastrup, U., Kind, F., Kradolfer, U., Künzle, W., Röthlisberger, S., Schler, T., Salichon, J., Sellami, S., Spühler, E., Wiemer, S. 2000a: Earthquakes in Switzerland and surrounding regions during 1999. Eclogae Geol. Helv., 93/3, 395–406.

Deichmann, N., Ballarin Dolfin, D., & Kastrup, U. 2000b: Seismizität der Nord- und Zentralschweiz. Nagra Technischer Bericht, NTB 00–05, Nagra, Wettingen. Deichmann, N., Baer, M., Braunmiller, J., Ballarin Dolfin, D., Bay, F., Bernardi, F., Delouis, B., Fäh, D., Gerstenberger, M., Giardini, D., Huber, S., Kradolfer, U., Maraini, S., Oprsal, I., Schibler, R., Schler, T., Sellami, S., Steimen, S., Wiemer, S., Wössner, J., Wyss, A. 2002: Earthquakes in Switzerland and surrounding regions during 2001. Eclogae Geol. Helv. – Swiss J. Geosciences, 95/2, 249–261.

Eva, E., Pastore, S. & Deichmann, N. 1998: Evidence for ongoing extensional deformation in the western Swiss Alps and thrust-faulting in the southwestern Alpine foreland. Journal of Geodynamics 26/1, 27–43.

Fäh, D., Giardini, D., Bay, F., Bernardi, F., Braunmiller, J., Deichmann, N., Furrer, M., Gantner, L., Gisler, M., Isenegger, D., Jimenez, M.-J., Kästli, P., Koglin, R., Masciadri, V., Rutz, M., Scheidegger, C., Schibler, R., Schorlemer, D., Schwarz-Zanetti, G., Steimen, S., Sellami, S., Wiemer, S., Wössner, J. 2003: Earthquake catalog of Switzerland (ECOS) and the related macroseismic database. Eclogae Geol. Helv. – Swiss J. Geosciences, 96, 219–236.

Kastrup, U. 2002: Seismotectonics and stress-field variations in Switzerland. Ph.D. Thesis Nr. 14527, ETH-Zürich.

Kradolfer, U. 1996: AutoDRM – The First Five Years. Seism. Res. Let., 67, 30–33.

Kradolfer, U., & Mayer-Rosa, D. 1988: Attenuation of seismic waves in Switzerland. In: Recent seismological investigations in Europe. Proceedings of the XIX General Assembly of the ESC. Moscow, October 1–6, 1984, 481–488.

Lee, W. H. K. & Lahr, J. C. 1972: HYPO-71 a computer program for determining hypocenter, magnitude and first motion pattern of local earthquakes. U.S. Geol. Surv., Open-File Rep.

Maurer, H., & Ansorge, J. 1992: Crustal structure beneath the northern margin of the Swiss Alps. Tectonophysics 207, 165–181.

Maurer, H. & Kradolfer, U. 1996: Hypocentral parameters and velocity estimation in the western Swiss Alps by simultaneous inversion of P- and S-wave data. Bull. Seis. Soc. Am. 86, 32–41.

Maurer, H., Burkhard, M., Deichmann, N., Green, A. G. 1997: Active Tectonism in the Western Swiss Alps. Terra Nova, 9, 91–94.

Nabelek, J. & Xia, G. 1995: Moment-tensor analysis using regional data: application to the 25 March, 1993, Scotts Mills, Oregon earthquake. Geophys. Res. Lett., 22, 13–16.

Pavoni, N. 1977: Erdbeben im Gebiet der Schweiz. Eclogae geol. Helv. 70/2, 351–370.

Pavoni, N. 1984: Seismotektonik Nordschweiz. Nagra Technischer Bericht, NTB 84–45, Nagra, Baden.

Pavoni, N. & Roth, P. 1990: Seismicity and seismotectonics of the Swiss Alps. Results of microearthquake investigations 1983–1988. In: Deep Structure of the Alps. (Ed. by F. Roure, P., Heitzmann and R. Polino). Mem. Soc. geol. France, N. S., 156, 129–134.

PAVONI, N., MAURER, H., ROTH, P., DEICHMANN, N. 1997: SEISMICITY and seismotectonics of the Swiss Alps. In: Deep structure of the Swiss Alps, results of NRP 20, Birkhäuser, Basel, 241–250.

PFISTER, M. 1990: Gemeinsame Auswertung von Erdbeben-, Refraktions- und Reflexionsdaten in der Nordschweiz. Diploma thesis, Institute of Geophysics, ETH-Zürich.

ROTH, P., PAVONI, N., DEICHMANN, N. 1992: Seismotectonics of the eastern Swiss Alps and evidence for precipitation-induced variations of seismic activity. Tectonophysics, 207, 183–197.

RÜTTENER, E. 1995: Earthquake hazard estimation for Switzerland. Matér. Géol. Suisse, Geophys. Nr. 29, Schweizerische Geophysikalische Kommission, ETH-Zürich, 106 pp.

RÜTTENER, E., EOGOZCUE, J., MAYER-ROSA, D. & MUELLER, S. 1996: Bayesian estimation of seismic hazard for two sites in Switzerland. Natural Hazards 14, 165–178.

SÄGESSER & MAYER–ROSA 1978: Erdbebengefährdung in der Schweiz. Schweizerische Bauzeitung 78/7, 3–18.

SMIT, P. 1998: The Swiss National Strong Motion Network – Achievements and prospects. Proc. 11th Conference Earthquake Engineering, 6.–11. September 1998, Paris.

WALDHAUSER, F. 1996: A parametrized three-dimensional Alpine crustal model and its application to teleseismic wavefront scattering. Ph.D. Thesis Nr. 11940, ETH-Zürich, 137 pp.

WALDHAUSER, F., KIESSLING, E., ANSORGE, J., MUELLER, ST. 1998: Three-dimensional Interface Modeling with two-dimensional Seismic Data: the Alpine Crust-Mantle boundary. Geoph. J. Int., 135, 264–278.

WYSS, A. 2003: Swiss National Strong Motion Network: Strong Motion Bulletin, January 2002 – December 2002. Publ. Series of the Swiss Seismological Service, Nr. 115, ETH-Zürich.

YAN, Q. Z., & MECHIE, J. 1989: A fine structural section through the crust and lower lithosphere along the axial region of the Alps. Geophys. J. Int. 98, 465–488.

YE, S., ANSOREG, J., KISSLING, E. & MUELLER, S. 1995: Crustal structure beneath the eastern Swiss Alps derived from seismic refraction data. Tectonophysics 242, 199–221.

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