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Earthquakes in Switzerland and surrounding regions during 2003

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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 2003. During this period, 532 earthquakes and 118 quarry blasts were detected and located in the region under consideration. With 30 events with $M_L \geq 2.5$, the seismic activity in the year 2003 was slightly above the average over the last 29 years. As in previous years, most of the seismic activity was concentrated in the Valais and in Graubünden. In addition, several earthquakes occurred along the northern front of the Alps. The strongest event, with M_L 4.0 and epicentral intensity V, occurred in the area of Urnerboden, on the border between the cantons Uri and Glarus. Two earthquakes with M_L 3.9 occurred in the Valais near the town of Salgesch and south of the Sanetsch Pass. In Graubünden, the Sertig valley south of Davos was the site of a sequence of 51 earthquakes that included three events with magnitudes between M_L 3.6 and 3.9.

ZUSAMMENFASSUNG

Dieser Bericht des Schweizerischen Erdbebendienstes ist eine Zusammenfassung der im Vorjahr in der Schweiz und Umgebung aufgetretenen Erdbeben. Im Jahr 2003 wurden im erwähnten Gebiet 532 Erdbeben sowie 118 Sprengungen erfasst und lokalisiert. Mit 30 Beben der Magnitude $M_L \geq 2.5$ war die seismische Aktivität im Jahr 2003 leicht überdurchschnittlich. Wie schon in früheren Jahren ereigneten sich die meisten Beben vor allem im Wallis und in Graubünden. Ausserdem gab es einige Beben entlang der nördlichen Front der Alpen. Das stärkste Beben erreichte eine Magnitude von M_L 4.0 und eine Epizentralintensität von V; das Epizentrum befand sich in der Gegend vom Urnerboden, an der Grenze zwischen Uri und Glarus. Zwei Erdbeben der Magnitude M_L 3.9 ereigneten sich im Wallis bei Salgesch und südlich des Sanetsch Passes. In Graubünden war das Sertigtal südlich von Davos das Epizentrum einer Erdbebenserie mit 51 Ereignissen, von denen drei die Magnituden M_L 3.6–3.9 erreichten.

RESUME

Le présent rapport du Service Sismologique Suisse résume l'activité sismique en Suisse et dans les régions limitrophes au cours de l'année écoulée. En 2003, 532 tremblements de terre et 118 tirs de carrière furent détectés et localisés. Avec 30 événements de magnitude $M_L \geq 2.5$, l'activité sismique de l'année 2003 est au dessus de l'activité moyenne. Comme les années précédentes, l'activité sismique s'est prinicipalement concentrée dans le Valais et dans les Grisons, mais il y a aussi eu plusieurs tremblements de terre du long le front nord des Alpes. L'événement le plus significatif, d'une magnitude M_L 4.0 et d'une intensité épicentrale de V, s'est produit dans la région d' Urnerboden, entre les cantons Uri et Glaris. Deux séismes de magnitude M_L 3.9 ont eu lieu en Valais près de Salgesch et au sud du Col de Senin. La vallée de Sertig au sud de Davos en Grisons a été la zone épicentrale d'une séquence de 51 séismes, dont trois ont atteint magnitudes de M_L 3.6 à 3.9.

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 Bulletin of the Swiss Seismological Service)*. Since 1996, annual reports summarizing

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Table 1. Seismograph stations operational at the end of 2003. Instrument types: SP = 1 second, EB = 5 seconds, BB = broad band, SM = accelerometer, 1 = vertical component only, 3 = vertical and horizontal components. Signals of APL, LKBD2 and BBS are transmitted via analog telemetry; data of BBS are recorded by the Landeserdbebendienst Baden-Württemberg and those of BERT and GNV are recorded locally on paper.

National high-gain network recorded in Zürich		
Code	Station name	Type
ACB	Acheberg, AG	EB-3
AIGLE	Aigle, VD	BB-3
APL	Alpnach, OW	SP-3
BALST	Balsthal, SO	BB-3
BERNI	Bernina, GR	BB-3
BNALP	Bannalpsee, NW	BB-3
BOURR	Bourrignon, JU	BB-3, SM-3
BRANT	Les Verrières, NE	BB-3
CHKAM	Kamor, SG	BB-3
DAVOX	Davos, GR	BB-3
DIX	Grande Dixence, VS	BB-3
EMV	Vieux Emosson, VS	BB-3
FLACH	Flach, ZH	EB-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
LKBD2	Leukerbad, VS	SP-3
LLS	Linth-Limmern, GL	BB-3
PLONS	Mels, SG	BB-3
MMK	Mattmark, VS	BB-3, SM-3
MUGIO	Muggio, TI	BB-3
MUO	Muotathal, SZ	BB-3
SALAN	Lac de Salanfe, VS	EB-3
SENIN	Senin, VS	BB-3, SM-3
SLE	Schleitheim, SH	BB-3
STEIN	Stein am Rhein, SH	EB-3
SULZ	Cheisacher, AG	BB-3
TORNY	Torny, FR	BB-3
TRULL	Trullikon, ZH	EB-3
VDL	Valle di Lei, GR	BB-3, SM-3
WEIN	Weingarten, TG	EB-3
WILA	Wil, SG	BB-3
WIMIS	Wimmis, BE	BB-3
ZUR	Zürich-Degenried, ZH	BB-3

Single stations		
Code	Station name	Type
BBS	Basel-Blauen, BL	SP-1
BERT	Bern, BE	SP-3
GNV	Geneva, GE	SP-1

the seismic activity in Switzerland and surrounding regions have been published in the present form (Baer et al. 1997, 1999, 2001, 2003; Deichmann et al. 1998, 2000a, 2002). Recently, during 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; Kastrup et al. 2004).

Seismic stations in operation during 2003

The Swiss Seismological Service operates two separate nation-wide 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, whereas the latter is principally aimed at engineering concerns and thus only records so-called strong motions. The observations presented here are based mainly on the high-sensitivity monitoring network. The data collected by the strong-motion network during 2003 is documented separately (Wyss 2004).

Since February 2002, the national high-gain network consists almost entirely of digital data acquisition systems with high dynamic range and with either three-component broad-band STS-2 seismometers or Lennartz 5-second sensors (BB and EB in Table 1). For a detailed description of the new data acquisition system, see Baer et al. (2001). In the course of the year 2003, one of the remaining analog short-period stations (ACB) and four additional sites (FLACH, STEIN, TRULL and WEIN) have been equipped with the new digital instruments. An additional broad-band instrument (CHKAM) was installed for test purposes in the vicinity of and as a possible alternative to the excessively noisy station KAMOR. Thus the total number of digital stations in operation in Switzerland had increased to 36 by the end of 2003 (Table 1 and Figure 1). The only two remaining short-period analog stations were APL and the additional station (LKBD2) installed in 2002 near Leukerbad (Baer et al. 2003). Station BAS, a short-period three-component instrument with on-site PCM recording, operated in Basel for many years first by the University of Karlsruhe and then by the Landeserdbebendienst in Freiburg, Germany, was removed in August 2003.

The data of the national strong-motion network is recorded on site or can be downloaded interactively by telephone (Wyss 2004). To complement this acceleration data with signals that are available in real-time, the four stations BOURR, MMK, SENIN and VDL of the broad-band network have been equipped in 2003 with an additional three-component Kinemetrics EpiSensor accelerometer (Table 1).

Data from foreign networks

For detailed studies of selected earthquakes and for constraining the location and the focal mechanisms of earthquakes situ-

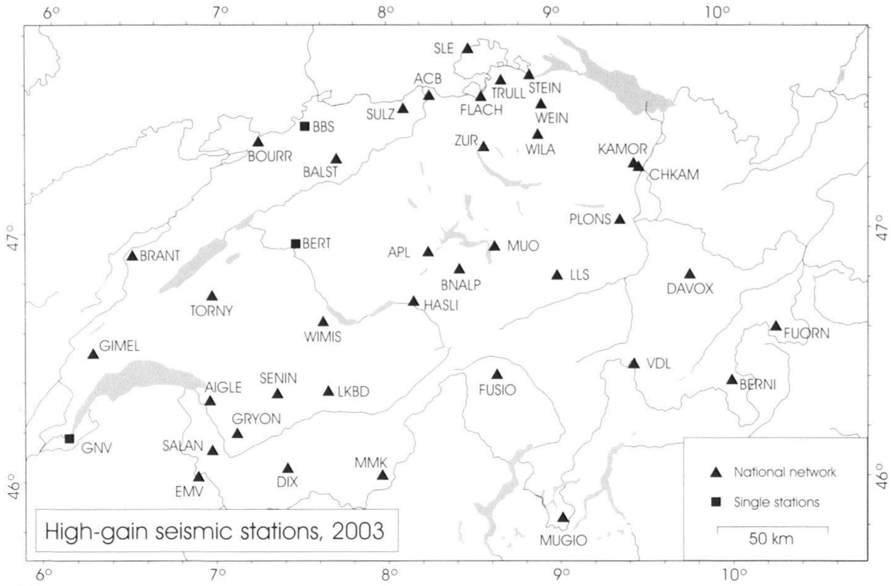

Figure 1. Seismograph stations in Switzerland operational at the end of 2003.

ated 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, 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 data from some of the institutions listed above (Baer et al. 2003).

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 synthetic 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

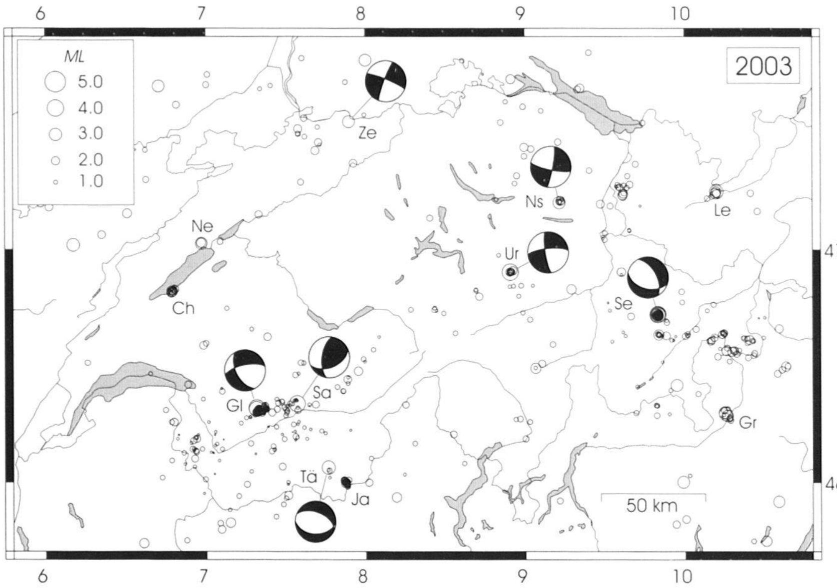

Figure 2. Epicenters and focal mechanisms of earthquakes recorded by the Swiss Seismological Service during 2003. Epicenters of earthquakes mentioned in the text are Cheyres (Ch), Glarey (Gl), Grosio (Gr), Cima di Jazzi (Ja), Lech (Le), Neuchâtel (Ne), Nesslau (Ns), Salgesch (Sa), Sertig (Se), Täsch (Tä), Urnerboden (Ur), Zeiningen (Ze).

Table 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
2003.01.27 16:17:25	45.917	10.587	844/ 90	14	2.8	D	V. Giudicarie, I
2003.01.29 08:00:04	47.261	10.191	808/238	7	3.4	B	Lech, A
2003.01.29 15:18:14	47.241	10.172	807/236	4	2.5	B	Lech, A
2003.02.03 13:11:43	47.027	6.971	564/208	3	2.9	A	Neuchâtel, NE
2003.02.04 20:49:41	46.065	7.765	625/101	6	3.3	B	Täsch, VS
2003.02.09 08:22:46	46.289	10.266	818/130	12	2.8	C	Grosio, I
2003.02.09 16:55:52	46.303	10.249	816/132	14	2.9	C	Grosio, I
2003.02.18 07:42:44	47.246	10.198	809/236	4	2.5	B	Lech, A
2003.02.19 11:30:17	46.297	10.254	817/131	13	3.2	C	Grosio, I
2003.02.24 21:21:21	47.020	6.175	504/208	1	3.1	C	Reugney, F
2003.03.24 07:54:22	47.692	6.707	545/283	18	2.9	C	Belfort, F
2003.04.29 04:55:09	46.341	7.570	610/132	10	3.9	A	Salgesch, VS
2003.05.06 21:59:43	46.905	8.908	712/196	3	4.0	A	Urnerboden, UR
2003.07.16 22:00:33	46.723	9.827	783/177	7	2.8	A	Sertig, GR
2003.07.17 02:27:17	46.729	9.838	783/178	7	3.6	A	Sertig, GR
2003.07.18 10:40:40	46.719	9.832	783/177	7	2.7	A	Sertig, GR
2003.07.18 11:01:36	46.723	9.840	783/177	7	3.9	A	Sertig, GR
2003.07.21 05:45:58	46.823	6.789	550/186	11	2.6	A	Cheyres, FR
2003.08.01 03:20:23	46.729	9.837	783/178	7	3.9	A	Sertig, GR
2003.08.02 08:07:57	46.637	9.838	784/168	7	2.5	B	Piz Kesch, GR
2003.08.12 00:38:54	46.723	9.829	783/177	7	2.9	A	Sertig, GR
2003.08.22 09:21:32	46.323	7.316	590/130	6	3.9	A	Glarey, VS
2003.08.22 09:30:09	46.318	7.315	590/130	6	3.6	A	Glarey, VS
2003.08.24 12:43:41	47.801	8.003	642/295	27	2.9	C	Todtnau, D
2003.08.26 08:58:03	46.420	9.950	793/144	8	2.9	B	Diavolezza, GR
2003.08.31 05:06:35	46.002	9.989	797/ 98	12	2.9	C	Valbondione, I
2003.08.31 05:38:58	47.542	7.898	635/266	17	2.9	A	Zeiningen, AG
2003.10.01 07:31:06	47.200	9.216	735/229	8	3.0	A	Nesslau, SG
2003.11.18 02:44:36	46.493	9.066	725/150	7	2.5	B	Rheinquellhorn, GR
2003.12.02 10:10:26	45.745	10.508	839/ 71	10	2.5	D	Lago d'Idro, I

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://www.seismo.ethz.ch/mt/).

Table 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 broad-band stations. The broad-band signals are digitally filtered to simulate the response of a Wood-Anderson seismograph, and the local magnitude 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 determined 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 local magnitude M_L determined routinely by the Swiss Seismological Service is 0.2 magnitude units higher than M_w (Braunmiller et al. 2005).

To meet the increasing demands of both the public and the media for rapid information, in May 2003 the Swiss Seismological Service started to automatically update its web-page with information about earthquakes in Switzerland whose magnitude exceeds M_L 3.0 (http://www.seismo.ethz.ch). In addition, location and magnitude together with a preliminary assessment of possible damage are disseminated automatically to authorities and media within minutes after a strong seismic event.

Seismic activity during 2003

Overview

During 2003, the Swiss Seismological Service detected and located 532 earthquakes in the region shown in Figure 2. Based on such criteria as the time of occurrence, the location, the signal character or on direct information, 118 additional seismic events were identified as quarry blasts.

Magnitude values of the events recorded in 2003 range between $M_L = 0.2$ and 4.0. 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 3.

In what follows, we present the highlights of the seismic activity observed during 2003.

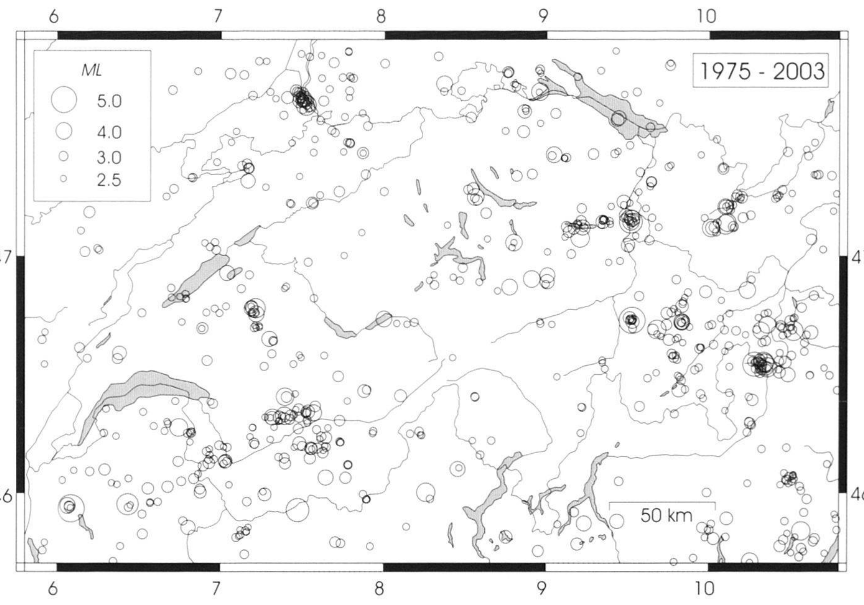

Figure 3. Epicenters of earthquakes with magnitudes $M_L \geq 2.5$, during the period 1975 – 2003.

Significant earthquakes of 2003

Neuchâtel

Although the magnitude of this event, that occurred on February 3rd, reached only a value of M_L 2.9, it was felt quite strongly by the population in the city of Neuchâtel and surroundings. The E-W component of the instrument of the Swiss Strong Motion Network in Neuchâtel, located at an epicentral distance of about 2 km, recorded a peak ground acceleration of 3% g (Wyss 2004). It was followed by a single aftershock with M_L 2.2 on February 5th. Based on the travel-time difference of only 0.44 seconds between the S- and P-waves recorded by the accelerograph in Neuchâtel, and allowing for uncertainties in epicentral location and seismic velocities, the focal depth must lie between 1.8 and 2.5 km. The sediment thickness in the epicentral area is estimated to be about 2.3 km (Sommaruga 1997). Thus within the remaining hypocentral uncertainty it is not possible to determine whether the source of this event was located in the basement or the overlying Mesozoic sediments. The fact that the signals recorded at several seismic stations in the Swiss and French Jura show very strong and long-lasting surface waves, similar to those usually observed from strong quarry blasts at the Earth's surface, suggests that the source was located in the sediments rather than in the basement. However, this hypothesis needs to be tested with synthetic seismograms. Given the focal depth uncertainty and the relatively low magnitude of this event, it was not possible to determine a unique focal mechanism either from first-motion polarities or from a full-waveform inversion. Based on first-motion polarities, both a strike-slip and a thrust-fault mechanism are possible solutions. In both cases, the P-axis is oriented in a NW-SE direction.

Täsch

This event occurred on February 4th in the southern Valais between Randa and Täsch and had a magnitude M_L 3.3 and M_w 3.2. Although it was also recorded by temporary instruments deployed above the landslide of Randa at an epicentral distance of about 6 km, and arrival times were modelled by 2D ray-tracing, the focal depth cannot be constrained to better than 6 ± 3 km. Nevertheless, the focal mechanism is well constrained by both first-motion polarities and a full-waveform moment tensor inversion: both solutions correspond to normal fault mechanisms whose T-axes agree within $<10°$. Both the style of faulting and the NNE-SSW orientation of the T-axis is typical of events in the Penninic domain of the southern Valais (Eva et al. 1998, Maurer et. al. 1997, Kastrup et al. 2004).

Rambervillers – Saint Dié

The epicenter of this earthquake, which occurred on February 22nd at 20:41 UTC, was located between the towns of Rambervillers and Saint Dié, in the Vosges mountains of France. It is consequently outside the map in Figure 2 and is therefore not included in Table 2. Nevertheless, this earthquake caused shaking of intensity IV (EMS-98) across all of northwestern Switzerland (Fig. 4) and certainly was the seismic event in 2003, which the public was most aware of. In the area of Basel at an epicentral distance of about 140 km, a strong-motion instrument recorded a peak horizontal ground acceleration of 1% g (Wyss 2004).

The local magnitude M_L calculated from the Swiss broadband records with the hypocenter fixed at 48.37°N/6.64° and 10 km depth, the location calculated by RéNass in Strasbourg from the French and German networks, gives a value of 5.4 (http://eost.u-strasbg.fr/bcsf/). This is the same value as given by RéNass and matches the value of 5.9 given by LDG (http://eost.u-strasbg.fr/bcsf/), for which magnitudes are on average 0.5 units higher than those calculated by the Swiss network (Braunmiller et al. 2005). On the other hand, the moment magnitude M_w from moment tensor inversion of waveforms recorded by Swiss, German and French broad-band stations is only 4.8. The moment tensor itself corresponds to a normal faulting mechanism with a small strike-slip component and a NE-SW oriented T-axis (Fig. 5). The relatively large discrepancy of 0.6 magnitude units between M_L and M_w, compared to the average difference of 0.2, suggests that the source of this event radiated more high-frequency energy than usual.

Salgesch

The M_L 3.9 event that occurred shortly before 7 in the morning on April 29th (local time) caused shaking of intensity IV and V

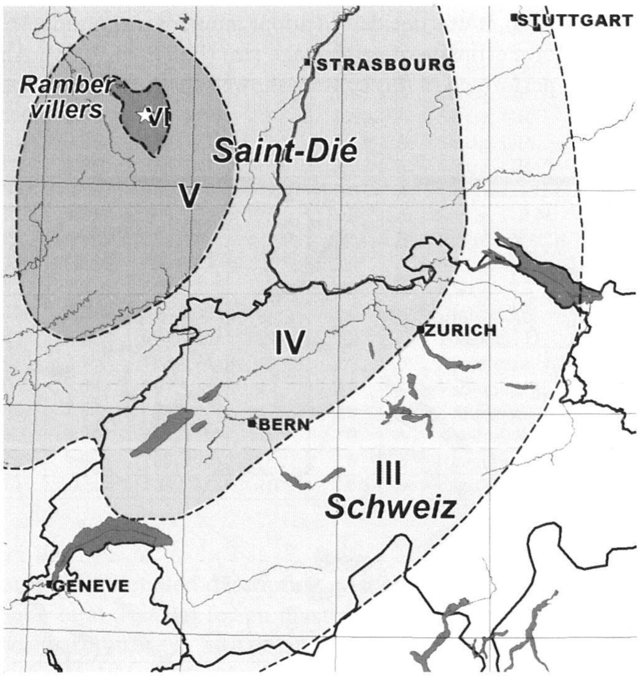

Figure 4. Isoseismal map of the M_L 5.4 Rambervillers event of 2003/02/22 (after Cara et al. 2005).

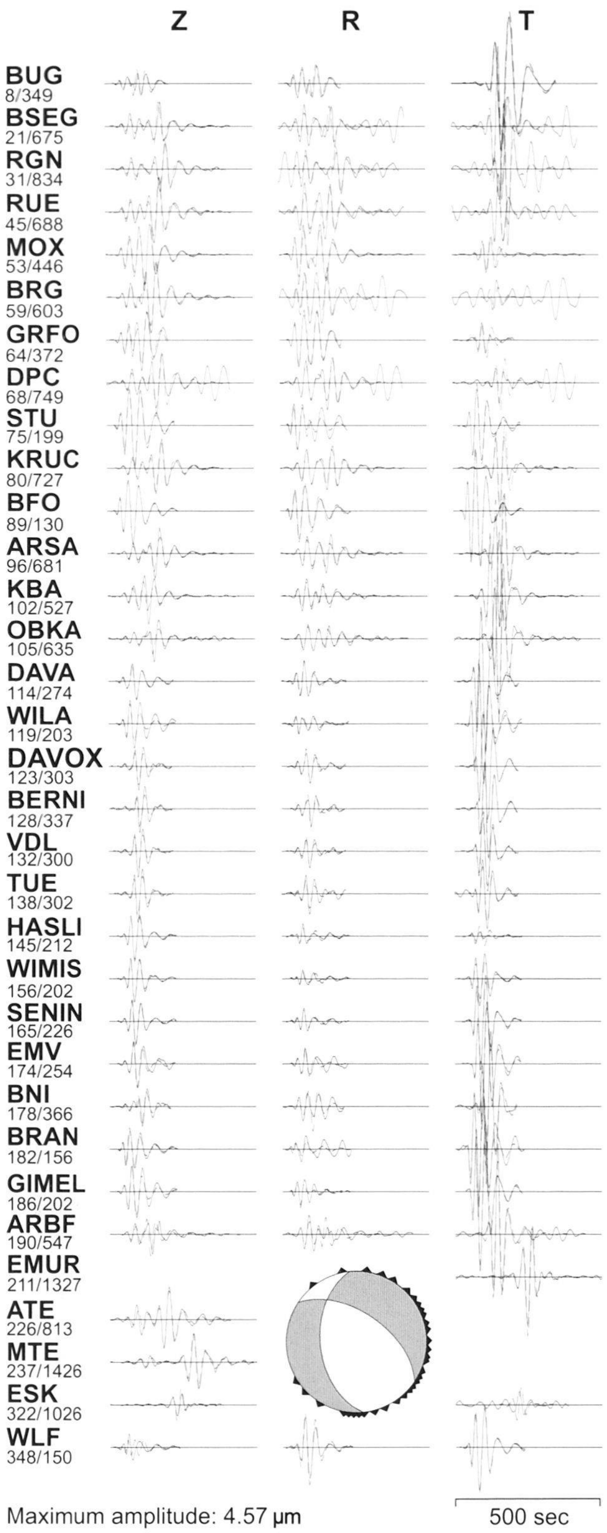

Figure 5. Moment tensor and waveform fit of the Rambervillers event of 2003/02/22. The best fit is obtained for $M_w = 4.8$ and for a focal depth of 12 km. Shown are the vertical (Z), radial (R) and transverse (T) components of the observed (continuous line) and computed (dashed line) seismograms. Uncertainties estimated from the misfit function are ± 5° for strike, dip and rake and +1/–3 km for depth.

(EMS98) throughout the central Valais (Fig. 6). It was followed 43 minutes later by an aftershock of $M_L = 1.2$. It is also possible that some of the other events detected during the following months in the vicinity of this earthquake constitute additional aftershocks, but this could not be determined with certainty.

The source was located at a depth of 10 km below the town of Salgesch. With four stations (including two strong-motion instruments) within an epicentral distance of only 10 km, the routinely calculated focal depth is reliable. The value of 10 km is confirmed, moreover, by 2D ray-tracing and by the full-waveform inversion, which gives a best fit at 12 km (Table 4).

The focal mechanism, which is well-constrained by numerous first-motion polarities, corresponds to a thrust fault with a strike-slip component and NW-SE oriented P-axis. The moment tensor derived from the full-waveform inversion corresponds to a thrust fault as well, but with a somewhat stronger strike-slip component (Fig. 7). However, strike and dip of the ENE-WSW striking nodal plane violate the first-motion data. In the Valais, where normal faulting mechanisms predominate in the Penninic domain south of the Rhone valley and strike-slip mechanisms are the rule in the Helvetic domain to the north, (Maurer et al. 1997; Eva at al. 1998; Kastrup et al. 2004), such thrust fault mechanisms are rare. Nevertheless, the NW-SE orientation of the P-axis matches the direction of maximum horizontal compression derived previously for the northern Valais (Kastrup et al. 2004).

Urnerboden

Shortly before midnight (local time) on May 6th, the population in the region between the cantons Glarus and Uri experienced a moderate earthquake with intensities up to V. The strong-motion station in Linthal, 8 km from the epicenter located in the area of Urnerboden, recorded a peak horizontal acceleration of 7% g (Wyss 2004). The magnitudes calculated for this event are M_L 4.0 and M_w 3.7.

With a minimum epicentral distance of 8 km, the focal depth obtained from routine location procedures is not well constrained. However, the epicenter of this earthquake is located only 7–8 km west of the epicenter of an earthquake that occurred on March 17th 2001 near the town of Linthal. The focal depth of the latter was determined to be 3 km, based on the S-P arrival-time difference observed at the strong-motion station in the immediate vicinity of the epicenter (Deichmann et al. 2002). A comparison of selected seismograms of these two earthquakes shows that focal depths must be practically identical. As shown in Figure 8, travel-time differences between the wave reflected at the Moho (PmP) and the direct wave through the upper crust (Pg) at stations SULZ and BALST, situated at comparable distance and azimuths from the two epicenters, differ by less than 0.1 seconds for the two events. A similar agreement is observed for the travel-time differences between the Pg at SLE and the wave refracted at the Moho (Pn) at station LANF situated on the western border of

Table 4. Focal mechanism parameters based on first-motion polarities (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
Täsch	2003/02/04 20:50	6	M_L 3.3	091/40/-106	292/52/-077	252/78	013/06
		9	M_w 3.2	105/47/-102	303/44/-077	303/81	204/01
Salgesch	2003/04/29 04:55	10	M_L 3.9	067/48/ 138	188/60/ 050	305/07	045/55
		12	M_w 3.5	080/68/ 139	188/53/ 028	137/09	038/44
Urnerboden	2003/05/06 22:00	3	M_L 4.0	264/74/-169	171/79/-016	127/19	218/03
		4	M_w 3.7	256/81/-170	164/80/-009	120/13	030/00
Sertig	2003/07/18 11:02	7	M_L 3.9	105/44/-127	331/56/-060	296/64	040/07
		6	M_w 3.6	109/43/-133	341/60/-057	301/60	048/09
Glarey	2003/08/22 09:22	6	M_L 3.9	151/54/-027	258/68/-141	120/43	022/08
		6	M_w 3.7	153/55/-016	252/77/-144	119/34	018/15
Zeiningen	2003/08/31 05:39	17	M_L 2.9	292/82/-172	201/82/-008	156/11	246/00
Nesslau	2003/10/01 07:31	8	M_L 3.0	102/78/-172	010/82/-012	326/14	057/03

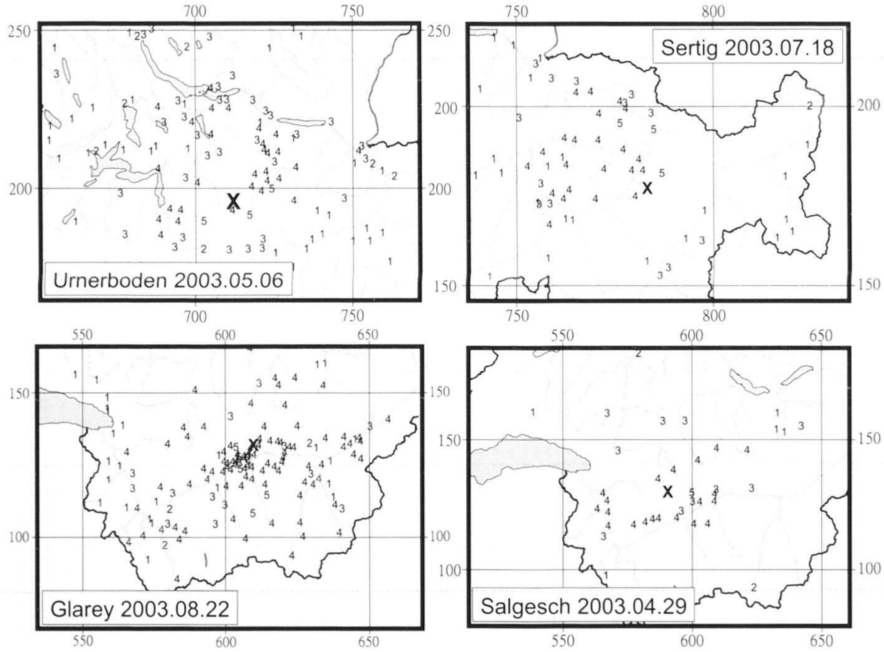

Figure 6. Macroseismic observations for the events of Urnerboden (2003/05/06, 21:59), Sertig (2003/07/18, 11:01)), Salgesch (2003/04/29, 04:55) and Glarey (2003/08/22, 09:21). Each value represents the macroseismic intensity (EMS-98) assigned to a single postal code zone.The X corresponds to the instrumental epicenter. The Swiss cartesian coordinate grid is labeled in km.

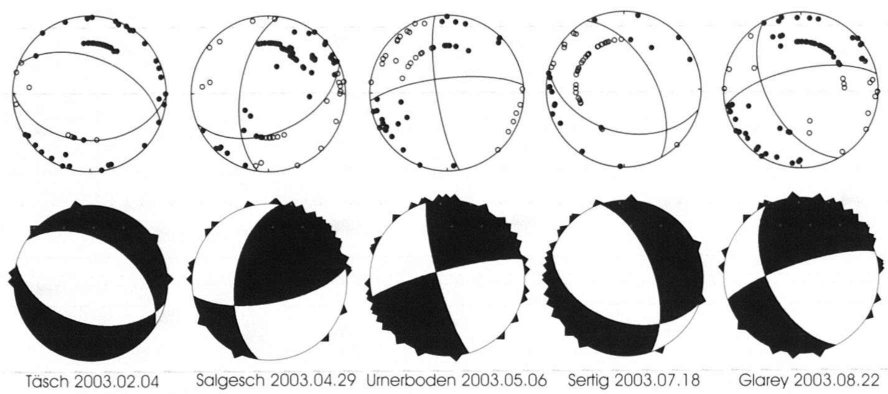

Figure 7. Faultplane solutions (above) based on first-motion polarities and moment tensors (below) based on full-waveform inversion (lower hemisphere, equal area projection). In the faultplane solutions, solid circles correspond to compressive first motion (up) and empty circles to dilatational first motion (down); on the moment tensors, triangles show the station locations.

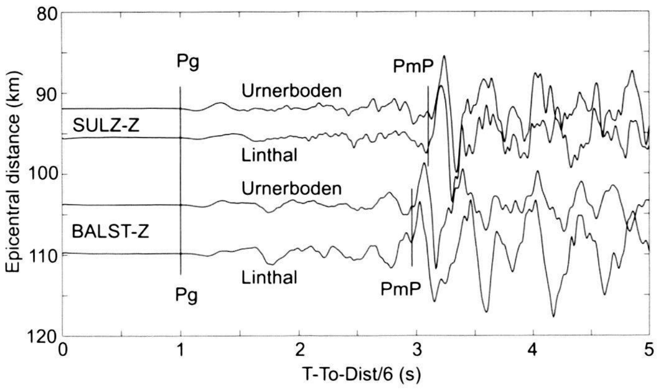

Figure 8. Pairs of signals of the 2003 Urnerboden and the 2001 Linthal events recorded at stations SULZ and BALST. Note the almost identical travel-time differences between PmP and Pg for the two events, which implies that focal depths must be practically the same.

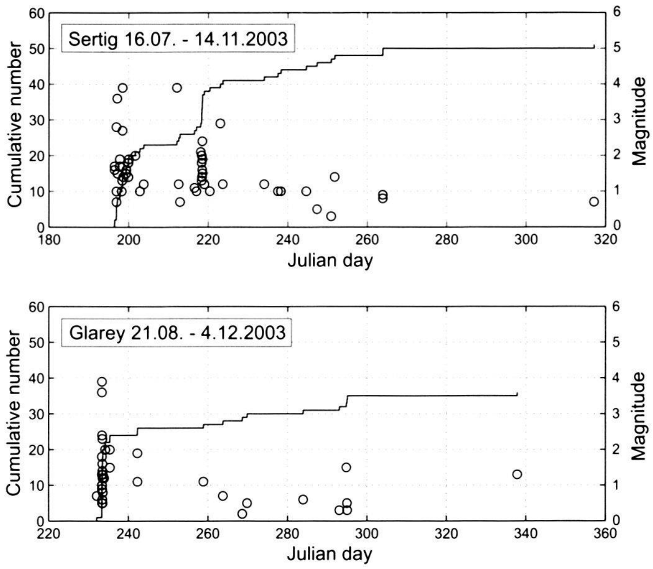

Figure 9. Magnitudes and cumulative number of events for the Sertig and the Glarey earthquake sequences. The concentration of the largest magnitudes and the peak activity at the beginning of the Glarey sequence is typical for a classical mainshock-aftershock pattern; the Sertig sequence, on the other hand, exhibits a more swarm-like behaviour: there are several stronger events and their occurrence does not necessarily coincide with the periods of peak activity.

the Rhinegraben. Thus we fix the focal depth at 3 km for the Urnerboden event as well. This relatively shallow focal depth agrees also with the value of 4 km obtained from the moment tensor inversion.

The strike-slip focal mechanism ist well-constrained by both the first-motion polarities and the full-waveform inversion (Fig. 7). The NW-SE orientation of the P-axis is similar to that observed for the two Linthal events of 1990 and 2001 (Deichmann et al. 2002; Kastrup et al. 2004).

Sertig

July 16th marked the beginning of a swarm-like earthquake sequence of 51 events located about 10 km south of Davos near the village of Sertig Dörfli. As illustrated in Figure 9, the sequence occurred over two distinct time intervals: the first, consisting of 23 events, lasted for one week and included an M_L 3.6 and an M_L 3.9 event (Table 2); after a pause of one week, activity resumed with another M_L 3.9 event on August 1st, and a peak rate of 9 events in less than 12 hours on August 7th. The last event in the sequence was recorded on Nov. 14th.

After the second stronger event on July 18th, a temporary seismograph was deployed 2 km from the epicenter. This instrument recorded 7 events with magnitudes M_L between 1.0 and 2.0. Based on the P- and S-onsets observed at this site, the source of these events must be at a depth of 6–8 km. From a comparison of the arrival times of the reflection from the Moho observed at station MUO, it is evident that the focal depth of all 51 events in the sequence does not vary significantly. We have therefore fixed the focal depth of the $M_L \geq 2.5$ events in Table 2 at 7 km.

Faultplane solutions of the three strongest events are exceptionally well constrained by numerous first-motion polarities. Since all three mechanisms are identical, we include only the focal mechanism of the July 18th event in Table 4 and in Figures 2 and 7. The parameters of the focal mechanisms derived from the full-waveform inversion agree with the faultplane solutions to within less than 10° for the first two events, and the corresponding focal depth is 6 km in both cases. For the third event, the full-waveform inversion gives a best fit for a focal depth of 9 km and some of the focal mechanism parameters deviate by more than 20° from the other two events. However, a 6 km deep source does not give a significantly larger misfit than the one at 9 km, and in that case the focal mechanism is again within about 10° of the first-motion solution. All solutions correspond to a normal faulting mechanism and the orientations of the T-axis differ by less than 10°. Extensional mechanisms with NE-SW orientation of the T-axis are typical for earthquakes in the eastern Swiss Alps (Kastrup et al. 2004).

Attempts to identify the active faultplane from high-precision relative relocations of the individual hypocenters in this earthquake swarm failed. Most of the rays to the stations at short epicentral distances have take-off angles that are close to one of the nodal planes. As a consequence, the P-waves are weak, and even small focal mechanism variations degrade the signal similarity to the extent that accurate arrival-time determinations based on signal correlations are not possible.

Glarey

In contrast to the swarm-like behaviour of the Sertig sequence, the earthquake sequence of Glarey, Valais, followed a classical foreshock-mainshock-aftershock pattern (Fig. 9). After a single small foreshock the day before (M_L 0.7), the sequence started August 22nd at 11:21 (local time) with the M_L 3.9

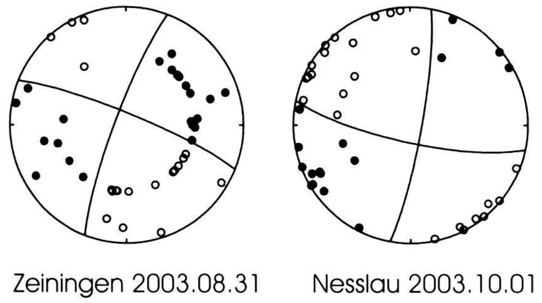

Figure 10. Faultplane solutions based on first-motion polarities for the Zeiningen and Nesslau events.

(M_w 3.7) mainshock. Over the following 4 months an additional 34 events were detected within a 2 by 2 km large epicentral area that includes the mainshock. The peak activity, however, was concentrated at the beginning of the sequence, with the occurrence of 18 events in the first 5 hours, including an M_L 3.6 (M_w 3.5) event less than 8 minutes after the mainshock. In addition to station SENIN at an epicentral distance of 5 km, six strong-motion stations recorded the mainshock within a radius of 8–12 km. Thus both the epicenter and the focal depth are well constrained. The epicenter is located 3–4 km SE of the Sanetsch Pass. Shaking intensities as high as V (EMS-98) were reported in the area of Ayent, which coincides with a peak horizontal acceleration of close to 6% g recorded by an accelerograph in Ayent-Fortunoz, about 7 km from the epicenter (Wyss 2004). Intensities of IV were observed out to epicentral distances of about 30 km.

The focal depth of 6 km determined routinely matches the value obtained from the full-waveform inversion. The focal mechanism of the mainshock from both the first-motion analysis and the moment tensor inversion corresponds to a normal fault with a strong strike-slip component (Table 4 and Fig. 7). The moment tensor solution for the strongest aftershock does not differ significantly from that of the mainshock and is thus not included separately. The resulting NNE-SSW orientation of the T-axis lies within the range of T-axis orientations observed previously in the northern Valais (Kastrup et al. 2004).

Zeiningen

Both the focal depth and the faultplane solution (Fig. 10) of this M_L 2.9 event, which occurred August 31st near the town of Zeiningen, Aargau, are well-constrained by numerous observations and by 2D ray-tracing. This event is typical for the lower-crustal earthquakes below the Tabular Jura mountains of northern Switzerland (Deichmann et al. 2000b; Kastrup et al. 2004). In fact, the focal depth of 17 km as well as the strike-slip mechanism with NNW-SSE oriented P-axis are almost identical to those of the event that occurred in 1999 about 15 km further west near the town of Pratteln (Deichmann et al. 2000a).

Nesslau

The M_L 3.0 earthquake that occurred on October 1st north of the Walensee near Nesslau was the second and strongest event of a sequence of 8 events: the first 4 occurred between October 1st and 2nd, while the second four occurred between November 10th and 12th. Magnitudes of the other events are between M_L 0.7 and 2.1.

Routine location procedures give a focal depth of 12 km. However, with a minimum epicentral distance of 21 km, this value is unreliable. The focal depth of 8 km, which results from a non-linear location procedure based on a 3-D velocity model (Husen at al. 2003) and which is supported by 2-D ray tracing, is the more likely value. Given the thickness of the sedimentary cover in this region (Stäuble & Pfiffner 1991) and the remaining focal depth uncertainty, it is not possible to decide whether the source is located in the crystalline basement or above.

The strike-slip focal mechanism (Fig. 10) is well constrained and is very similar to that of the M_L 3.6 Walenstadt event of April 21st, 1998 (Baer et al. 1999). The latter was located 11 km east of the Nesslau event at a depth of about 10 km and its P- and T-axes are rotated 20° clockwise with respect to the Nesslau event. The mechanisms of both events agree with the predominant NW-SE oriented compression in this region (Roth et al. 1992; Kastrup et al. 2004).

Discussion

Figure 3 shows the epicenters of the 731 earthquakes with $M_L \geq 2.5$, which have been recorded in Switzerland and surrounding regions over the period of 1975 – 2003. 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.

Averaged over the last 29 years, we observe about 25 events with $M_L \geq 2.5$ and 8 events with $M_L \geq 3$ per year. With 30 $M_L \geq 2.5$ events and 11 events reaching $M_L \geq 3$ in 2003 (Table 2 and Fig. 11), the seismic activity in these magnitude ranges was thus slightly higher than the 29 year average.

The enhanced activity between mid July and end of August, visible in the plot of the temporal evolution of seismicity (Julian days 185–240 in Fig. 11), corresponds to the earthquake sequences of Sertig and Glarey, which together contribute 16% to the total number of recorded earthquakes in 2003. Two additional small earthquake sequences with about a dozen events each occurred near Grosio, south of Graubünden in Valtellina, and near Cheyres, at the southern end of Lake Neuchâtel (Fig. 2). The seismic activity below Cima di Jazzi, between Zermatt and Macugnaga, which started in 2002 (Baer et al. 2003), continued with an additional 24 events over the first half of 2003 and with 4 more between September and December.

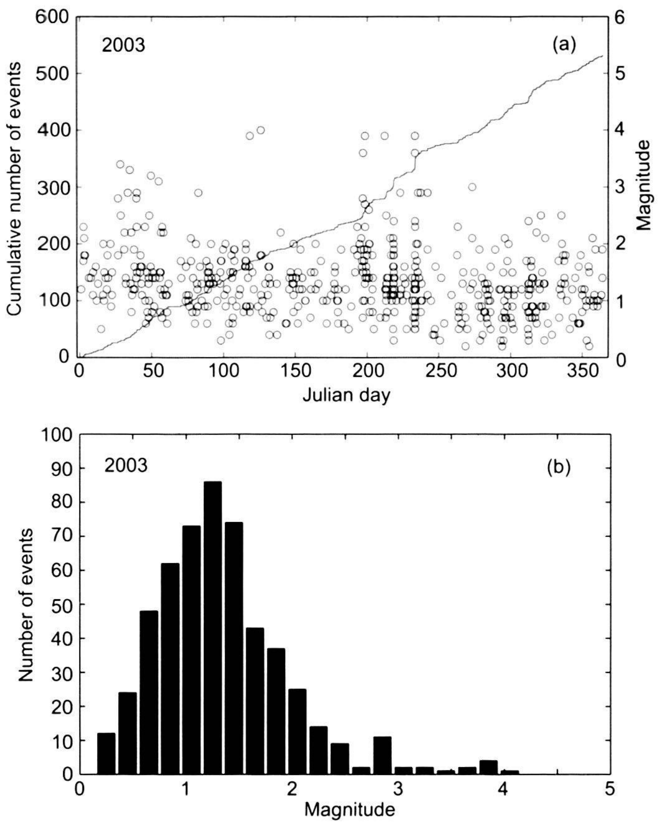

Figure 11. Earthquake activity during 2003: magnitude of each event and cumulative number of events (a); histogram of magnitudes (b).

As in previous years, most of the earthquakes occurred in the Valais and in Graubünden. However, the events of Urnerboden, Nesslau and Lech are evidence for continuing seismic activity also along the northern Alpine front (Fig. 2).

Routinely calculated focal depths for the 532 earthquakes recorded in 2003 range between 1 and 32 km, but only 23 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 the Molasse Basin of northern Switzerland.

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