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Earthquakes in Switzerland and surrounding regions during 2004

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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 2004. During this period, 677 earthquakes and 96 quarry blasts were detected and located in the region under consideration. With 22 events with $M_L \geq 2.5$, the seismic activity in the year 2004 was close to the average over the last 30 years. As in previous years, most of the activity was concentrated in the Valais and in Graubünden. In addition, several moderate earthquakes occurred in the lower crust below the northern Alpine foreland. Unusual was that five earthquakes were sufficiently strong to cause ground shaking of intensity IV over large portions of the territory. Two were located in Switzerland (Liestal, M_L 3.8, and Brugg, M_L 4.0). The epicenters of the other three strong events were located outside Switzerland (Besançon in the French Jura, M_L 4.8, Waldkirch in southern Germany, M_L 5.1, and Lago di Garda in northern Italy, M_L 5.3).

ZUSAMMENFASSUNG

Dieser Bericht des Schweizerischen Erdbebendienstes stellt eine Zusammenfassung der im Vorjahr in der Schweiz und Umgebung aufgetretenen Erdbeben dar. Im Jahr 2004 wurden im erwähnten Gebiet 677 Erdbeben sowie 96 Sprengungen erfasst und lokalisiert. Mit 22 Beben der Magnitude $M_L \geq 2.5$ war die seismische Aktivität im Jahr 2004 nahe dem Durchschnitt. Wie schon in früheren Jahren ereigneten sich die meisten Beben vor allem im Wallis und in Graubünden. Ausserdem gab es wieder einige Beben in der unteren Kruste des nördlichen Alpenvorlandes. Ungewöhnlich war, dass fünf Erdbeben stark genug waren, um Erschütterungen der Intensität IV über grössere Gebiete des Landes zu verursachen. Zwei davon haben sich in der Schweiz ereignet (Liestal, M_L 3.8, und Brugg, M_L 4.0). Die Epizentren der anderen drei befanden sich hingegen ausserhalb der Schweiz (Besançon im französischen Jura, M_L 4.8, Waldkirch in Süddeutschland, M_L 5.1, und Gardasee in Norditalien, M_L 5.3).

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 2004, 677 tremblements de terre et 96 tirs de carrière furent détectés et localisés. Vingt-deux événements de magnitude $M_L \geq 2.5$ ont été enregistrés; ainsi, l'activité sismique de l'année 2004 suivait plus ou moins la moyenne. Comme les années précédentes, l'activité sismique s'est principalement concentrée dans le Valais et les Grisons, mais il y a aussi eu plusiers tremblements de terre dans la croûte inferieure sous l'avantpays nord des Alpes. Cinque tremblements de terre étaient assez inhabituels parce qu'ils ont causé des secousses d'intensité IV dans plusieurs régions du pays. Deux de ces événements ont eu lieu en Suisse (Liestal, M_L 3.8, et Brugg, M_L 4.0). Les épicentres des autres trois événements étaient par contre situés en dehors du pays (Besançon, dans le Jura Français, M_L 4.8, Waldkirch dans le sud de l'Allemagne, M_L 5.1, et Lac de Garde dans le nord de l'Italie, M_L 5.3).

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 the seismic activity in Switzerland and surrounding regions have been published in the present form

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Tab. 1. Seismograph stations operational at the end of 2004. Instrument types: SP = 1 second, EB = 5 seconds, BB = broad band, SM = accelerometer, 1 = vertical component only, 3 = vertical and horizontal components. Signals of LKBD2 and BBS are transmitted via analog telemetry; data of BBS are recorded by the Landeserdbebendienst Baden-Würtemberg 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
BALST	Balsthal, SO	BB-3
BERNI	Bernina, GR	BB-3
BNALP	Bannalpsee, NW	BB-3, SM-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, SM-3
EMV	Vieux Emosson, VS	BB-3, SM-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
LIENZ	Kamor, SG	BB-3, SM-3
LKBD	Leukerbad, VS	EB-3
LKBD2	Leukerbad, VS	SP-3
LLS	Linth-Limmern, GL	BB-3, SM-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, SM-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, SM-3
Single stations		
Code	Station name	Type
BBS	Basel-Blauen, BL	SP-1
BERT	Bern, BE	SP-3
GNV	Geneva, GE	SP-1

(Baer et al. 1997, 1999, 2001, 2003; Deichmann et al. 1998, 2000a, 2002, 2004). In the course 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://www.seismo.ethz.ch, Swiss Earthquake Catalogs). The new seismic hazard map of Switzerland based on this catalog was officially released in 2004 (Giardini et al. 2004). 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. Deichmann 1990; Pavoni & Roth 1990; Rüttener 1995; Rüttener at al. 1996; Pavoni et al. 1997; Deichmann et al. 2000b; Kastrup et al. 2004).

Seismic stations in operation during 2004

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, 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 2004 is documented separately (Wyss 2005).

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 broadband STS-2 seismometers or Lennartz 5-second sensors (BB and EB in Table 1). For a detailed description of this new data acquisition system, see Baer et al. (2001).

In August 2004, station APL located near Alpnach, OW, which was one of the last two short-period instruments with analog data transmission, ceased functioning and was decommissioned. The only other significant change with respect to the previous year consisted in the replacement of the excessively noisy station KAMOR by a new station (LIENZ), located close to the site (CHKAM) that had been instrumented temporarily in 2003 (Deichmann et al. 2004). Thus the total number of digital stations in operation in Switzerland remained at 36 during 2004 and the only short-period analog telemetry station left is LKBD2 near Leukerbad (Table 1 and Figure 1).

The data of the national strong-motion network is recorded on site and can be downloaded interactively by telephone (Wyss 2005). To complement this acceleration data with signals that are available in real-time, seven more stations of the broad-band network (BNALP, DIX, EMV, LIENZ, LLS, SULZ and ZUR) have been equipped in 2004 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 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

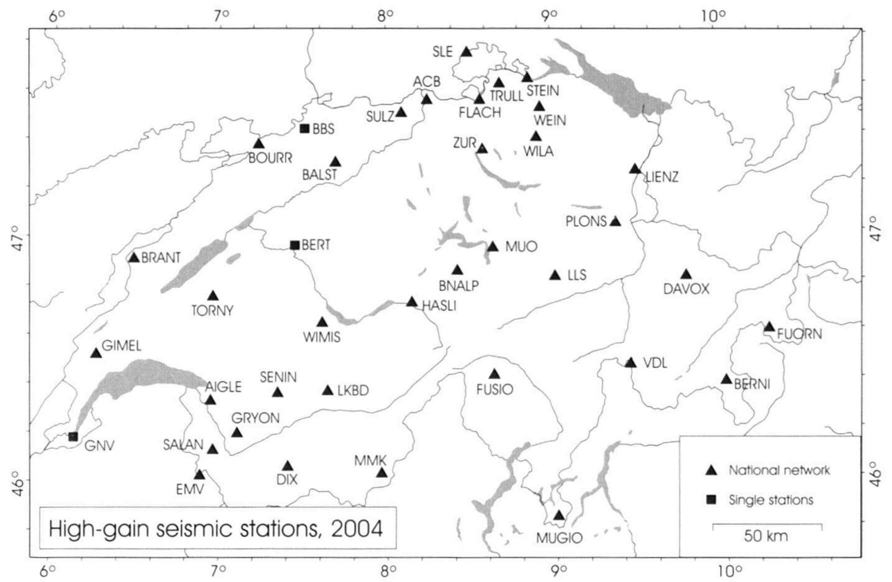

Fig. 1. Seismograph stations in Switzerland operational at the end of 2004.

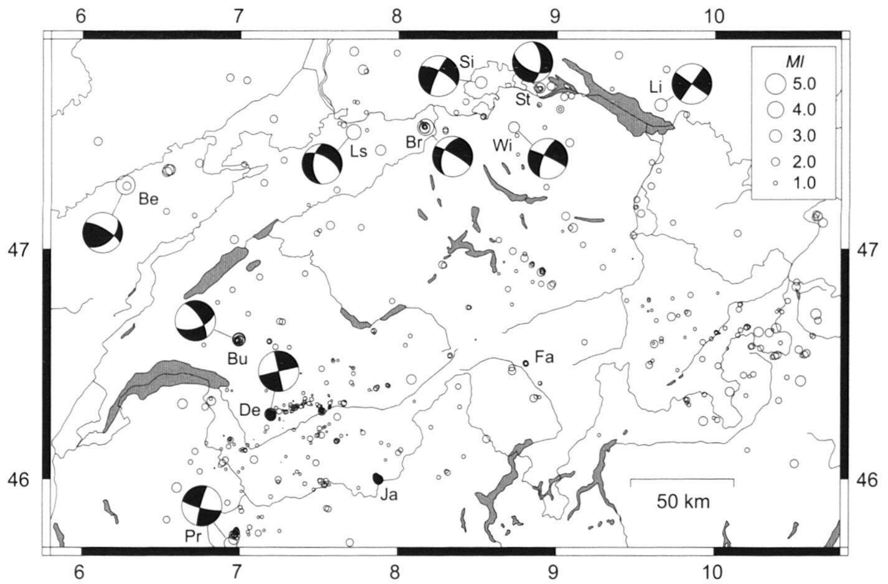

Fig. 2. Epicenters and focal mechanisms of earthquakes recorded by the Swiss Seismological Service during 2004. Epicenters of earthquakes mentioned in the text are Besançon (Be), Brugg (Br), Bulle (Bu), Derborance (De), Faido (Fa), Cima di Jazzi (Ja), Liestal (Ls), Lindau (Ld), Pré St.-Didier, Siblingen (Si), Stein am Rhein (St), Winterthur (Wi).

Württemberg in Freiburg (LED), from the Zentralanstalt für Meteorologie und Geodynamik in Vienna (ZAMG), from the SISMALP array operated by the Laboratoire de Géophysique Interne et Tectonophysique, Observatoire de Grenoble (LGIT), from the Laboratoire de Détection et Géophysique in Bruyères-le-Châtel (LDG), from the RéNaSS array operated by the Ecole et Observatoire des Sciences de la Terre in Strasbourg, from the Istituto Nazionale di Geofisica e Vulcanologìa in Rome (INGV), 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 near-realtime data from some of the institutions listed above (Baer et al. 2003).

Seismic activity during 2004

Overview

During 2004, the Swiss Seismological Service detected and located 677 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, 96 additional seismic events were identified as quarry blasts.

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
2004.02.17 03:53:44	46.721	10.642	845/179	21	2.5	B	Val Venosta, I
2004.02.18 14:26:01	46.607	6.995	566/162	9	3.1	A	Bulle, FR
2004.02.18 14:31:58	46.609	6.995	566/162	9	3.3	A	Bulle, FR
2004.02.18 15:29:36	46.604	6.999	566/161	9	2.6	A	Bulle, FR
2004.02.23 17:31:21	47.278	6.270	512/237	15	4.8	B	Besançon, F
2004.04.15 15:14:58	47.525	8.726	697/264	13	2.7	A	Winterthur, ZH
2004.04.18 03:21:05	47.621	9.655	767/277	31	3.0	A	Lindau, D
2004.04.18 08:23:35	47.692	8.892	709/283	22	2.6	A	Stein am Rhein, SH
2004.05.17 08:35:06	45.735	6.966	563/ 65	12	2.6	B	Pré St.-Didier, I
2004.05.30 07:20:15	46.284	7.191	581/126	9	2.7	A	Derborence, VS
2004.05.30 09:46:17	46.284	7.193	581/126	9	2.9	A	Derborence, VS
2004.06.12 04:44:33	45.717	6.947	562/ 63	12	3.3	B	Pré St.-Didier, I
2004.06.12 16:47:24	46.276	7.197	581/125	8	2.6	A	Derborence, VS
2004.06.21 23:10:02	47.505	7.713	621/261	22	3.8	A	Liestal, BL
2004.06.28 23:42:30	47.525	8.169	655/264	20	4.0	A	Brugg, AG
2004.06.29 00:02:12	47.523	8.163	654/264	20	2.7	A	Brugg, AG
2004.06.29 22:43:04	47.520	8.165	655/263	20	2.6	A	Brugg, AG
2004.07.27 23:05:24	47.342	6.543	532/244	1	2.7	C	Col de Ferriere, F
2004.07.28 16:25:17	47.342	6.555	533/244	1	2.5	C	Col de Ferriere, F
2004.10.09 22:19:35	46.430	10.545	839/147	13	2.5	C	M. Cevedale, I
2004.11.08 11:52:40	47.715	8.519	681/285	23	2.8	A	Siblingen, SH
2004.12.06 01:52:17	47.426	7.885	634/253	11	2.5	B	Gelterkinden, BL

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

Magnitude values of the events recorded in 2004 range between $M_L = 0.1$ and 4.8. 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. For the stronger events, the traditional determination of focal mechanisms from the azimuthal distribution of first-motion polarities (faultplane solutions) has been complemented by a moment tensor based on full-waveform inversion. For these events we list the moment magnitude (M_w) in addition to the local magnitude (M_L). Moment magnitude is calculated from the seismic moment M_0 obtained from the moment tensor inversion using the relation $M_w = (2/3) \log M_0 - 6$, where M_0 is given in N-m (Hanks & Kanamori 1979). 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/). More comprehensive and detailed explanations of the data analysis procedures are given in previous annual reports (e.g Deichmann et al. 2004) and can be downloaded from our website (*Introduction.pdf* under *Reports* at http://www.seismo.ethz.ch).

Figure 3 shows the epicenters of the 753 earthquakes with $M_L \geq 2.5$, which have been recorded in Switzerland and surrounding regions over the period of 1975 – 2004. 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 less than 10 % of the total number of events detected during that time period in the same area. In what follows, we present the highlights of the seismic activity observed during 2004.

Significant earthquakes of 2004

The sequence of Bulle

On February 18th at 15:26 local time, the region between Lausanne and Fribourg was jolted by a first earthquake of magni-

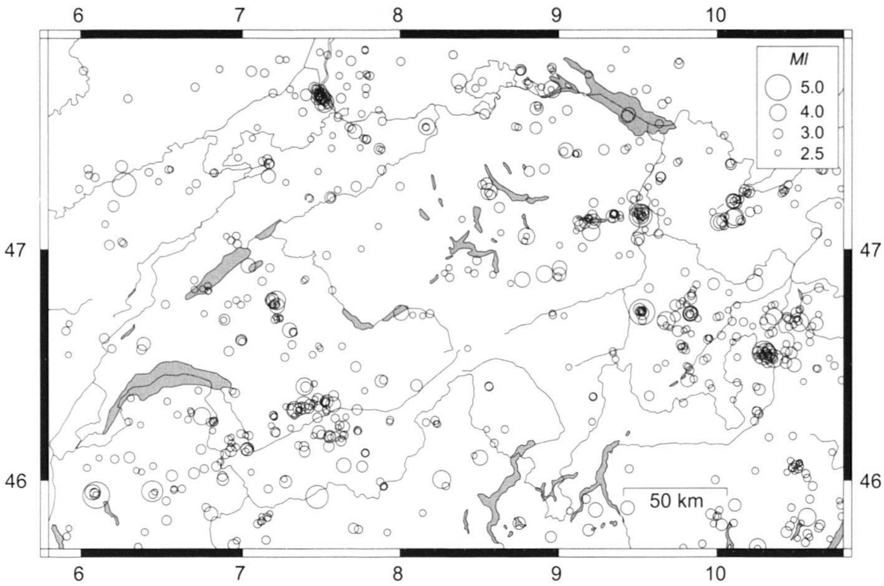

Fig. 3. Epicenters of earthquakes with Magnitudes $M_L \geq 2.5$, during the period 1975 – 2004.

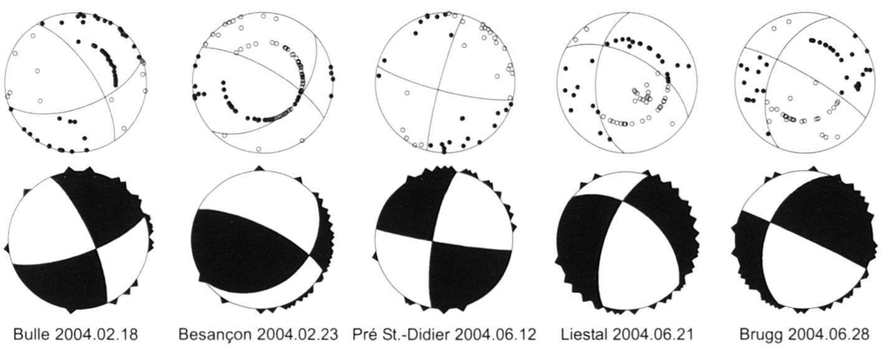

Fig. 4. Faultplane solutions (above) based on first-motion polarities and moment tensors (below) based on full-waveform inversion (lower hemisphere, equal area projection). In the faultplane solutions, solid circles correspond to compressive first motion (up) and empty circles to dilatational first motion (down); on the moment tensors, triangles show the station locations.

tude M_L 3.0. It was followed six minutes later by a second slightly stronger event (M_L 3.3) and an hour later by a third one with M_L 2.6. All three were felt by the public. These three stronger events were part of a small sequence of 12 recorded events during the time between January 2nd and October 9th. The epicenters were located about 5 km west of the town of Bulle. Routine hypocenter location gives a focal depth of around 10 km for the strongest and best recorded event. However, with an epicentral distance to the closest station of 20 km, this value is poorly constrained. Using a 3D velocity model (Husen et al. 2003) and Pn arrivals out to distances of more than 200 km gives a focal depth of 9 km. This value is the most likely focal depth and is confirmed by 2D ray tracing along a profile trending NE from the epicenter and by the result of the full-waveform moment tensor inversion. For the strongest of theses events, both the moment tensor and the faultplane solution based on first motion polarities result in a strike-slip focal mechanism with a slight normal-faulting component (Figure 4 and Table 4). Based on the strong waveform similarity and the almost identical P to S amplitude ratios, it is evident that the three strongest events occurred almost at the same location and with the same focal mechanism. The moment magnitude, M_w, is 3.0 for the first and 3.2 for the second of the two strongest events. The WNW-ESE orientation of the P-axis and the corresponding NNE-SSW orientation of the T-axis are what one would expect from the stress field deduced from previous earthquakes in the Alpine foreland of western Switzerland (Kastrup et al. 2004).

Besançon – Roulans

The strongest event of 2004 in the region covered by the map in Figure 2 occurred on February 23rd at 18:31 local time. Its epicenter was located in the French Jura, near the town of Roulans, approximately 20 km NE of Besançon. According to a compilation of the Bureau Central Sismologique Français, this earthquake caused some light damage in the epicentral area, so that the epicentral intensity I_0 was estimated to be V-VI on the European Macroseismic Scale (BCSF 2004). As shown in Figure 5, it was clearly felt (intensity IV) across most

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
Bulle	2004/02/18 14:32	9	M_L 3.3	327/69/-032	070/60/-155	286/38	020/05
		9	M_w 3.2	336/80/-019	070/71/-020	292/20	024/06
Besançon	2004/02/23 17:31	15	M_L 4.8	300/73/ 134	047/47/ 024	359/16	253/44
		12	M_w 4.5	296/74/ 119	053/32/ 031	004/24	240/53
Winterthur	2004/04/15 15:15	13	M_L 2.7	203/70/-007	295/83/-160	161/19	068/09
Lindau	2004/04/18 03:21	31	M_L 3.0	215/90/ 000	125/90/ 180	170/00	080/00
Stein am Rhein	2004/04/18 08:23	22	M_L 2.6	116/56/-139	360/57/-042	327/51	058/01
Derborence	2004/05/30 09:46	9	M_L 2.9	347/90/ 000	077/90/-180	302/00	212/00
Pré St.-Didier	2004/06/12 04:44	12	M_L 3.3	104/80/-006	195/84/-170	060/11	329/03
		12	M_w 3.3	099/86/-013	190/77/-176	054/12	145/06
Liestal	2004/06/21 23:10	22	M_L 3.8	182/53/-041	300/58/-135	154/53	060/03
		21	M_w 3.4	199/66/-043	309/51/-149	158/47	257/09
Brugg	2004/06/28 23:42	20	M_L 4.0	202/48/-012	300/81/-137	170/36	064/21
		21	M_w 3.5	202/44/-004	295/88/-134	169/33	059/28
Siblingen	2004/11/08 11:53	23	M_L 2.8	298/70/-170	205/81/-020	160/21	253/07
Lago di Garda	2004/11/24 22:59	9	M_w 5.0	068/60/ 103	223/32/ 069	148/14	008/72
Waldkirch	2004/12/05 01:52	12	M_w 4.6	014/75/-016	109/74/-165	331/22	062/01

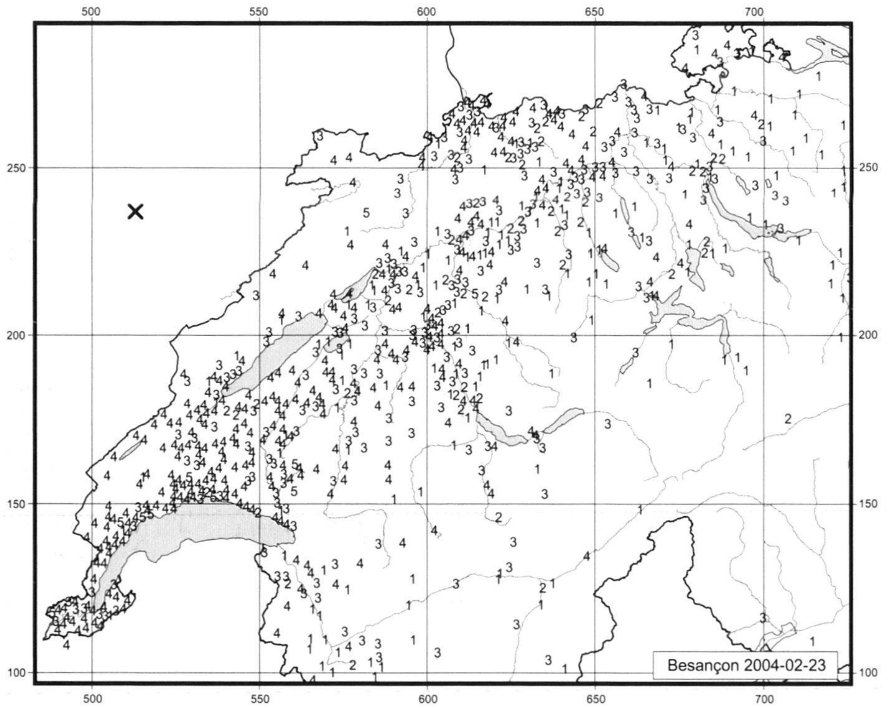

Fig. 5. Macroseismic observations for the event of Besançon (2004/02/23, 18:31 local time). Each value represents the macroseismic intensity (EMS-98) assigned to a single postal code zone. The X corresponds to the instrumental epicenter. The Swiss cartesian coordinate grid is labeled in km.

of western and northern Switzerland. Magnitudes calculated by the Swiss Seismological Service are M_L 4.8 and M_w 4.5. Local magnitudes reported by other institutions are in part significantly higher: 5.0 (LED *Jahresbulletin 2004*), 5.1 (RéNaSS) and 5.9 (LDG; BCSF, 2004). One aftershock, on Feb. 26th at 01:58 local time, was strong enough (M_L 2.1) to trigger the Swiss network. Locations based both on 1D and 3D crustal models give focal depths in the range between 11 and 17 km. Given that the closest epicentral distance is over 40 km, these depth values are unreliable. The best fit of the full-waveform inversion is obtained for 12 km and a good match between observed and calculated travel-time differences for 2D raytrace profiles trending SE and E is obtained for 15 and 16 km. In Table 2 and for calculating take-off angles for the faultplane solution, the focal depth was fixed at 15 km. Both the moment tensor and the faultplane solution correspond to an oblique

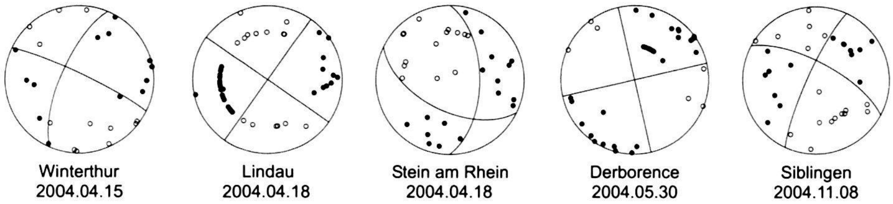

Fig. 6. Faultplane solutions based on first-motion polarities for four small earthquakes in northeastern Switzerland.

thrust (Table 4 and Figure 4). The strike and dip of the NW-SE trending nodal plane is very well constrained by the observed first motion polarities and differ by less than 5 degrees from the moment tensor solution. For some stations, later arrivals with impulsive onsets, which could be identified unequivocally as direct waves based on 2D ray tracing, were also used in the faultplane solution. The orientation of the other nodal plane and thus the degree of thrusting depend strongly on the take-off angles of the negative onsets observed in the SE quadrant of the faultplane solution. Whereas the strike of this nodal plane differs by only 5 degrees between faultplane solution and moment tensor, the dip differs by 14 degrees. Nevertheless, both the style of faulting and the orientation of the P-axis are well constrained and are rather unusual. Earthquakes with a strong thrust component are rare in the crystalline basement of the northern Alpine foreland, and from an extrapolation of regional stress inversions one would expect a NW-SE oriented P-axis rather than the observed N-S orientation (Müller et al. 1992; Delouis et al., 1993; Plenefisch & Bonjer 1997; Kastrup et al. 2004).

Seismic events and rockbursts in the new Gotthard tunnel

Between March 26th and April 16th, 2004, a small earthquake sequence of five events with magnitudes M_L between 0.9 and 1.4 occurred near Faido, TI. This sequence was not recognised as being anything unusual, until it became known that both the time of occurrence and the epicentral location of these events correlate with some rather violent rockbursts in a section of the new Gotthard railroad tunnel, that is still under construction. Given that the seismic activity has flared up again in 2005, the causal relation between the earthquakes, rockbursts and observed deformation of the tunnel cross-section is the object of further studies, that include the deployment of an additional temporary network of seismometers in the epicentral area.

Winterthur

Despite its small magnitude (M_L 2.7), this earthquake, that occurred on April 15th at 17:15 local time near Winterthur, was felt by a few people. With good azimuthal station coverage and with two stations at epicentral distances close to the focal depth, both the epicenter location and the focal depth of 13 km are well constrained. The strike-slip focal mechanism with NNE-SSW and ENE-WSW oriented P- and T-axes (Figure 6) is typical for midcrustal earthquakes in northeastern Switzerland (Deichmann et al. 2000b; Kastrup et al. 2004).

Lindau

The earthquake with M_L 3.0 that occurred at 05:21 local time on April 18th NE of Lake Constance near the town of Lindau was the deepest event recorded in 2004 in and around Switzerland. Focal depths for this event determined routinely with a 1D velocity model range between 29 and 33 km. The location based on the 3D model of Husen et al. (2003) also gives a focal depth of 33 km. Modelling of travel-time differences between the direct arrival (Pg) and the refracted at the Moho (Pn) shows that the source must be one or two km above the Moho, which according to Waldhauser et al. (1998) is at a depth of 32 km. In Table 2 and for calculating take-off angles for the faultplane solution, the focal depth was thus fixed at 31 km. Although the available first-motion data allow for some variability in strike and dip of the nodal planes, the style of faulting (strike-slip) is unambiguous (Figure 6). Both the orientation of the P- and T-axes and the focal depth are not unusual for northeastern Switzerland and the neighboring parts of southern Germany. In 2001 an earthquake with M_L 2.9, a focal depth of 30 km and a similar strike-slip mechanism occurred near Oberriet, SG, just 30 km to the south of the Lindau event (Deichmann et al. 2002).

Stein am Rhein

This small earthquake (M_L 2.6), which occurred only 5 hours after the Lindau event, was located at a depth of 22 km just north of Stein am Rhein. The high station density provided by the newly installed instruments in northeastern Switzerland in 2003 and by the stations in southern Germany provide an excellent azimuthal coverage and thus a reliable location and a well-determined faultplane solution (Figure 6). With four stations within an epicentral distance of less than 20 km, the focal depth is also well constrained. The oblique normal faulting mechanism with a ENE-WSW striking T-axis is similar to that of the M_L 4.2 event that occurred near Steckborn in 1986 (Deichmann et al. 2000b; Kastrup et al. 2004).

The sequence of Pré St.-Didier

Between April 15th and November 9th the Swiss seismograph network recorded a sequence of 17 events near Pré St.-Didier, east of Courmayeur, Italy. The magnitudes range between M_L 0.9 and 3.3. Five of these events, including one with M_L 2.6, occurred on May 17th and four, including the strongest event, on June 12th (Table 2). Because of their location outside of the Swiss network, the quality of the routine epicenter determina-

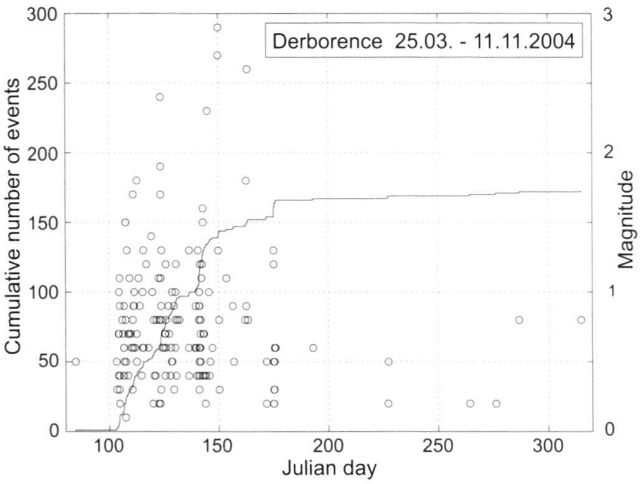

Fig. 7. Magnitudes and cumulative number of events for the Derborence earthquake sequence.

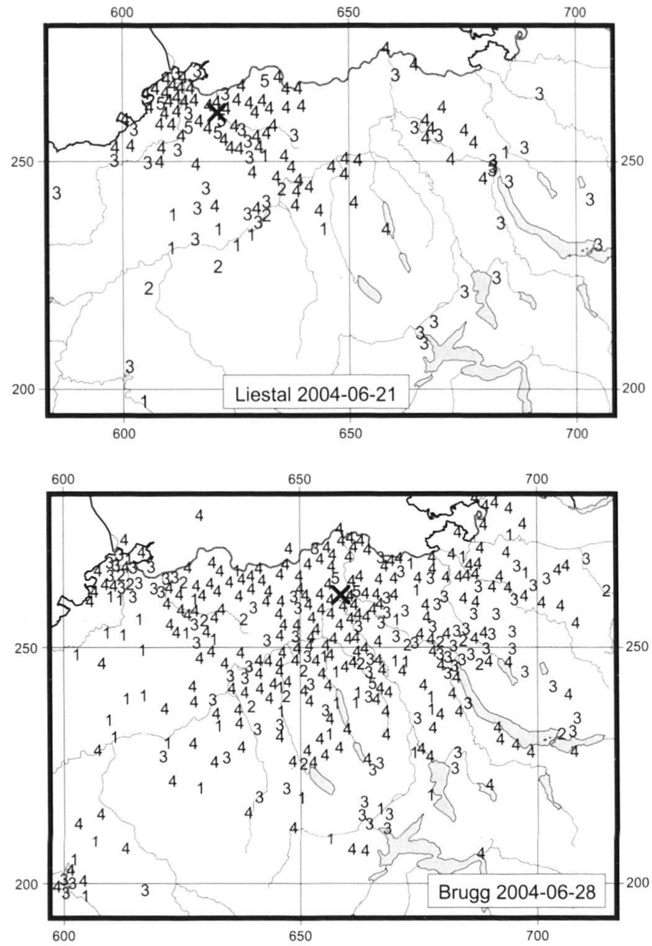

Fig. 8. Macroseismic observations for the events of Liestal (2004/06/22 01:10 local time) and Brugg (2004/06/29, 01:42 local time). Otherwise as in Figure 5.

tion is poor and the focal depth can not be determined. For the strongest event, we merged the Swiss data with the waveforms obtained from the universities of Genova and of Grenoble. To ensure a sufficiently good azimuthal coverage and to minimize the effects of crustal heterogeneity, for the final location we used 16 P and 5 S readings at stations out to 70 km. Despite this measure, some traveltime residuals, in particular for the S-readings, remain high, indicating that the crustal model used is probably unsuitable for this region. Thus, given also that the epicentral distance to the closest station is 19 km, the resulting focal depth of 7 km is not reliable. The optimal depth obtained from matching the waveforms in the inversion for the moment tensor as well as the travel-time differences between the direct waves (Pg) and the waves refracted at the Moho (Pn) along a 2D ray-trace profile across the Alps and northern Alpine foreland is 12 km. This is the depth that was used to calculate the take-off angles of the rays at the source for the faultplane solution. However it was not possible to construct a completely self-consistent faultplane solution. The result shown in Figure 4 and listed in Table 4 is the one with a minimum number of inconsistent polarities (3) that most closely matches the moment tensor solution. While the exact orientation of the nodal planes, because of the remaining inconsistencies, is still slightly ambiguous, the style of faulting (strike-slip) is well constrained by both the faultplane solution and the moment tensor. The orientation of the T-axis at a high angle to the strike of the Alpine chain in this area is typical for the extensional regime observed in many zones of high elevations in the Alps (e.g. Maurer et al. 1997; Eva et al. 1998; Kastrup et al. 2004).

The sequence of Derborence

In Table 2, we list three events with magnitudes M_L 2.7, 2.9 and 2.6 at location Derborence. The two strongest ones occurred within a few hours of each other on May 30th. All three are part of an earthquake sequence comprising 173 detected events in the magnitude range between 0.2 and 2.9. As shown in Figure 7, the first event was recorded on March 25th and the last one on November 11th. However, the main activity (165 events) was concentrated between April 13th and June 25th, with the peaks, in terms of number of events per 24 hours, on May 21st-22nd (17 events) and on June 24th-25th (12 events). It is noteworthy that after this last activity spurt the event frequency dropped very abruptly and that the three strongest events occurred during a period of relative quiescence. Routine locations put the epicenter of this cluster near Pas de Cheville, located 2 km south of the summit of Les Diablerets, and epicenters of 90% of the events are scattered within a radius of 1 km about the mean location. Based on the high degree of signal similarity, these events are probably clustered even more tightly in reality, but this would need to be verified by signal correlation and relative location procedures. Routinely calculated focal depths range between 6 and 9 km. Modelling of travel-time differences between Pn and Pg at stations in northern Switzerland and southern Germany suggests a depth of 9 km. The faultplane solution for the strongest event based on the available first-motion data is compatible with a pure strike-slip focal mechanism (Table 4 and Figure 6), with one of the nodal planes striking in the same diretion as the general trend of the epicenter alignment in the northern Valais (Figure 2). Whereas this nodal plane is well contrained by the data, the orientation of the other nodal plane is poorly determined. It is thus possible that the actual direction of slip was more oblique than suggested by Figure 6, but this would not change the NW-SE and NE-SW orientation of the P- and T-axes significantly.

Liestal

The earthquake, which occurred during the night of June 21st to 22nd near Liestal, BL, woke up many people in northwestern Switzerland. The epicentral intensity reached IV and magnitudes are M_L 3.8 and M_w 3.4 (Figure 8). Given a large number of strong-motion stations in the Basel area, the focal depth of 22 km is well constrained by 14 records within an epicentral distance of less than 20 km. Thanks to the excellent azimuthal distribution of records from seismic stations in southern Germany as well as in Switzerland, the normal faulting focal mechanism with an ENE-WSW oriented T-axis obtained from the faultplane solution is also very well determined (Figure 4). The moment tensor has a slightly stronger strike-slip component and its T-axis is rotated clockwise by 17 degrees with respect to the faultplane solution (Table 4). No aftershocks were detected for this earthquake.

Brugg

Almost exactly one week after the Liestal event, during the night of June 28th to 29th, another moderate earthquake produced shaking of intensity IV over most of northern Switzerland (Figure 8). Magnitude values computed for this event are M_L 4.0 and M_w 3.5. The focal depth, constrained by clear P- and S-arrivals at stations SULZ and ACB, located at epicentral distances of 4 and 9 km, is 20 km. The faultplane solution and the moment tensor are well determined and almost identical (Figure 4 and Table 4). The resulting focal mechanism is rather unusual: it corresponds either to lateral motion on a flatly dipping NNE-SSW striking faultplane or to oblique normal faulting on an almost vertical NW-SE striking faultplane. However, the ENE-WSW orientation of the T-axis agrees with the regional deformation pattern and stress regime of the region (Deichmann et al. 2000b; Kastrup et al. 2004). This earthquake was followed by seven aftershocks with M_L between 0.7 and 2.7. The first four occurred within 24 hours of the mainshock, the next two followed on July 2nd and 10th, and the last one occurred almost six months later, on October 10th. The earthquake of Brugg and its aftershocks occurred in a previously aseismic area of northern Switzerland. Practically no other earthquake had been detected in this area since the beginning of modern instrumental monitoring in 1975, and at most one single comparable event is likely to have occurred here since the foundation of the Swiss Earthquake Commission in 1878 (Deichmann et al. 2000b). It is noteworthy that, judging from Figure 8, the event of Brugg seems to have been felt much more widely than the Liestal event, although their magnitudes M_L differ by only 0.2 units and they both occurred at the same time of day, at almost the same focal depth and in the same general region.

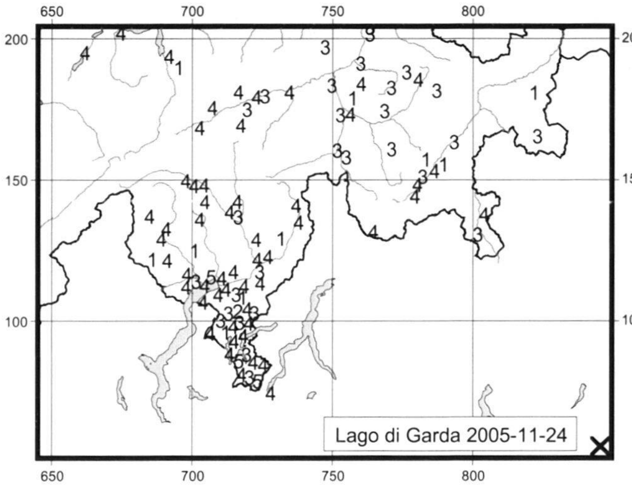

Fig. 9. Macroseismic observations for the event of Lago di Garda (2004/11/24, 23:59 local time). Otherwise as in Figure 5.

Siblingen

The small event (M_L 2.8) that occurred on November 8th near Siblingen, NW of Schaffhausen, is another one of those lower-crustal earthquakes commonly observed below the northern Alpine foreland. Its location and focal depth of 23 km are well constrained by a uniform azimuthal station distribution and by three stations within an epicentral distance of 20 km. The well-determined strike-slip mechanism with an ENE-WSW oriented T-axis (Figure 6) is typical for northeastern Switzerland (Deichmann et al. 2000b; Kastrup et al. 2004).

Lago di Garda, northern Italy

One minute before midnight, local time, on November 24th, a moderately strong earthquake in northern Italy caused ground shaking that woke up many people in southern and southeastern Switzerland (Figure 9). The epicenter was located near the town of Saló, W of Lake Garda. In the epicentral region the shaking was severe, causing the collapse of several poorly built

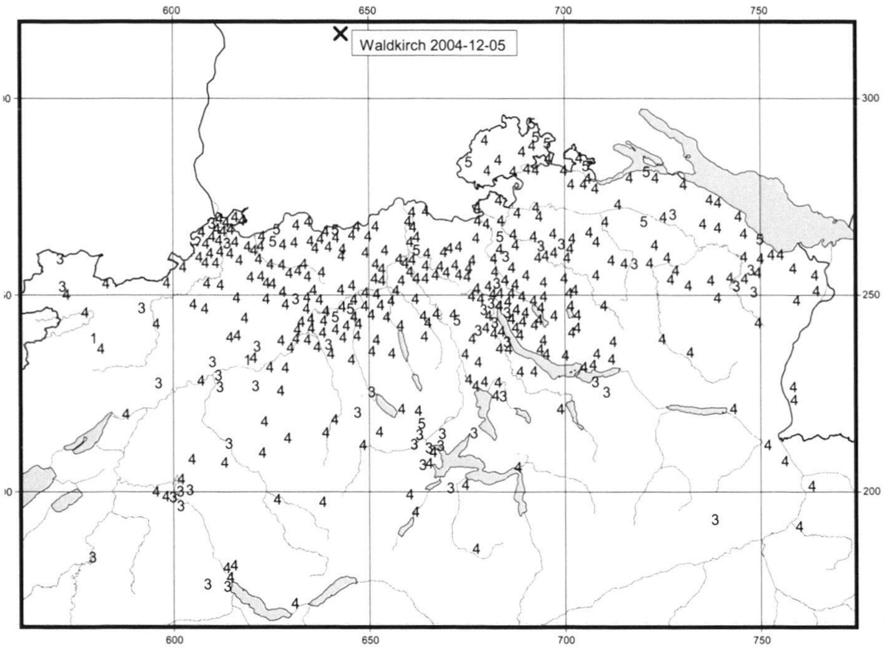

Fig. 10. Macroseismic observations for the event of Waldkirch (2004/12/05, 02:52 local time). Otherwise as in Figure 5.

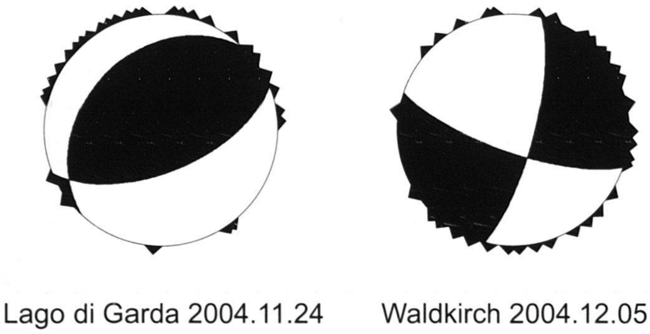

Fig. 11. Moment tensors of the Lago di Garda and Waldkirch events.

houses and forcing people to abandon some heavily damaged buildings. This corresponds to an epicentral intensity I_0 of VII–VIII. Although the epicenter of this event was located outside the area covered by the map in Figure 2, we mention it here, because it was the strongest earthquake in 2004 that produced significant ground shaking in Switzerland. In fact in canton Ticino it caused the most intense shaking in many years and intensities of IV were observed as far north as Lucerne. Magnitudes calculated by the Swiss Seismological Service are M_L 5.3 and M_w 5.0, which agree well with the values of M_L 5.2 and M_w 5.0 published by INGV (2004). The focal mechanism derived from the moment tensor inversion is a thrust fault with a NW-SE oriented P-axis at a depth of 9 km (Figure 11 and Table 4), which also differs only little from results obtained by INGV (2004).

Waldkirch, southern Germany

Another earthquake in 2004, which caused significant shaking in Switzerland and was located outside the map in Figure 2, occurred on December 5th at 02:52 local time. The epicenter was in southern Germany near the town of Waldkirch, about 17 km north of Freiburg im Breisgau. Magnitude values computed by the Swiss Seismological Service are M_L 5.1 and M_w 4.6, and the focal depth corresponding to the best fit of the moment tensor inversion is 12 km. Despite the relatively small difference in M_L with respect to the event of Lago di Garda, structural damage was only slight, being limited to minor cracks in walls and chimneys and some fallen roof shingles (LED 2004). Thus the epicentral intensity was not greater than VI, but it was nevertheless clearly felt over most of northern Switzerland and some people were awakened as far south as Chur and Interlaken (Figure 10). The moment tensor corresponds to a strike-slip focal mechanism with sinistral slip on a NNE-SSW striking fault or dextral slip on a WNW-ESE striking fault (Figure 11 and Table 4). The orientation of the NW-SE and NE-SW orientation of the P- and T-axes matches the stress field derived from other earthquakes in the crystalline basement of the Black Forest (Plenefisch & Bonjer 1997).

Discussion

On a global level, the seismicity of the year 2004 will undoubtedly be remembered for the enormous earthquake on December 26th off the west coast of Sumatra, which was one of the two or three largest earthquakes of the past century and which caused one of the most disastrous tsunamies in known history.

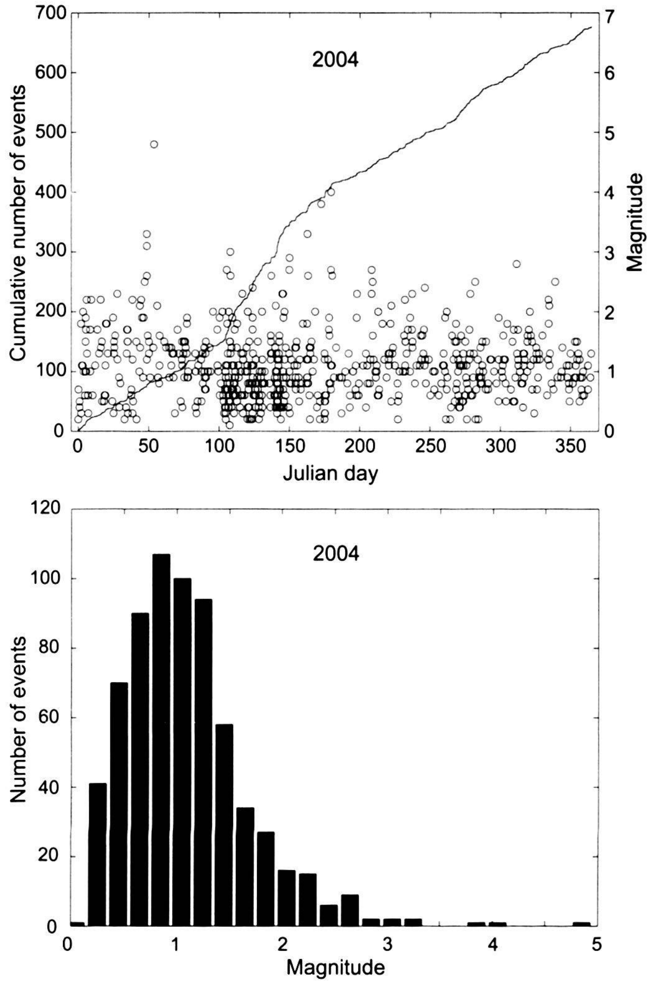

Fig. 12. Earthquake activity during 2004: magnitude of each event and cumulative number of events (above); histogram of magnitudes (below).

Although the direct seismological consequences of this earthquake were comparably insignificant for Switzerland, it is noteworthy that the broad-band seismometers of the Swiss Seismological Service recorded a vertical displacement of more than 2 cm as the long-period surface waves propagated across the country.

On a local scale, the five earthquakes in 2004 that produced ground shaking of intensity IV over large regions of the country were somewhat unusual and served to remind the public that seismic hazard is a concern also for Switzerland. Nevertheless, in terms of numbers of recorded earthquakes, the year 2004 in Switzerland and immediate surroundings was not out of the ordinary. Averaged over the last 30 years, we observe about 25 events with $M_L \geq 2.5$ and 8 events with $M_L \geq 3$ per year. With 22 $M_L \geq 2.5$ events and 7 events reaching $M_L \geq 3$ in 2004 (Table 2 and Fig. 12), the seismic activity in these magnitude ranges was thus close to the 30 year average.

The enhanced activity in April and May, visible in the plot of the temporal evolution of seismicity (Julian days 100–150 in Fig. 12), corresponds to the earthquake sequence of Derborence, which alone contributes 25 % to the total number of recorded earthquakes in 2004. The seismic activity in the region of Cima di Jazzi, between Zermatt and Macugnaga, which started in 2002 (Baer et al. 2003, Deichmann et al. 2004), flared up again in March 2004 and continued throughout the whole year with an additional 31 events ranging in magnitude between 0.9 and 2.3. Moreover, in autumn a small cluster of a dozen events with magnitudes between 0.4 and 1.9 appeared near Sierre. Thus the large total number of detected earthquakes (677) in 2004, compared to previous years, is due in part to these earthquake sequences and in part to an increase in sensitivity of the high-gain network since switching the event detection from the old analog data acqusition system to the new broad-band digital instrumentation at the end of August 2001 (Deichmann et al. 2002).

As in previous years, most of the earthquakes occurred in the Valais and in Graubünden. However, the strongest events (Besançon, Brugg and Liestal) occurred below the northern Alpine foreland. Routinely calculated focal depths for the 677 earthquakes recorded in 2004 range between 0 and 31 km, but only 39 of these hypocenters are deeper than 15 km. As in the past (e.g. Deichmann et al. 2000a), almost all these deep sources, and in particular the magnitude M_L 4.0 event of Brugg with its 7 aftershocks, are located in the lower crust beneath the Jura Mountains or the Molasse Basin of northern Switzerland.

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