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Earthquakes in Switzerland and surrounding regions during 2005

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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 2005. During this period, 611 earthquakes, 96 quarry blasts and two landslides were detected and located in the region under consideration. With 19 events with $M_L \geq 2.5$, the seismic activity in the year 2005 was below the average over the last 30 years. However, with the earthquake of Vallorcine (M_L 4.9) located just across the border to France, between Martigny and Chamonix, and the two earthquakes of Rumisberg and Brugg (M_L 4.1), located in the lower crust beneath the Jura Mountains of northern Switzerland, the year 2005 saw three events that produced shaking of intensity IV and V (EMS98). Of the 611 recorded earthquakes more than 110 events are aftershocks of the Vallorcine quake. Moreover, 51 events occurred within two days at the end of August during a period of very intense rainfalls. The epicenters of these events were concentrated in several clusters distributed over a wide area of central Switzerland, and their focal depths were shallow, so that they most likely constitute a case of precipitation-induced seismicity.

ZUSAMMENFASSUNG

Dieser Bericht des Schweizerischen Erdbebendienstes stellt eine Zusammenfassung der im Vorjahr in der Schweiz und Umgebung aufgetretenen Erdbeben dar. Im Jahr 2005 wurden im erwähnten Gebiet 611 Erdbeben sowie 96 Sprengungen und zwei Bergstürze erfasst und lokalisiert. Mit 19 Beben der Magnitude $M_L \geq 2.5$ war die seismische Aktivität im Jahr 2005 unter dem Durchschnitt der vergangenen 30 Jahre. Mit dem Erdbeben von Vallorcine (M_L 4.9), in Frankreich nahe der Grenze zur Schweiz zwischen Martigny und Chamonix gelegen, und den zwei Ereignissen von Rumisberg und Brugg (M_L 4.1), in der unteren Kruste des Nordschweizer Juras, haben sich jedoch drei Beben ereignet, die Erschütterungen der Intensität IV und V (EMS98) verursacht haben. Von den 611 aufgezeichneten Erdbeben gehören mehr als 110 Ereignisse zu den Nachbeben von Vallorcine. Ausserdem sind 51 mehrheitlich kleine Beben innerhalb von nur zwei Tagen Ende August während einer Periode ausserordentlich intensiver Regenfälle aufgetreten. Die Epizentren dieser Beben waren in verschiedenen Häufungen konzentriert, die über ein grösseres Gebiet der Zentralschweiz verteilt waren, und ihre Herdtiefen waren durchwegs flach. Somit handelt es sich hier sehr wahrscheinlich um einen Fall von niederschlagsinduzierter Seismizität.

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 2005, 611 séismes, 96 tirs de carrière et deux glissements de terrain ont été détectés et localisés. Avec 19 événements de magnitude $M_L \geq 2.5$, l'activité sismique de l'année 2005 a été inférieure à la moyenne de ces 30 dernières années. Cependant, des intensités IV et V (EMS98) ont localement été atteintes lors du séisme de Vallorcine (M_L 4.9) localisé de l'autre côté de la frontière avec la France, entre Martigny et Chamonix et lors des deux séismes de Rumisberg et Brugg (M_L 4.1), localisés dans la croûte inférieure sous les montagnes du Jura du nord de la Suisse. Parmi les 611 séismes enregistrés, plus de 110 étaient des répliques du séisme de Vallorcine et 51 se sont produits pendant deux jours à la fin du mois d'août lors de pluies très intenses. Localisés proche de la surface et distribués par paquets, sur une grande partie de la Suisse centrale, ces 51 événements constituent probablement un exemple de sismicité induite par précipitations.

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

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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 (Baer et al. 1997, 1999, 2001, 2003, 2005; 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://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 2005

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 continuously to 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.

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 data acquisition system, see Baer et al. (2001).

In order to monitor with greater precision an ongoing sequence of earthquakes in the immediate vicinity of the southern segment of the new Gotthard railway tunnel that is still under construction, a set of eight stations with short-period seismometers and in part with three-component accelerometers were installed during the late Fall of 2005 in the region between the Lukmanier Pass and the Leventina Valley (Table 1 and Fig. 1). In addition, an accelerometer has been installed in the tunnel itself (MFSFA in Table 1). These eight stations are operated under a contract with AlpTransit-Gotthard AG. The signals of six of these stations are integrated in realtime in the national high-gain network, while the data of one station (LUKA1) is downloaded per telephone, and two stations (CHAT1 and CHAT2) store the data on site.

Table 1. Seismograph stations operational at the end of 2005. 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 the single station 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
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,	SM-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
AlpTransit-Gotthard Network		
Code	**Station name**	**Type**
CHAT1	Predelp, TI	SP-3
CHAT2	Alpe di Cari, TI	SP-3
CHIR1	Chironico, TI	SP-3, SM-3
DOETR	Doetra, TI	SP-3, SM-3
LUKA1	Lucomagno, TI	SP-3, SM-3
MFSFA	Faido (Tunnel), TI	SM-3
NARA	Leontica, TI	SP-3
RITOM	Lago Ritom, TI	SP-3, SM-3
TONGO	Tortengo, TI	SP-3
Single stations		
Code	**Station name**	**Type**
BBS	Basel-Blauen, BL	SP-1
BERT	Bern, BE	SP-3
GNV	Geneva, GE	SP-1

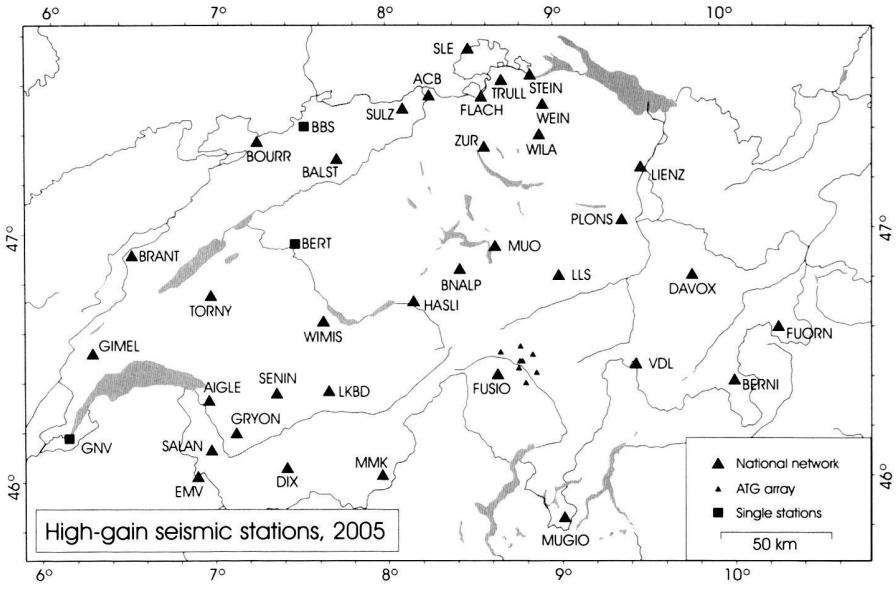


Fig. 1. Seismograph stations in Switzerland operational at the end of 2005. The set of small triangles without station labels correspond to the Alp-Transit-Gotthard network (ATG-array).

Thus, by the end of 2005, the number of stations transmitting data in realtime to the recording center of the Swiss Seismological Service in Zurich included 28 broad-band instruments (STS2), 8 five-second seismometers, 6 short-period sensors and one accelerometer. (Table 1 and Fig. 1).

The data of the national strong-motion network is recorded on site and can be downloaded interactively by telephone. To complement this acceleration data with signals that are available in realtime, 12 stations of the broad-band network are equipped with an additional three-component Kinemetrics EpiSensor accelerometer (Table 1). In 2005, FUSIO was added to this set of stations.

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 (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). Moreover, in the course of a cross-frontier cooperative effort to exchange seismic data in realtime, we continuously record and archive the signals of two Austrian stations (DAVA and WTTA) as well as four stations in northern Italy (MABI, MDI, MONC and DOI).

Hypocenter location procedures

In the past, source locations were 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 based on direct foreward modeling of travel times. The seismic velocity models used 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 (for more details see Deichmann et al. 2004). An added feature of these two algorithms includes the possibility to use secondary arrivals, such as the reflection at the Moho, PmP, or the direct wave, Pg, at distances were the Moho refraction, Pn, is the first arrival.

With the year 2005, hypocenters of most of the local earthquakes have been calculated using the software package NonLinLoc (Lomax et al. 2000). This procedure is based on a combination of probabilistic earthquake location and non-linear, global search algorithms using nested grids or the Oct-Tree Importance sampling algorithm (Lomax & Curtis, 2001). The probabilistic, non-linear formulation of the earthquake location problem contains a complete description of location uncertainties. In this approach, a priori known errors such as

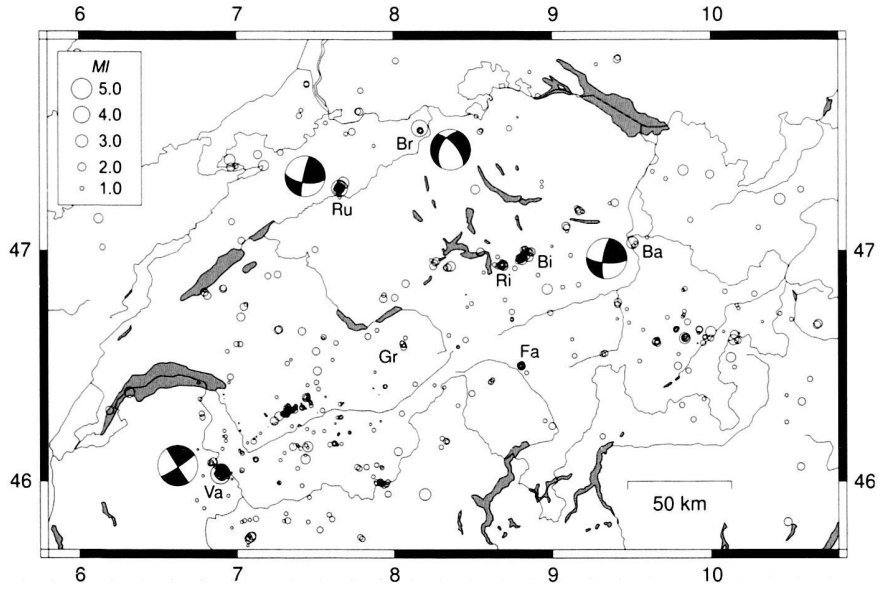


Fig. 2. Epicenters and focal mechanisms of earthquakes recorded by the Swiss Seismological Service during 2005. Epicenters of earthquakes mentioned in the text are Bad Ragaz (Ba), Bisistal (Bi), Brugg (Br), Faido (Fa), Grindelwald (Gr), Riemenstalden (Ri), Rumisberg (Ru), Vallorcine (Va).

measurement errors or travel time calculation errors are explicitly incorporated in terms of probability density functions. These methods not only provide a complete description of uncertainty estimates, but can also be used with any available velocity model and method of travel time calculation. The P-wave velocity model used in this context was derived from a 3D tomographic inversion of local earthquake data with constraints from controlled source seismics (Husen et al. 2003). A 3D S-wave velocity model is not available yet, so that the S-velocities are calculated from the P-velocity using a V_P/V_S ratio of 1.71. In regions where it is well-constrained, the 3D velocity model gives more accurate ray paths, in particular at larger distances and for arrivals refracted at the Moho. This permits more reliable focal depth determinations, even for events where the minimal epicentral distance is large relative to the focal depth.

Seismic activity during 2005

Overview

During 2005, the Swiss Seismological Service detected and located 611 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 and two as landslides.

Magnitude values of the events recorded in 2005 range between M_L 0.1 and 4.9. 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 in Table 4 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). In general a full-waveform inversion is performed for all events with $M_L \geq 3.5$, but in some cases, with recordings with particularly good signal-to-noise ratios at low frequencies, it has been possible to invert for the moment tensor even for events with $M_L < 3$. 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 770 earthquakes with $M_L \geq 2.5$, which have been recorded in Switzerland and surrounding regions over the period of 1975–2005. 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 2005.

Date & Time UTC	Lat. [°N]	Lon. [°E]	X / Y [km]	Depth [km]	Mag. [M_L]	Q	Location
2005.01.19 14:46:51	47.365	7.174	580/246	3	2.6	B	Saint Ursanne, JU
2005.02.27 08:20:15	47.345	9.828	780/246	1	2.5	B	Mellau, A
2005.03.16 03:41:31	47.389	6.962	564/249	8	2.7	A	Chevenez, JU
2005.05.08 14:29:40	47.291	7.681	618/238	25	2.9	A	Klus, SO
2005.05.12 01:38:05	47.267	7.657	616/235	25	4.1	A	Rumisberg, BE
2005.05.19 14:56:54	46.152	7.450	601/111	2	2.5	B	Saint-Martin, VS
2005.05.19 17:16:28	45.943	8.195	659/ 88	10	2.9	B	Cima Capezzone, I
2005.05.27 17:22:44	47.034	9.509	757/211	8	2.9	A	Bad Ragaz, SG
2005.06.24 16:20:57	46.615	10.114	805/166	1	2.5	A	Piz Quattervals, GR
2005.07.04 23:02:35	47.221	10.432	827/234	6	2.7	D	Arlberg, A
2005.07.10 18:44:21	46.835	8.969	717/188	1	2.6	A	Selbsanft, GL
2005.07.21 03:20:33	47.269	7.657	616/235	25	2.6	A	Rumisberg, BE
2005.09.01 05:28:20	46.388	6.320	514/138	1	2.6	B	Nyon, VD
2005.09.08 11:27:17	46.032	6.897	558/ 98	7	4.9	A	Vallorcine, F
2005.09.08 11:53:10	46.031	6.905	559/ 98	6	3.0	A	Vallorcine, F
2005.09.08 14:10:02	46.033	6.897	558/ 98	7	2.9	A	Vallorcine, F
2005.11.12 19:31:16	47.523	8.166	655/264	20	4.1	A	Brugg, AG
2005.12.03 03:31:41	46.651	9.998	796/170	4	2.5	B	Brail, GR
2005.12.30 16:50:01	46.623	9.835	783/166	4	2.7	B	Albulapass, GR

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.

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	≤ 1.5×Z	≤ 2	≤ 3
B	≤ 200	≤ 25	≤ 5	≤ 10
C	≤ 270	≤ 60	≤ 10	> 10
D	> 270	> 60	> 10	> 10

Significant earthquakes of 2005

Rumisberg – Balsthal

The first of the three $M_L > 4$ events in 2005 occurred on May 12th at 03:38 local time. The epicenter was located near the town of Rumisberg on the southern edge of the Jura Mountains between the cantons Solothurn and Bern. Computed magnitudes are M_L 4.1 and M_w 3.7. The epicentral intensity I_0 reached IV (EMS98), and intensities of III and IV were reported from across most of northwestern Switzerland (Fig. 4 top). Such a large area of perceptible shaking for this event of moderate magnitude is due to its large focal depth of 25 km. This value is well-constrained by P- and S-wave arrivals at station BALST located 8 km from the epicenter and at several strong-motion stations at distances around 30 km in the Basel region. It is also confirmed by 2-D ray-tracing of Pn arrivals at several stations in eastern Switzerland.

The faultplane solution based on first-motion polarities corresponds to a strike-slip mechanism with NW-SE and NE-SW oriented P- and T-axes, typical of northwestern Switzerland. The full-waveform inversion results in a moment tensor with a stronger thrust component (Figure 5). Whereas the E-W striking nodal plane of the moment tensor is similar to the one obtained from the faultplane solution, the strike and dip of the other nodal plane deviate by 16 and 22 degrees from the nodal plane compatible with the observed first-motion polarities.

The Rumisberg mainshock was preceded by a magnitude M_L 2.9 event on May 8th (Table 2) and a magnitude M_L 0.9 event on May 9th. Whereas the latter was probably located in the immediate vicinity of the mainshock and can therefore be considered a foreshock, the former was located 3–4 km further to the NE near Klus (SO), so that its relation to the mainshock is less evident. A total of 20 aftershocks were detected: after a series of 6 events with magnitudes ranging between 0.9 and 2.4 in the first 24 hours after the main event, sporadic activity, including an event of magnitude M_L 2.6 on July 21st, continued over the rest of the year (Table 2).

Bad Ragaz

The M_L 2.9 event of May 27th near Bad Ragaz (Table 2 and Fig. 2) is not very spectacular in itself. However, it is interesting, because its hypocenter coincides with that of a M_L 3.6 earthquake that occurred on February 23rd, 2000, and of another M_L 2.9 event on January 30th, 2001 (Baer et al. 2001; Deichmann et al. 2002). In fact, all three events seem to be part of a cluster that has been active off and on since the year 1998. From the broad-band signals of the event of 2005 it was possible to compute the moment tensor (Fig. 5). With a moment magnitude M_w 2.8 the corresponding focal mechanism is practically identical to that of the mainshock in the year 2000 (Baer et al. 2001).

Vallorcine

The strongest event of 2005 in the region covered by the map in Figure 2 occurred on September 8th, 13:27 local time. The

Location	Date & Time [UTC]	Depth [km]	Mag.	Plane 1 Strike/Dip/Rake	Plane 2	P-Axis Az/Dip	T-Axis
Rumisberg	2005/05/12 01:38	25	M_L 4.1	098/63/ 172	192/83/ 027	322/13	058/24
		24	M_w 3.7	101/60/ 146	208/61/ 034	335/00	065/44
Bad Ragaz	2005/05/27 17:22	9	M_w 2.8	189/75/ 019	094/72/ 164	321/02	052/24
Vallorcine	2005/09/08 11:27	8	M_w 4.5	147/88/ 006	057/84/ 178	282/03	013/06
Brugg	2005/11/12 19:31	20	M_L 4.1	206/48/-034	320/65/-133	182/50	079/10
		18	M_w 3.6	191/50/-130	314/57/-045	167/57	071/04

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

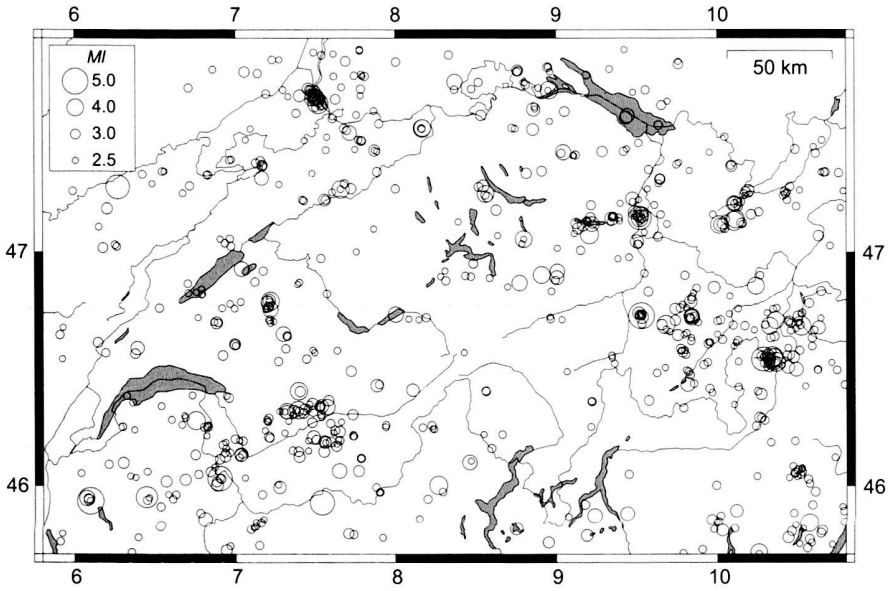


Fig. 3. Epicenters of earthquakes with Magnitudes $M_L \geq 2.5$, during the period 1975–2005.

computed magnitudes are M_L 4.9 and M_w 4.5. Its epicenter was located near the village of Vallorcine, on the French side of the border along the road between Martigny and Chamonix. The cracks in the walls of several houses and the numerous rockfalls along roads in the region north of the epicenter correspond to a maximum intensity of V (EMS98). It was clearly felt also over most of western Switzerland. A comprehensive macroseismic map that includes also observations in France and Italy is in preparation.

The moment tensor derived from a full-waveform inversion of a large number of broad-band records corresponds to a strike-slip mechanism with NNE-SSW and WNW-ESE trending P- and T-axes (Figure 5). To study the relation of this earthquake and its aftershocks to the known faults in the region, a temporary seismograph array was deployed in the epicentral area immediately following the mainshock (Fréchet et al. 2006). Over 300 events were recorded during the one-month campaign, and the Swiss national network routinely detected more than 110 aftershocks until the end of the year. Only two of these aftershocks reached a magnitude $M_L > 2.5$ (Table 2). The routinely calculated focal depths of 6 and 7 km for the mainshock and the two strongest aftershocks listed in Table 2 are based on arrivals at Swiss stations alone. Because of the poor azimuthal station distribution, these values are poorly constrained. First results of the aftershock monitoring campaign suggest that a focal depth of 3–5 km is more likely (Thouvenot et al. 2006).

Brugg

The third earthquake to cause shaking felt over a large region in 2005 occurred on November 12th at 20:31 local time. Its epicenter was located near the village of Mönthal (AG), 4 km W of Brugg. Computed magnitudes are M_L 4.1 and M_w 3.6. Shaking intensity of IV (EMS98) was reported not only from the epicentral region, but also from many locations across most of northern Switzerland (Fig. 4). Just as in the case of the Rumisberg event, the wide area over which this event was felt is due to the relatively large focal depth. In fact, both the routinely calculated depth, which is well constrained by P- and S-arrivals at stations SULZ and ACB located at epicentral distances of 4 and 9 km, as well as the depth resulting from 2-D ray-tracing give a value of 20 km.

The source location of this earthquake coincides within the location uncertainty with the M_L 4.0 event of June 28th, 2004 (Baer et al. 2005). This is illustrated by the seismograms in Figure 6(a): the identical arrival-time difference between the S- and P-onsets as well as the striking similarity of the waveforms of the S-phase imply that the hypocenters of the events of 2004 and 2005 are located at the same distance from station SULZ and that the paths between source and station are practically

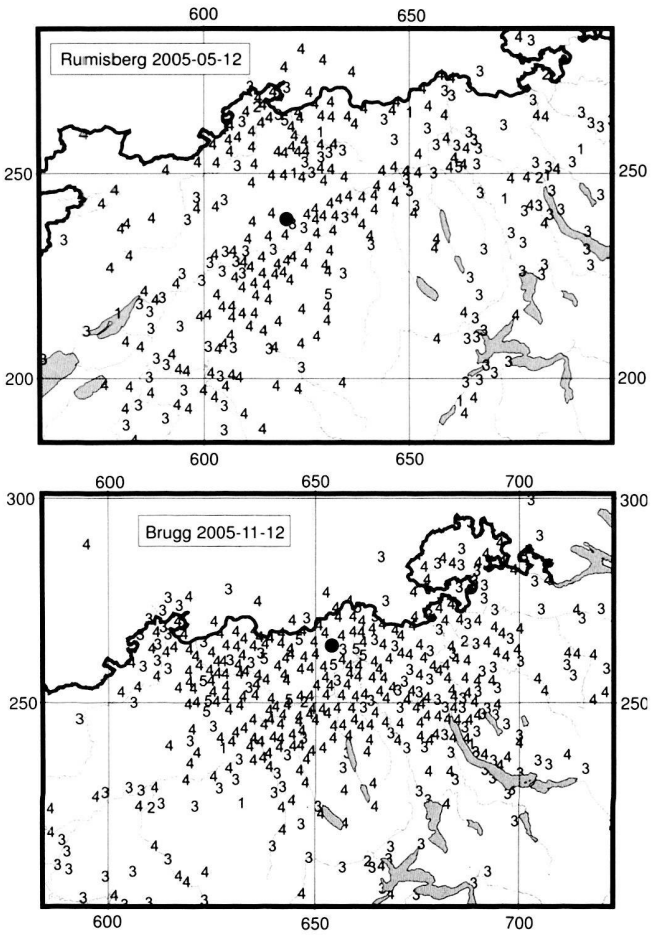


Fig. 4. Macroseismic observations for the events of Rumisberg (2005/05/12, 03:38 local time) and Brugg (2005/11/12, 21:31 local time). Each value represents the macroseismic intensity (EMS-98) assigned to a single postal code zone. The black dot corresponds to the instrumental epicenter. The Swiss cartesian coordinate grid is labeled in km.

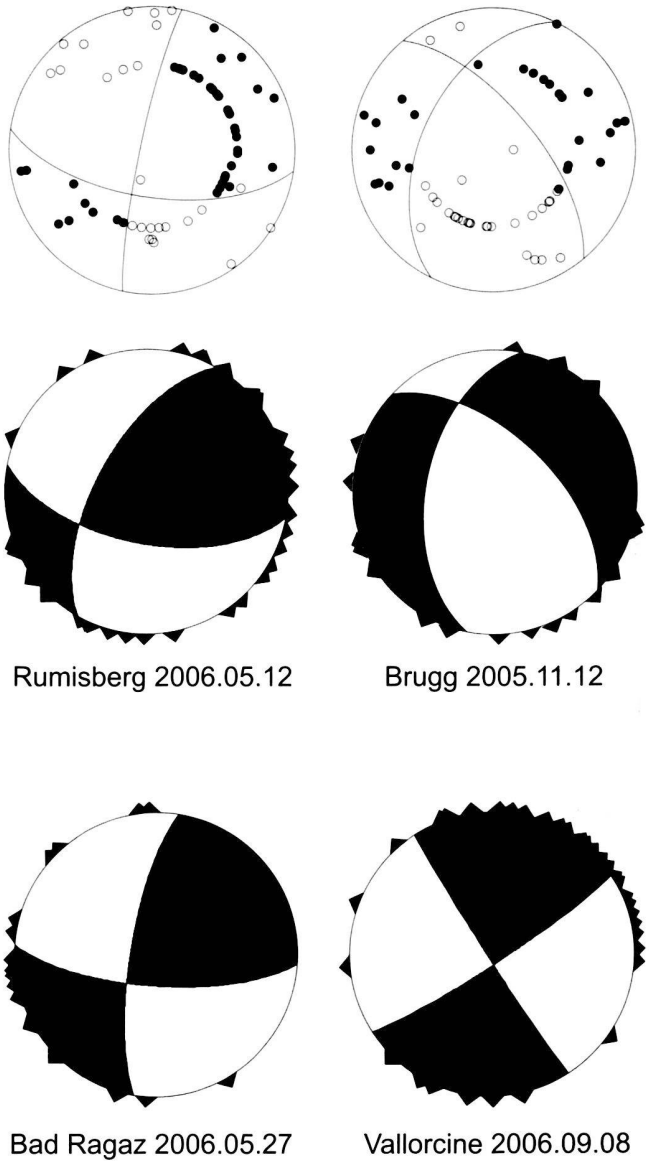


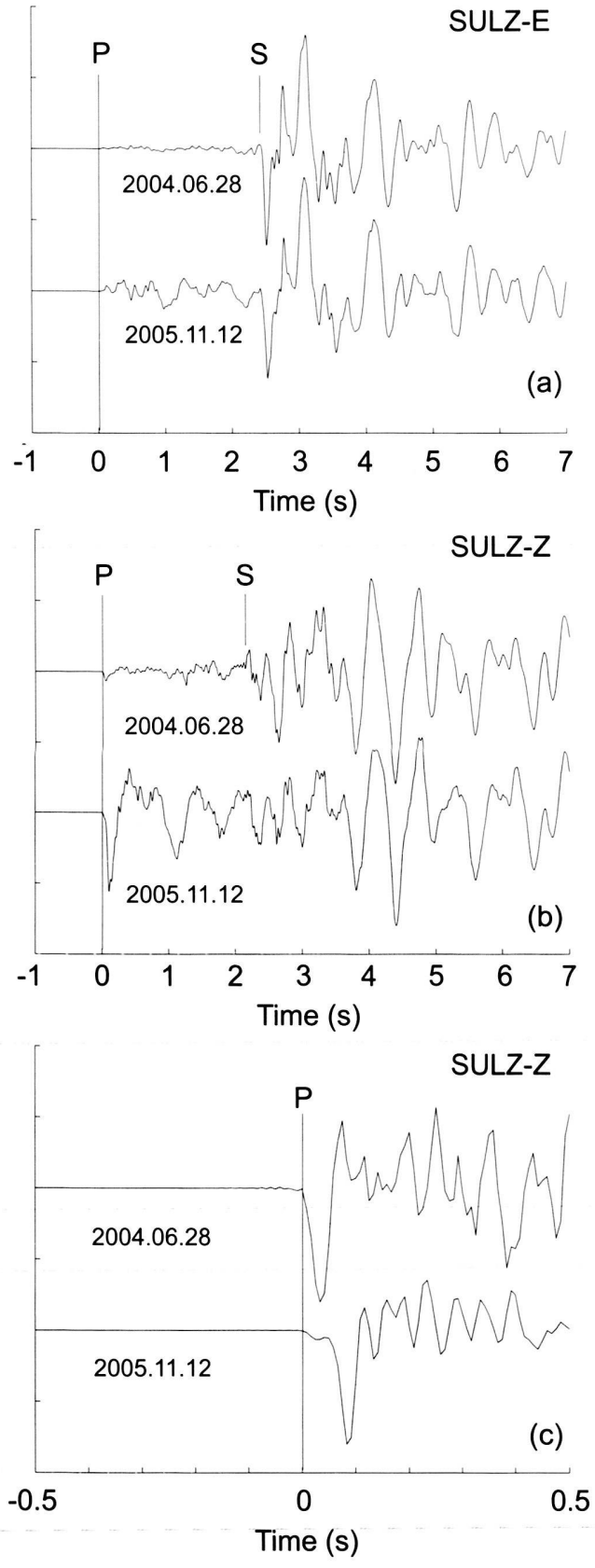
Fig. 5. Faultplane solutions (above) based on first-motion polarities and moment tensors (below) based on full-waveform inversion (lower hemisphere, equal area projection). In the faultplane solutions, solid circles correspond to compressive first motion (up) and empty circles to dilatational first motion (down); on the moment tensors, triangles show the station locations.

the same. However, the different relative amplitudes of the P- and S-phases visible on the vertical components at station SULZ shown in Figure 6(b) are an indication that the focal mechanisms of the two events differ. In fact, both the faultplane solution based on first-motion polarities and the moment tensor derived from the full-waveform inversion give a normal faulting mechanism (Fig. 5), for which the orientation of one of the nodal planes differs significantly from the mechanism of previous year's event (Baer et al. 2005). It is also interesting to note that the P-wave onset of the event of 2005 observed at station SULZ (Fig. 6(c)) exhibits a small precursor phase before the onset of the main P-pulse, whereas the seismogram of the event of 2004 starts with a simple single pulse. Given the close spacing of the two hypocenters and the fact that this precursor phase is visible also at other stations situated at different azimuths relative to the source, this difference in signal character can not be due to path effects but is probably due to a more complex rupture process in 2005 than in 2004.

The mainshock in 2005 was preceded by a small foreshock (M_L 1.2) on August 2nd and was followed from November 13th to December 5th by four aftershocks with magnitudes between M_L 0.6 and 1.5.

Seismic events and rockbursts in the new Gotthard tunnel

In the Spring of 2004, a sequence of five small earthquakes (M_L 0.9–1.4) occurred near Faido, TI. This sequence was not recognised as being anything unusual at first. It was only in June



2005, after a magnitude M_L 1.9 earthquake at the same location that it became clear that these events were part of an ongoing sequence of small earthquakes whose time of occurrence and epicentral location correlate with some rather violent rockbursts in a section of the new Gotthard railroad tunnel, which is still under construction. In fact during the course of 2005, the national seismic network detected and located eight other events with the same epicenter and with magnitudes between M_L 0.9 and 1.6. An additional event with M_L 1.0 occurred on November 10th, 3–4 km SE of the others, and it correlates with a rockburst in a segment of the tunnel close to the epicenter. Computed focal depths, though poorly constrained, suggest a shallow source located at a depth of less than 2 km. To examine the causal relation between the earthquakes, rockbursts and observed deformation of the tunnel cross-section, an additional temporary network of seismometers was deployed in the epicentral area in the Fall of 2005, under contract from AlpTransit-Gotthard AG. (Table 1 and Fig. 1). First results based on records from these stations confirm the shallow focal depth as well as the correlation between these earthquakes and the observed rockbursts in the tunnel.

Rain-induced seismicity

As can be seen in Figure 7, the curve of the cumulative number of events with time shows a pronounced jump at Julian day 235. This jump corresponds to an anomalous burst of activity that includes 51 events over a period of less than 48 hours that started on the afternoon of August 22nd. Of these events, 39 occurred within 12 hours between 9 PM and 9 AM of the following day. Magnitudes of these events range between 1.0 and 2.4. Single earthquake swarms that produce a large number of small earthquakes over a period of a few days are quite common. What is however unusual about this concentration of seismic activity is that it occurred simultaneously over a very large region that extends from Canton Schwyz in the northeast across the region around Stans and Alpnach, south of Lake Lucerne, all the way to Grindelwald in the Bernese Oberland. The main centers of activity were two separate clusters around Bisistal and south of Riemenstalden in Canton Schwyz (Fig. 2). Together these two clusters contributed more than half the total number of earthquakes observed in those two days. Although focal depths of most of these events are poorly constrained by routine location procedures, the shallow sources are confirmed at least qualitatively by both the signal character of the events

Fig. 6. Seismograms of the Brugg events of 2004 and 2005 recorded at station SULZ at an epicentral distance of 4 km. The traces are aligned at the arrival time of the P-wave: (a) horizontal displacement in EW direction, (b) vertical diplacement and (c)vertical velocity. Note the different time scales: (a) and (b) include both the P- and S-phases, while (c) shows an enlargement of the P-arrival alone. The identical S-P times and the similar waveforms of the S-phase seen in (a) are evidence for a similar source location. The different amplitude ratios between the P- and S-phases seen in (b) are due to differences in the focal mechanisms, and the smali precursor before the P-wave onset of the event of 2005 seen in (c) is evidence for a more complex rupture process.

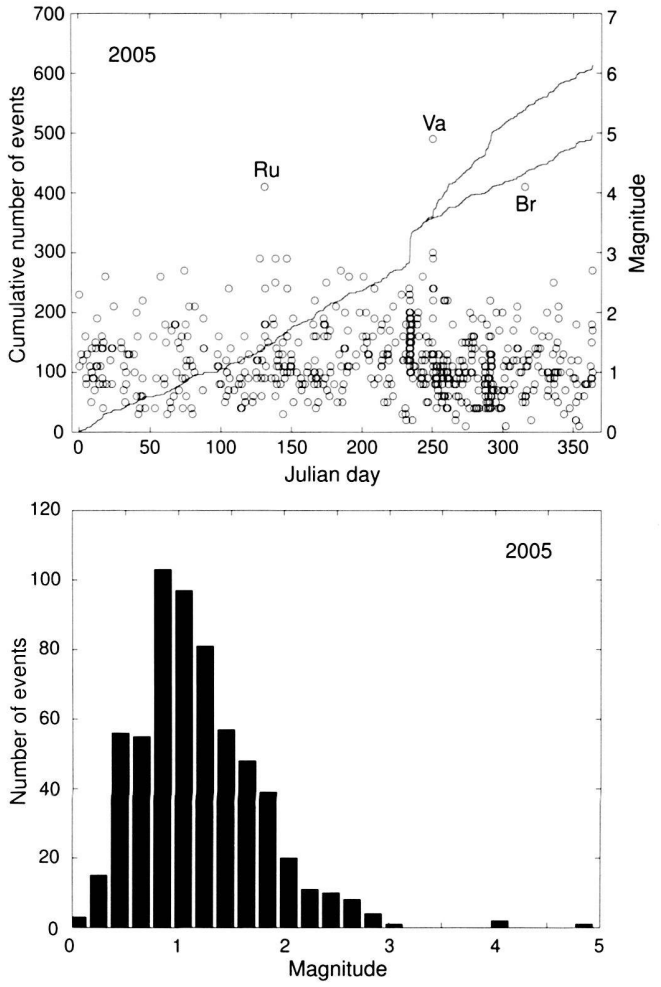


Fig. 7. Earthquake activity during 2005: magnitude of each event and cumulative number of events (above); histogram of magnitudes (below). The events with $M_L > 4$ are labled: Brug (Br), Rumisberg (Ru) and Vallorcine (Va). The lower curve beyond Julian day 245 in the plot of the cumulative number of events represents the evolution in time without the Vallorcine sequence. The prominent step in the cumulative number of events at Julian day 235 is the contribution of the rain-induced seismicity between August 22nd and 24th.

(conspicuous surface waves even at short epicentral distances) and the fact that numerous events with magnitudes less than 2 were perceived by the population as loud bangs.

During this time, the region in which all of these earthquakes ocurred, suffered very intense rainfalls, which caused massive floods and numerous landslides. Given this spatial and temporal coincidence and the shallow focal depths, it is thus likely that this unusual seismic activity was induced by a sudden increase in pore pressure due to the intense precipitation. This hypothesis is furthermore supported by the fact that the two main centers of activity around Bisistal and Riemenstalden are highly permeable karst regions, where surface waters and thus fluid pressure perturbations can propagate rapidly to greater depths.

Landslides

On May 14th at 18:49 local time, a sizeable landslide came down between Gondo and Zwischbergen, south of the Simplon Pass. The corresponding seismic signals were visible over most of the national network with amplitudes equivalent to a M_L 2.1 earthquake.

Twelve days later, on May 26th at 7:16 local time, the seismograph network detected another event with similar signal character and an epicenter west of station SALAN, in the region of the Dents du Midi. Although it is higly unlikely that the recorded signals were produced by an earthquake or an explosion, it has not been possible to associate this event with a known landslide.

Discussion

In 2005, the total number of 19 events with $M_L \geq 2.5$ was below the 30-year average of 25 events in this magnitude category per year. However, this apparent activity deficit was compensated for by three earthquakes with M_L between 4.1 and 4.9 and by the surge in microseismic activity associated with the intense precipitation at the end of August (Fig. 7). The main event of the year was certainly the M_L 4.9 earthquake of Vallorcine on September 8th and its large number of aftershocks.

Overall, as in previous years, most of the earthquakes occurred in the Valais and in Graubünden. However, two of the strongest events (Rumisberg and Brugg) occurred below the northern Alpine foreland. Routinely calculated focal depths for the 611 earthquakes recorded in 2005 range between close to the surface and 30 km, but only 44 of these hypocenters are deeper than 15 km. As in the past (e.g. Deichmann et al. 2000a), all of those deep sources with reasonably well-constrained focal depths, and in particular the magnitude M_L 4.1 events of Rumisberg and Brugg, are located in the lower crust beneath the Jura Mountains or the Molasse Basin of northern Switzerland.

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