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Earthquakes in Switzerland and surrounding regions during 2010

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Abstract This report of the Swiss Seismological Service summarizes the seismic activity in Switzerland and surrounding regions during 2010. During this period, 407 earthquakes and 85 quarry blasts were detected and located in the region under consideration. With a total of only 19 events with $M_L \geq 2.5$, the seismic activity in the year 2010 was below the average over the previous 35 years. The two most noteworthy earthquakes were the M_L 3.4 Barrhorn event near Sankt Niklaus (VS) and the M_L 3.0 event of Feldkirch, both of which produced shaking of intensity IV.

Keywords Earthquakes · Focal mechanisms · Moment tensors · Switzerland

Zusammenfassung Dieser Bericht des Schweizerischen Erdbebendienstes stellt eine Zusammenfassung der im Vorjahr in der Schweiz und Umgebung aufgetretenen Erdbeben dar. Im Jahr 2010 wurden im erwähnten Gebiet 407 Erdbeben sowie 85 Sprengungen erfasst und lokalisiert. Mit nur 19 Beben der Magnitude $M_L \geq 2.5$, lag die seismische Aktivität im Jahr 2010 unter dem Durchschnitt der vorhergehenden 35 Jahre. Die zwei bedeutendsten Ereignisse waren das Barrhorn Beben (M_L 3.4) bei Sankt Niklaus (VS) und das Beben von Feldkirch (M_L 3.0). Beide haben Erschütterungen der Intensität IV verursacht.

Resumé Le présent rapport du Service Sismologique Suisse résume l'activité sismique en Suisse et dans les régions limitrophes au cours de l'année 2010. Durant cette période, 407 tremblements de terre et 85 tirs de carrière ont été détectés et localisés dans la région considérée. Avec seulement 19 événements de magnitude $M_L \geq 2.5$, l'activité sismique de l'année 2010 est en dessous de la moyenne des 35 années précédentes. Les deux événements les plus significatifs étaient le tremblement de terre du Barrhorn (M_L 3.4) près de Sankt Niklaus (VS) et celui de Feldkirch (M_L 3.0), qui ont provoqué des secousses d'intensité IV.

1 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 thirteenth century have been summarized by Pavoni (1977) and provided the basis for the first seismic hazard map of Switzerland (Sägesser and 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 (Baer et al. 1997, 1999, 2001, 2003, 2005, 2007; Deichmann et al. 1998, 2000a, 2002, 2004, 2006, 2008, 2009, 2010). In the course of reassessing the seismic hazard in Switzerland, a uniform earthquake catalog

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covering both the historical and instrumental periods was compiled in 2002 (Fäh et al. 2003). The official seismic hazard map of Switzerland based on this catalog was released in 2004 (Giardini et al. 2004; Wiemer et al. 2009). In 2009, the Earthquake Catalog of Switzerland was revised (ECOS-09) and is now available on-line (<http://www.seismo.ethz.ch/prod/catalog/index>). 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 and Roth 1990; Rüttener 1995; Rüttener et al. 1996; Pavoni et al. 1997; Deichmann et al. 2000b; Kastrup et al. 2004, 2007).

2 Data acquisition and analysis

2.1 Seismic stations in operation during 2010

The Swiss Seismological Service operates two separate nationwide seismic networks (Fig. 1), a high-gain broadband seismometer network (Table 1) and a low-gain accelerograph network (Table 2). The former is designed to monitor continuously the ongoing earthquake activity

down to magnitudes well below the human perception threshold, whereas the latter is principally aimed at engineering concerns and thus focuses on recording so-called strong-motions in urban areas. Efforts are underway to merge these two networks, primarily by upgrading the accelerograph network with modern strong-motion sensors and digitisers, featuring real-time continuous communication, higher dynamic range, broader frequency bandwidth and higher sensitivity. Twelve stations of the high-gain broad-band network include an additional accelerometer. By 2009, 20 additional high quality strong motion stations were added, directly replacing pre-existing accelerometer network stations at 10 locations. In 2009, the Swiss Federal Council approved a project to renew the National Strong Motion Network; 30 high quality stations are to be installed within 4 years. The first four stations came online on 2010 (SBUB, SGRA, SLUW, SNIB). The on-going COGEAR project includes a local densification of the national networks in the Upper Valais, and in 2010, two additional broadband stations (SIMPL, LAUCH) and three strong motion stations (SVIT, SVIL, SVIO) became operational.

The SED continues to maintain a microseismic-network, originally set up in 2005, in the region between the

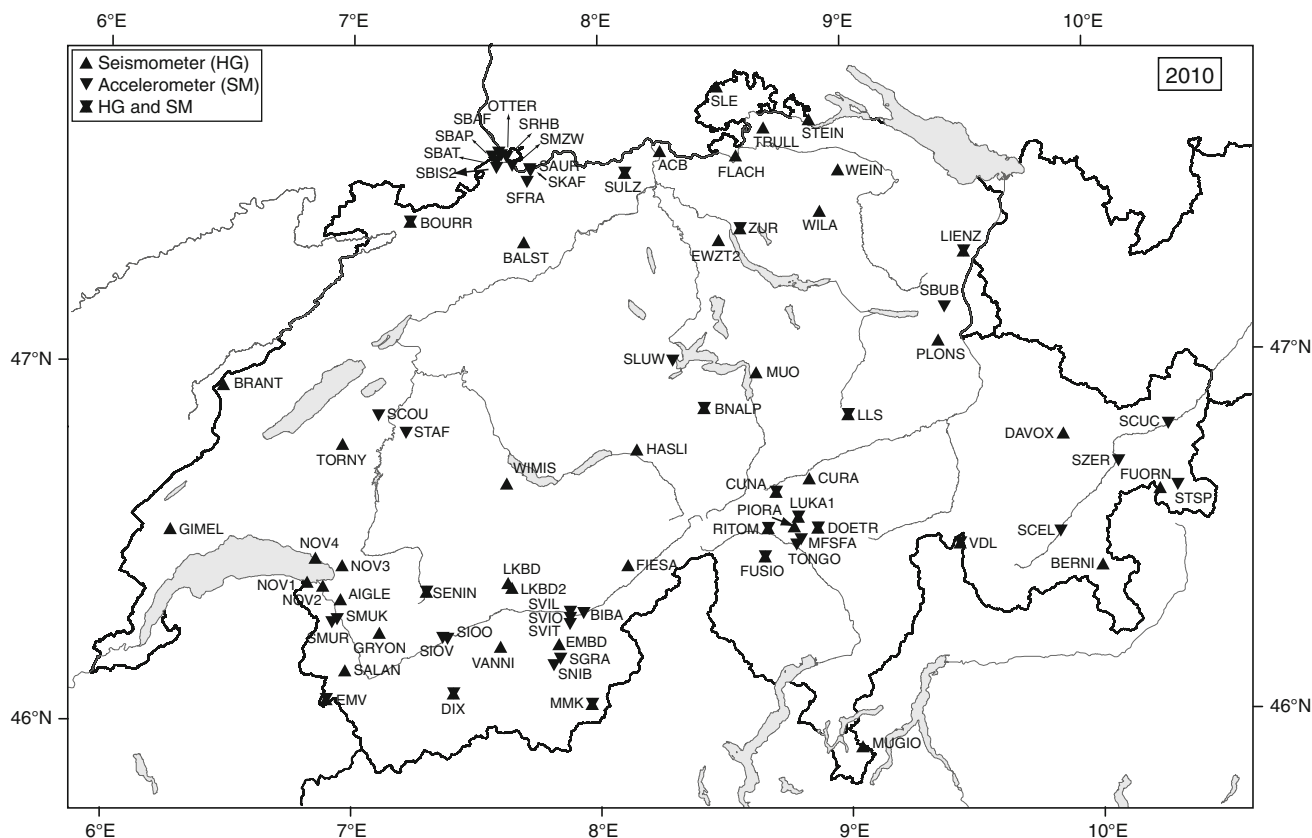


Fig. 1 Seismograph stations in Switzerland with on-line data acquisition operational at the end of 2010. The stations defined as high-gain (HG) are mostly equipped with broad-band or 5-second sensors,

whereas the strong-motion stations (SM) are accelerometers. For a map of the Basel-borehole array see Baer et al. (2007) or Deichmann and Ernst (2009)

Table 1 High-gain, three-component seismograph stations of the Swiss national network operational at the end of 2010

Code	Station name	Type
National on-line network recorded in Zürich		
ACB	Acheberg, AG	EB
AIGLE	Aigle, VD	BB
BALST	Balsthal, SO	BB
BERNI	Bernina, GR	BB
BNALP	Bannalpsee, NW	BB, SM
BOURR	Bourrignon, JU	BB, SM
BRANT	Les Verrières, NE	BB
DAVOX	Davos, GR	BB
DIX	Grande Dixence, VS	BB, SM
EMBD	Embd, VS	BB
EMV	Vieux Emosson, VS	BB, SM
EWZT2	Wetzwil, ZH	SP
FIESA	Fiescheralp, VS	BB
FLACH	Flach, ZH	EB
FUORN	Ofenpass, GR	BB
FUSIO	Fusio, TI	BB, SM
GIMEL	Gimel, VD	BB
GRYON	Gryon, VS	EB
HASLI	Hasliberg, BE	BB
LAUCH	Lauchernalp, VS	BB
LIENZ	Kamor, SG	BB, SM
LKBD	Leukerbad, VS	EB
LKBD2	Leukerbad, VS	SP
LLS	Linth-Limmern, GL	BB, SM
MMK	Mattmark, VS	BB, SM
MUGIO	Muggio, TI	BB
MUO	Muotathal, SZ	BB
PLONS	Mels, SG	BB
SALAN	Lac de Salanfe, VS	EB
SENIN	Senin, VS	BB, SM
SIMPL	Simplonpass, VS	BB
SLE	Schleitheim, SH	BB
STEIN	Stein am Rhein, SH	EB
SULZ	Cheisacher, AG	BB, SM
TORNY	Torny, FR	BB
TRULL	Trullikon, ZH	EB
VANNI	Vissoie, VS	BB
VDL	Valle di Lei, GR	BB, SM
WEIN	Weingarten, TG	EB
WILA	Wil, SG	BB
WIMIS	Wimmis, BE	BB
ZUR	Zürich-Degenried, ZH	BB, SM

Signals of LKBD2 are transmitted via analog telemetry

Instrument type: SP, 1-second; EB, 5-seconds; BB, broad-band; SM, accelerometer

Table 2 Strong-motion stations of the Swiss national network and local seismic networks with on-line data acquisition operational at the end of 2010

Code	Station name	Type
On-line strong-motion network		
BIBA	Brigerbad, VS	SM
OTTER	Otterbach, BS	SM
SAUR	Augst-Römermuseum, AG	SM
SBAF	Basel-Friedhofgasse, BS	SM
SBAP	Basel-PUK, BS	SM
SBAT	Basel-Tropenhaus, BS	SM
SBIS2	Binningen, BS	SM
SBUB	Buchserberg Malbun, SG	SM
SCEL	Celerina, GR	SM
SCOU	Cournillens, FR	SM
SCUC	Scuol-Clozza, GR	SM
SFRA	Frenkendorf, BL	SM
SGRA	Grächen-Ausblick, VS	SM
SIOO	Sion-Ophtalmologie, VS	SM
SIOV	Sion-Valere, VS	SM
SKAF	Kaiseraugst-Friedhof, AG	SM
SLUW	Luzern Werkhofstr., LU	SM
SMUK	Muraz-Kläranlage, VS	SM
SMUR	Muraz-Reservoir, VS	SM
SMZW	MuttENZ-Waldhaus, BL	SM
SNIB	Sankt Niklaus, VS	SM
SRHB	Riehen-Bäumlihof, BS	SM
STAF	Tafers, FR	SM
STSP	Tschier, GR	SM
SVIL	Visp-Litternaring, VS	SM
SVIO	Visp-ObereStapfeng., VS	SM
SVIT	Visp-Terbingerstr., VS	SM
SZER	Zernez, GR	SM
AlpTransit-Gotthard network		
CUNA	Cunera, GR	SP, SM
CURA	Curaglia, GR	SP
DOETR	Doetra, TI	SP, SM
LUKA1	Lucomagno, TI	SP, SM
MFSFA	Faido (Tunnel), TI	SM
PIORA	Piora (Tunnel), TI	BB
RITOM	Lago Ritom, TI	SP, SM
TONGO	Tortengo, TI	SP
Noville network		
NOV1	St. Gingolph, VS	SP
NOV2	Port Valais, VS	SP
NOV3	Caux, VD	SP
NOV4	La tour de Pellz, VD	SP

Table 2 continued

Code	Station name	Type
Basel borehole network		
HALTI	Haltingen (542)	SP
JOHAN	Sankt Johann (317)	SP
MATTE	Schützenmatte (553)	SP
OTER1	Otterbach (500)	BB, SM
OTER2	Otterbach (2740)	SP

The numbers in parentheses next to the borehole stations are the sensor depth with respect to ground surface in meters

Instrument type (all three-component): SP, 1-second; SM, accelerometer

Lukmanier Pass and the Leventina Valley to monitor with greater precision an ongoing sequence of earthquakes in the immediate vicinity of the southern segment of the new Gotthard railway tunnel, which is still under construction. The network is operated under a contract with AlpTransit-Gotthard AG. In 2010, no changes were made to the eight-station network configuration (Table 2).

In 2006 an additional array of seismic sensors was installed in six boreholes at depths between 317 and 2,740 m below Basel (e.g. Deichmann and Ernst 2009). This array was designed to monitor the seismicity induced by the injection of large quantities of water at high pressure into a 5 km deep well in the context of a project to extract geothermal energy. Except for station OTER1, the borehole array is operated by Geothermal Explorers Ltd in Pratteln. After one of the sensors was removed in 2007, the remaining five-station borehole network continued to operate without change through 2010. However in July, the data began to be collected by the SED continuously in real-time rather than on request after an event detection.

The earthquakes induced by the geothermal project in Basel have raised concerns about potential seismicity induced by other projects that might perturb the state of stress or the hydrological conditions of the subsurface (even those that do not involve the enhancement of permeability through massive water injections). Therefore, it has become common practice to include local monitoring capabilities for such projects. In 2010 an array of four stations was installed around the southeast tip of Lake Geneva associated to a project near Noville to drill for natural gas. Two similar networks installed in 2009 were closed in 2010: at Brigerbad, where an accelerometer had been installed to monitor a project to increase the geothermal productivity for a local spa, and in Zurich, where an array of four stations was operated in and around the city during an attempt by the local utility company (EWZ) to tap a possible aquifer at a depth of about 3 km. The Brigerbad station was merged into the National Strong Motion network (BIBA in Table 2), while three of the

EWZ stations were removed and station EWZT2 was migrated to the National high-gain network (Table 1).

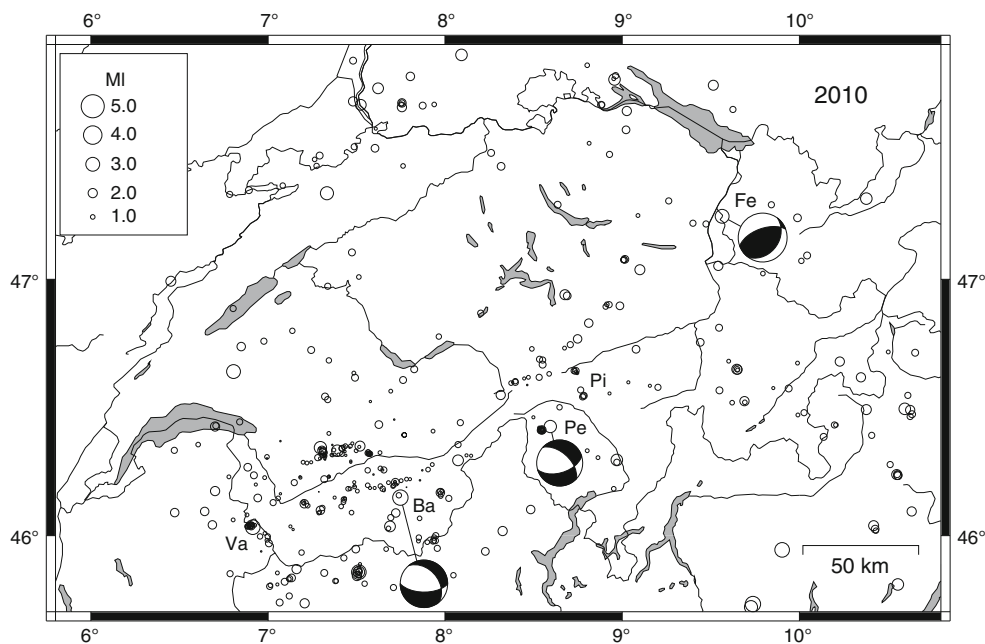
To improve the reliability of locations for events at the periphery or outside of Switzerland, we continue to be engaged in an ongoing cross-frontier cooperative effort to exchange seismic data in real-time. We continuously record and archive signals from stations in Austria operated by the Zentralanstalt für Meteorologie und Geodynamik in Vienna (ZAMG) and in Italy operated by the Istituto Nazionale di Geofisica e Vulcanologia in Rome (INGV), by the Istituto di Geofisica, Università di Genova, by the Zivilschutz der Autonomen Provinz Bozen-Südtirol (Baer et al. 2007) and by the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) in Trieste. In 2010, we began receiving data in real-time also from the Landesereidbedienst Baden-Württemberg in Freiburg. In total, 27 foreign stations were monitored at the SED in 2010, and the number continues to increase as new high-quality stations come on-line in the border region.

2.2 Hypocenter location, magnitude and focal mechanisms

Since the year 2005, hypocenter locations of most of the local earthquakes have been determined using the software package NonLinLoc (Lomax et al. 2000). The P-wave velocity model used was derived from a 3D tomographic inversion of local earthquake data with constraints from controlled source seismics (Husen et al. 2003), and the S-velocities are calculated from the P-velocity using a V_p/V_s ratio of 1.71.

Local magnitudes (M_L) are calculated from the maximum amplitude of the horizontal components of the digital broad-band seismograms filtered to simulate the response of a Wood–Anderson seismograph. The attenuation with epicentral distance is accounted for by an empirically determined relation (Kradolfer and Mayer-Rosa 1988). The final magnitude corresponds to the median value of all individual station magnitudes. For the stronger events, the traditional determination of focal mechanisms from the azimuthal distribution of first-motion polarities (fault-plane solutions) is complemented by moment tensors based on full-waveform inversion. This procedure, based on a time domain inversion scheme developed by Dreger (2003), also provides a moment magnitude, M_w , the best fitting double couple, and an optimal depth estimate based on the given location. Recently an additional procedure has been implemented that routinely and automatically provides estimates of M_w also for earthquakes of lower magnitudes. M_w values are computed using a spectral fitting technique following the method of Edwards et al. (2010). The far-field signal moments are obtained by simultaneously fitting the spectrum of a theoretical source model (Brune 1970,

Fig. 2 Epicenters and focal mechanisms of earthquakes recorded by the Swiss Seismological Service during 2010. Epicenters of events mentioned in the text are Barrhorn (*Ba*), Feldkirch (*Fe*), Valle di Peccia (*Pe*), Piora (*Pi*) and Vallorcine (*Va*)



1971) along with path variable attenuation and event stress-drop to observed Fourier velocity spectra. The seismic moment is derived from the far-field signal moments assuming a simple geometrical spreading model that accounts for body and surface wave propagation. Site amplification is assumed negligible for the computation of M_w due to the predominant use of hard-rock recording sites (Poggi et al. 2011).

A more detailed documentation of the data analysis can be found in previous annual reports (Deichmann et al. 2006; Baer et al. 2007).

3 Seismic activity during 2010

3.1 Overview

During 2010, the Swiss Seismological Service detected and located 407 earthquakes in the region shown in Fig. 2. Based on such criteria as the time of occurrence, the location, the signal character or on direct communication, 85 additional seismic events were identified as quarry blasts.

Magnitude values of the events recorded in 2010 range from M_L 0.1 to 3.5 (Fig. 3). 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 3 and 4. Table 3 includes also the available M_w values derived from the spectral fitting method of Edwards et al. (2010). Fault-plane solutions based on first-motion polarities are shown in Fig. 4 and their parameters are listed in Table 5.

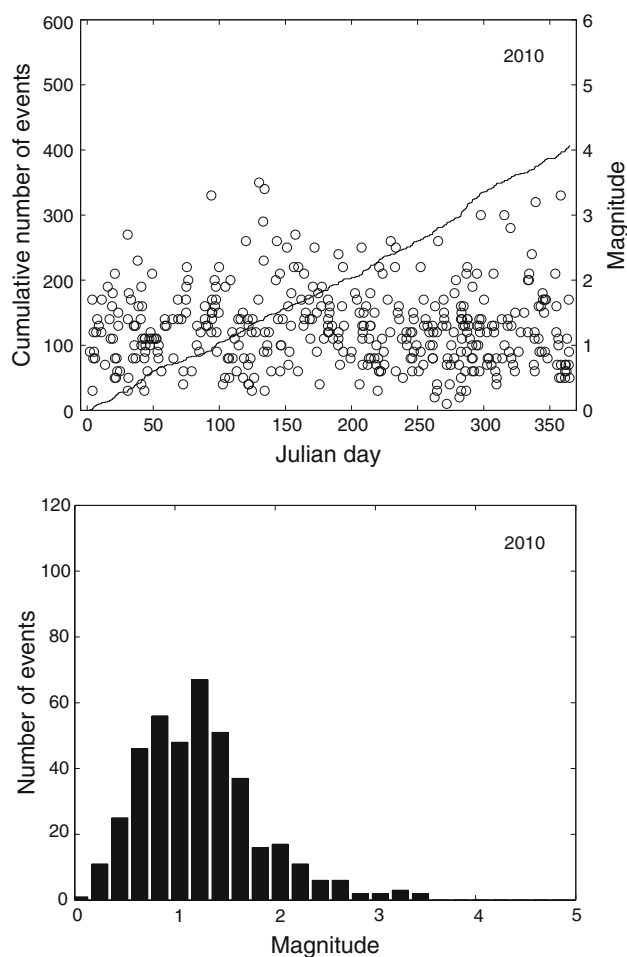


Fig. 3 Earthquake activity during 2010: magnitude of each event and cumulative number of events (*above*); histogram of magnitudes (*below*)

Table 3 Earthquakes with $M_L \geq 2.5$

Date and time (UTC)	Lat. (°N)	Lon. (°E)	X/Y (km)	Z (km)	Mag. (M_L)	Mag. (M_w)	Q	Location
2010.01.31 14:22:05	46.346	7.296	589/133	3	2.7	2.7	A	Col du Sanetsch, VS
2010.04.04 21:16:29	45.860	7.506	605/79	7	3.3	3.1	C	Becca de Leseney, I
2010.05.01 03:48:27	46.299	8.971	718/129	7	2.6	2.4	B	Lodrino, TI
2010.05.11 02:13:42	45.718	9.745	780/65	13	3.5	3.3	C	Albino, I
2010.05.14 03:35:28	45.718	9.727	778/65	0	2.9	2.7	D	Albino, I
2010.05.15 05:09:44	46.150	7.747	624/111	7	3.4	3.2	A	Barrhorn, VS
2010.05.24 12:32:49	47.767	8.957	714/292	11	2.6	2.6	B	Radolfzell, D
2010.06.01 03:30:06	45.856	7.512	606/78	7	2.5	2.5	C	Becca de Leseney, I
2010.06.07 13:19:27	46.424	8.598	689/142	7	2.7	2.4	A	Valle di Peccia, TI
2010.06.21 23:50:29	46.497	10.596	842/154	10	2.5	2.5	B	Ortles, I
2010.07.27 13:05:20	45.808	10.556	842/78	10	2.5	2.8	B	Lago d'Idro, I
2010.08.18 15:54:31	47.861	8.092	649/301	10	2.6	2.4	B	Feldberg, D
2010.08.22 11:14:12	46.334	7.391	596/131	6	2.5	2.6	A	Anzere (Sex Rouge), VS
2010.09.23 12:29:53	47.311	10.378	822/244	0	2.6	2.8	C	Lechtal, A
2010.10.25 20:00:31	47.243	9.564	761/235	5	3.0	2.9	A	Feldkirch, A
2010.11.12 12:42:06	46.642	6.805	551/166	8	3.0	2.9	B	Moudon, VD
2010.11.17 06:51:39	47.332	7.333	592/242	18	2.8	2.6	A	Courtételle, JU
2010.12.06 06:41:25	46.033	6.913	559/98	4	3.2	2.9	A	Vallorcine, F
2010.12.25 05:12:34	45.945	9.903	791/91	0	3.3	3.4	C	Ardesio, I

The values listed under M_w are the moment magnitudes calculated from the spectral fitting method documented in Edwards et al. (2010). The focal depth of the Feldkirch event has been set manually to the value constrained by comparison with the Vaduz events of 2009, and the quality has been changed from quality B to A (see text for details)

Table 4 Criteria and location uncertainty corresponding to the quality rating (Q) of the hypocentral parameters in the event list

Rating	Criteria		Uncertainty	
	GAP (°)	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

GAP largest angle between epicenter and two adjacent stations, DM minimum epicentral distance, H horizontal location, Z focal depth

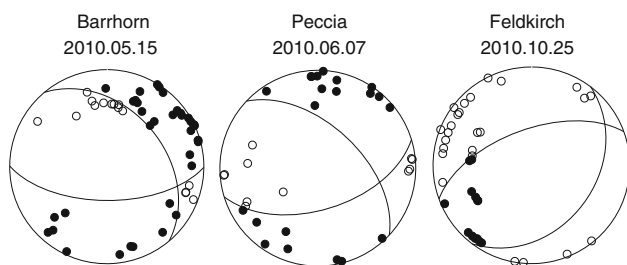


Fig. 4 Fault-plane solutions based on first-motion polarities. All stereographs are lower hemisphere, equal-area projections. Solid circles correspond to compressive first motion (up); empty circles correspond to dilatational first motion (down)

Figure 5 shows the epicenters of the 870 earthquakes with $M_L \geq 2.5$, which have been recorded in Switzerland and surrounding regions over the period of 1975–2010. These events represent about 8% of the total number of events detected during that time period in the same area. The chosen magnitude threshold of $M_L 2.5$ 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.

3.2 Significant earthquakes of 2010

3.2.1 Barrhorn

The strongest earthquake to have occurred within Switzerland in 2010 was the $M_L 3.4$ Barrhorn event of May 15, 7:09 local time. Its epicenter was located about 5 km SW of Sankt Niklaus, VS. It was clearly felt with intensities of IV throughout the Matternal and in the Rhone Valley as far as Brig (Fig. 6). A single aftershock of $M_L 1.2$ was recorded about seven hours later. The closest station (EMBD) is located at an epicentral distance of 10 km, so that the focal depth is constrained mainly by the more distant arrivals refracted at the Moho. The fault-plane solution based on take-off angles calculated for the 3-D velocity model used in the routine location procedure gives

Table 5 Focal mechanism parameters based on first-motion polarities

Location	Date and time (UTC)	Depth (km)	Mag.	Strike/dip/rake		Azimuth/dip	
				Plane 1	Plane 2	P-axis	T-axis
Barrhorn	2010/05/15 05:10	7	M_L 3.4	320/40/−048	090/61/−119	314/62	201/12
Peccia	2010/06/07 13:19	7	M_L 2.7	073/55/−135	313/55/045	283/55	193/00
Feldkirch	2010/10/25 20:00	5	M_L 3.0	250/60/108	037/35/062	327/13	198/69

Fig. 5 Epicenters of earthquakes with magnitudes $M_L \geq 2.5$, during the period 1975–2010

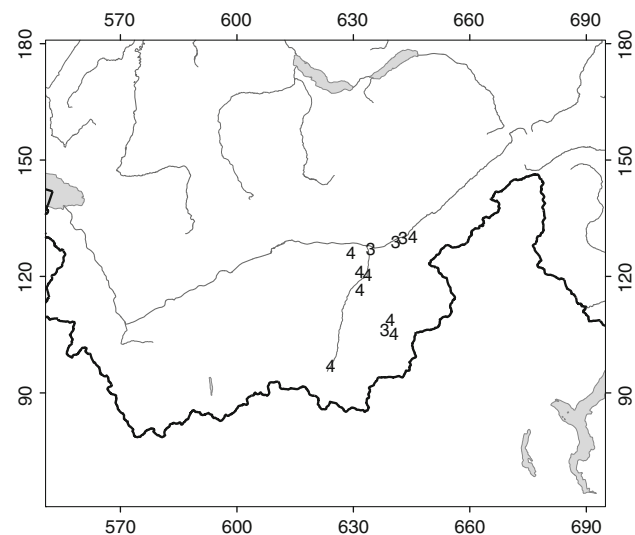
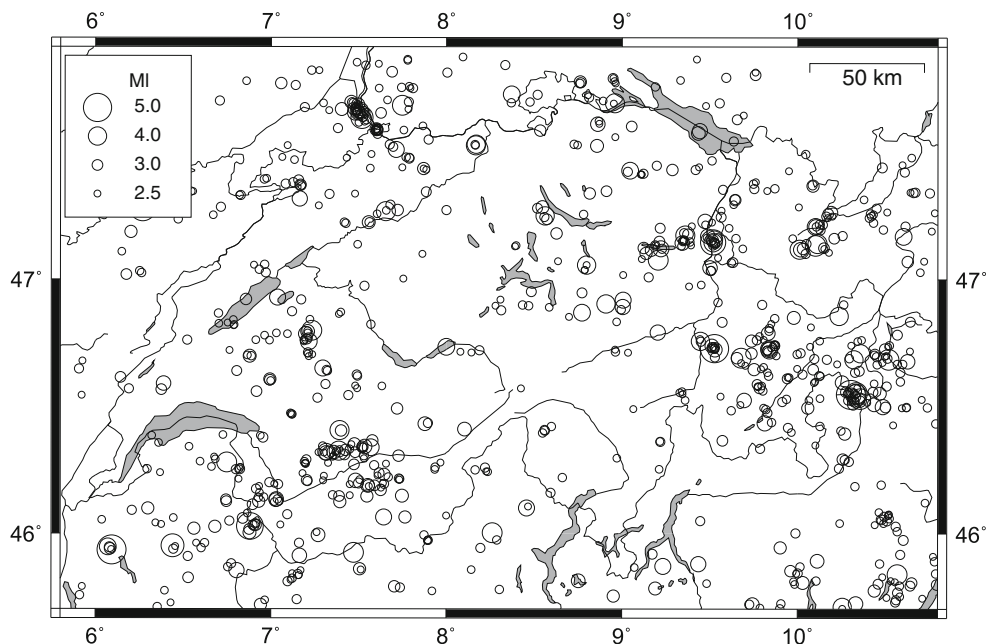


Fig. 6 Macroseismic intensities (EMS-98) reported for the 2010 Barrhorn event

a consistent and well-constrained normal-faulting mechanism (Fig. 4). This mechanism, with a NNE-SSW oriented T-axis, is typical for the earthquakes observed in the Penninic domain of the southern Valais (e.g. Kastrop et al. 2004).

3.2.2 Valle di Peccia

In the past, the northern part of canton Ticino was regarded as a region that is largely aseismic. However, in February 2008, an earthquake sequence became active near San Carlo in Val Bavona, a lateral valley of the upper Valle Maggia. More than 60 closely collocated events have been recorded to date and the strongest event, that occurred on April 17, 2008, attained a magnitude M_L of 2.7 (Deichmann et al. 2009). The M_L 2.7 event that occurred in 2010 on June 7, though located in the vicinity of this cluster, is clearly not part of this sequence. In fact its epicenter is located about 4 km ENE in the Valle di Peccia. The focal depth of about 7 km is constrained by P- and S-arrivals at station FUSIO situated at an epicentral distance of 6 km and by the Pn arrival recorded at station SLE in northern Switzerland. However, travel-time residuals on the order of 0.9 and 0.7 s are observed for the Pn arrivals recorded at stations BRANT and GIMEL in northwestern Switzerland. Considering that the RMS of the travel-time residuals to all other stations is 0.18 s, this points to deficiencies in the 3-D velocity model from the epicentral region in a WNW direction. The fault-plane solution obtained for this event corresponds to a normal faulting mechanism (Fig. 4) with a

NNE-SSW trending T-axis, very similar to the focal mechanism obtained for the Barrhorn event in the Penninic domain of the Valais. Given the relatively low magnitude of this event and that consequently the number of available polarities is limited, the result is not as reliable as that of the Barrhorn event. Nevertheless, to date, it is the only focal mechanism available in this region and thus worth noting.

3.2.3 Feldkirch

Already in 2009, the Sanktgaller Rheintal had experienced several earthquakes (Wildhaus, M_L 4.0, 3.1 and 3.0, and Vaduz, M_L 3.0), which were clearly felt by the local population (Deichmann et al. 2010). In the evening of October 25, the same area was again jolted by an M_L 3.0 event with epicenter near Feldkirch. It was clearly felt with intensities of IV in northern Liechtenstein and in the neighbouring areas of the Rhine Valley of Sankt Gallen (no data is available for Austria). The N–S elongation of the affected area seen in Fig. 7 is due to the geographical distribution of the population and should not be interpreted as source or site effects. The routinely calculated focal depth between 0 and 3 km is not well constrained. However, a comparison of the relative arrival times between Pg and Pn phases recorded for this event at several stations in northern Switzerland with those recorded for the Vaduz event of 2009, located 10 km further south, shows that the focal depths of these two events must be identical (Fig. 8). Thus we fixed the focal depth to 5 km in Table 3. Using the same take-off angles as those calculated for the 2009 Vaduz event, we obtain a well-constrained thrust faulting mechanism with a nearly NNW-SSE oriented P-axis.

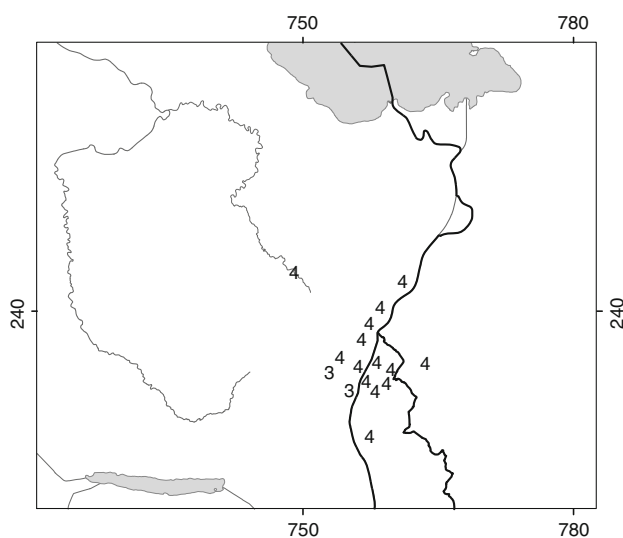


Fig. 7 Macroseismic intensities (EMS-98) reported for the 2010 Feldkirch event

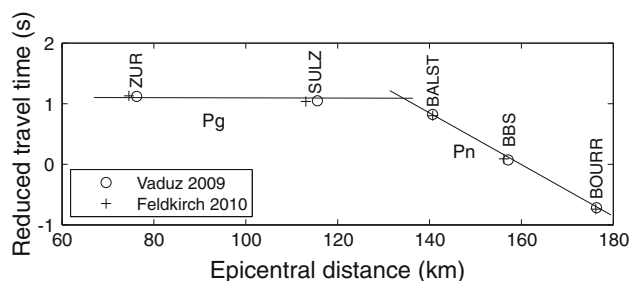


Fig. 8 Comparison of Pg and Pn arrival times of the 2009 Vaduz and the 2010 Feldkirch events recorded at five stations located at practically the same azimuths and distances from the two epicenters. The observations are aligned so that the Pg arrivals coincide, assuming a Pg velocity of 6 km/s. The coincidence of the Pn arrivals demonstrates that the focal depths of the two events must be identical

While this mechanism is substantially different from the normal faulting mechanism of the 2009 Vaduz event (Deichmann et al. 2010), it is almost identical to that of the nearby M_L 3.6 event of Buchs, which occurred in the year 2000 (Baer et al. 2001). The most likely focal depth of all three events is between 3 and 5 km. The relative proximity of thrust and normal faulting mechanisms raises some interesting questions regarding the local state of stress. Such a situation requires either substantial stress variations over a relatively small crustal volume or low levels of differential stress. The fact that earthquakes do occur would imply in the latter case that the faults that slipped must be weak. This in turn points to the likely existence of fluids at pressures above hydrostatic that reduce the effective stress and thus the strength of these faults, favouring the occurrence of earthquakes. A similar case of coexistence of thrust and normal faulting earthquakes at shallow focal depths is also observed in the region of Sarnen (Deichmann et al. 2000b).

3.2.4 Vallorcine

The epicenter of the M_L 3.2 event that occurred in the early morning of December 6 was located near Vallorcine, between Martigny and Chamonix, just south of the border with France. It was clearly felt in the epicentral area. Its location coincides with the aftershock zone of the M_L 4.9 event of September 8, 2005 (Deichmann et al. 2006; Fréchet et al. 2010). It represents the second largest event in a sequence that has been active for many years. In fact, individual events belonging to this sequence can be traced back at least as far as the year 2001 (Fréchet et al. 2010), but activity really picked up in 2005, when 57 events were recorded by the network of the SED. This activity continued with varying intensity in 2006 with 33 recorded events, in 2007 with 16 events, and in 2008, 2009 and 2010 with 17 events each. Of the 17 events recorded in 2010, 13 occurred over the last 4 months of the year. The

magnitudes of the other events in 2010 were between M_L 0.2 and 1.7. With activity still ongoing in the year 2011, an end of this seismic sequence is still not foreseeable.

3.2.5 Piora

During 2010, the AlpTransit network recorded 36 earthquakes with local magnitudes between 0.2 and 1.5 in the Piora region. Of these, 26 earthquakes could be located. The remaining earthquakes were too small and mostly recorded only at station PIORA, but four earthquakes were strong enough to be detected by the SDSNet. Their computed epicenter locations coincide to within a few hundred meters with the trace of the Gotthard base-tunnel, which was under construction at that time. Computed focal depths vary between less than 1 and 2 km and are well constrained by arrivals recorded at station PIORA, at epicentral distances of 1–4 km. The true focal depths are probably even shallower, as the regional 3-D P-wave velocity model used for location may not be appropriate at this small scale.

Activity was spread more or less homogeneously over the entire year. On average, three earthquakes were recorded per month. Their waveforms show a strong similarity within different groups of events, suggesting that several fault patches ruptured repeatedly. All earthquakes occurred north of the Piora zone at distinct locations that correlate with changes in the geology, such as the Corandoni zone that represents the transition from the Piora basin to the Medelser granites. It is noteworthy that seismicity was still occurring at locations where the excavation work finished several months before. Nevertheless, given the close spatial correlation, it is likely that the earthquake activity was induced by the excavation of the Gotthard base-tunnel.

The other small cluster of earthquakes visible in Fig. 2 about 10 km NNW of the Piora events is not in any way related to the tunnel construction. The epicenters are located 2 km W of the trace of the tunnel and the focal depths of 7–9 km are well constrained by stations CUNA and CURA at epicentral distances of 2 and 9 km. All seven events occurred between the 9th and 20th of October, with local magnitudes between 0.3 and 1.6.

3.3 Landslides

In 2010, the national network detected four rock-falls at two locations. The first occurred on September 8, 08:28 local time, when a cliff located above Almens, GR, collapsed and produced a seismic event with an equivalent M_L of 1.2. The other three occurred November 26, 19:58, and November 27, 03:41 and 14:27 local time at the lower end of the Richtitobel, 1.5 km W of Muotathal, SZ. The seismic events had an equivalent M_L of 1.7–1.9, and the total volume of rock involved was estimated to be about 100,000 m³.

4 Discussion

In 2010, a large portion of the seismic activity was concentrated in the Valais and the immediately adjacent regions, while activity in Graubünden was unusually low in comparison. Routinely calculated focal depths for all but 17 events recorded in 2010 are <16 km. All of the deeper hypocenters occurred below the Molasse basin and Jura of northern Switzerland and southern Germany. The deepest event was located at a depth of 31 km, northeast of the Bodensee. The seismic activity induced by the geothermal project in Basel in 2006 and 2007 (e.g. Deichmann and Ernst 2009; Deichmann and Giardini 2009) continued to decrease over the year 2010, and all events but one that have been recorded by the local borehole seismometers were too weak to be recorded by the national broad-band network. Overall, the seismic activity in and around Switzerland was low in 2010, both in terms of the number of events and in terms of the maximum event magnitude. The total number of 19 events with $M_L \geq 2.5$, of which only 7 events were actually located within Switzerland, was substantially below the yearly average of about 24 events over the previous 35 years in this magnitude range.

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