Zeitschrift: Eclogae Geologicae Helvetiae
Herausgeber: Schweizerische Geologische Gesellschaft
Band: 94 (2001)
Heft: 2

Artikel: Earthquakes in Switzerland and surrounding regions during 2000
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DOI: https://doi.org/10.5169/seals-168893

0012-9402/01/020253-12 $1.50 + 0.20/0
Birkhäuser Verlag, Basel, 2001

Eclogae geol. Helv. 94 (2001) 253–264

Earthquakes in Switzerland and surrounding regions during 2000

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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 2000. During this period, 256 earthquakes and 49 quarry blasts were detected and located in the region under consideration. With 37 events with $M_L \geq 2.5$, the seismic activity in the year 2000 was above the average over the last 26 years. However one third of the total number of events are associated with the aftershock sequence of the M_L 4.9 Bormio earthquake of Dec. 29, 1999. Apart from three small earthquake clusters in northwestern Switzerland, most of the earthquakes occurred in Graubünden, in the Rhine Valley of Sankt Gallen as well as in the Valais. Except for seven events beneath the northern foreland, all reliably located earthquakes of the year 2000 occurred in the upper 15 km of the crust. Fault-plane solutions were determined for eight events, which in seven cases were complemented by full-waveform moment tensor inversions of local broadband data.

ZUSAMMENFASSUNG

Dieser Bericht des Schweizerischen Erdbebendienstes stellt eine Zusammenfassung der im Vorjahr in der Schweiz und Umgebung aufgetretenen Erdbeben dar. Im Jahr 2000 wurden im erwähnten Gebiet 256 Erdbeben und 49 Sprengungen erfasst und lokalisiert. Mit 37 Beben mit Magnituden $M_L \geq 2.5$ war die seismische Aktivität überdurchschnittlich. Ein Drittel aller Ereignisse sind jedoch der Nachbebensequenz des Erdbebens von Bormio (M_L = 4.9) vom 29. Dez. 1999 zuzuordnen. Abgesehen von drei kleinen Erdbeben Häufungen in der Nordwestschweiz sind die meisten Erdbeben des Jahres 2000 in Graubünden, im Sanktgaller Rheintal sowie im Wallis zu verzeichnen. Mit Ausnahme von sieben Ereignissen unter dem Jura und der Molasse, ereigneten sich alle Beben in den oberen 15 km der Erdkruste. Für acht Ereignisse sind Herdflächenlösungen konstruiert worden, welche in sieben Fällen durch Momenten Tensoren aus der Wellenforminversion von lokalen Breitbanddaten ergänzt werden konnten.

RESUME

Le présent rapport du Service Sismologique Suisse résume l'activité sismique de l'année écoulée, en Suisse et dans les régions limitrophes. En 2000, 256 tremblements de terre ont été détectés et localisés dans la région considérée. De plus, 49 événements ont été identifiés comme des tirs de carrière. Avec 37 événements de magnitude $M_L \geq 2.5$ l'activité sismique de l'année 2000 se situe au dessus de la moyenne sur les 26 dernières années. Toutefois, un tiers du nombre total des événements appartient à la séquence de répliques du séisme de magnitude M_L 4.9 de Bormio du 29 Décembre 1999. Mis à part trois petits groupes de séismes dans le nord-ouest de la Suisse, la plupart des séismes se sont produits dans les Grisons, dans la vallée du Rhin de Saint Gall, ainsi que dans le Valais. En dehors de sept événements sous l'avant-pays nord, tous les séismes localisés de manière fiable durant l'année 2000 sont situés dans les 15 premiers kilomètres de la croûte. Des mécanismes au foyer ont été déterminés pour huit événements, qui dans sept cas ont été complétés par l'inversion du tenseur du moment sismique avec modélisation des formes d'onde d'enregistrements large-bande locaux.

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 current seismic hazard map of Switzerland (Sägesser & Mayer-Rosa 1978). With the advent of routine data processing

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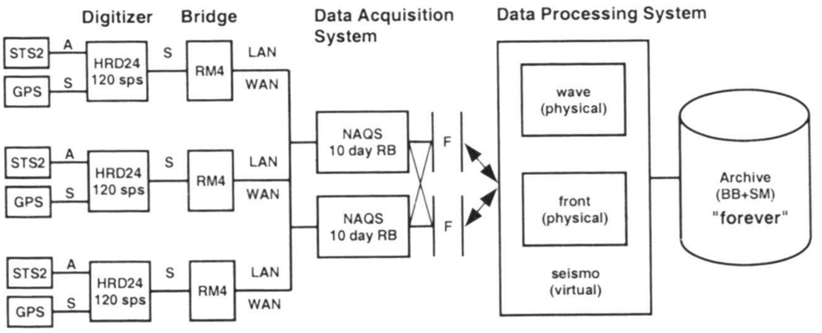

Fig. 1. Schematic diagram of the new digital data acquisition system. A and S: analog and serial transmission; LAN and WAN: local and wide area communication networks; F: firewall; seismo, front and wave: high-availability data processing computer system.

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; Deichmann et al. 1998; Baer et al. 1999; Deichmann et al. 2000a). In addition, numerous studies covering different aspects of the recent seismicity of Switzerland have been published in the scientific literature (for an overview and additional references see, e.g. Pavoni, 1984; Deichmann, 1990; Deichmann & Baer 1990; Pavoni & Roth 1990; Deichmann, 1992; Rüttener, 1995; Rüttener at al. 1996; Pavoni et al. 1997; Deichmann et al. 2000b).

Seismic stations in operation during 2000

The Swiss Seismological Service operates two separate nationwide seismic networks, a high-gain seismometer network and a low-gain accelerograph network. The former is designed to continuously monitor the ongoing earthquake activity down to magnitudes well below the human perception threshold (Baer 1990), whereas the latter is principally aimed at engineering concerns and thus only records so-called strong motions (Smit 1998). The observations presented here are based mainly on the high-sensitivity monitoring network. The data that has been collected until November 2000 by the strong-motion network is documented separately (Mattle 2000) and an additional report for the following time period is in preparation.

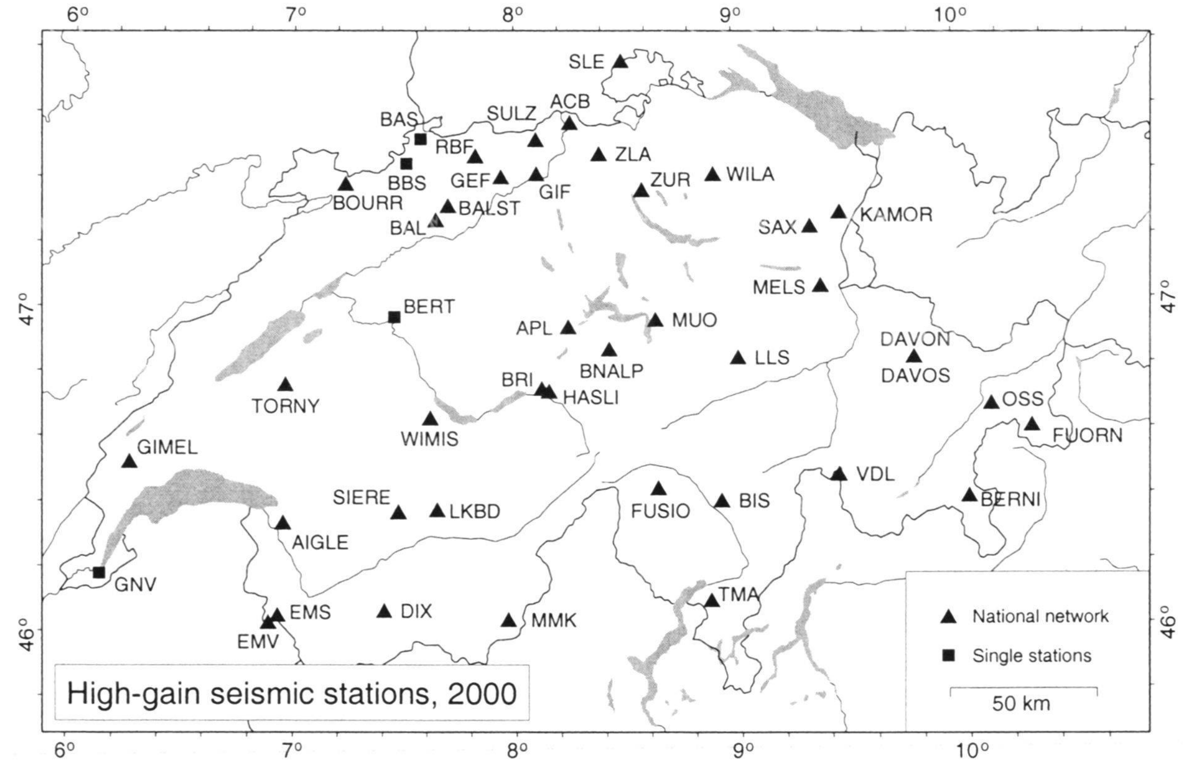

Fig. 2. Seismograph stations in Switzerland operational at the end of 2000.

Tab. 1. Seismograph stations operational at the end of 1998. Instrument types: SP = short period, BB = broad band, 1 = vertical component only, 3 = vertical and horizontal components, 4 = additional low-gain vertical component channel.

National telemetry network recorded in Zürich			
Code	Station name	Type	Remarks
ACB	Acheberg, AG	SP-3	
AIGLE	Aigle, VD	BB-3	
APL	Alpnach, OW	SP-4	
BAL	Balsthal, SO	SP-4	
BALST	Balsthal, SO	BB-3	
BERNI	Bernina, GR	BB-3	
BNALP	Bannalpsee, NW	BB-3	
BIS	Biasca, TI	SP-3	
BOURR	Bourrignon, JU	BB-3	
BRI	Brienz, BE	SP-4	
DAVOS	Davos, GR	SP-4	
DAVON	Davos, GR	BB-3	
DIX	Grande Dixence, VS	SP-1, BB-3	dam site
EMS	Emosson, VS	SP-1	
EMV	Vieux Emosson, VS	SP-1, BB-3	
FUORN	Ofenpass, GR	BB-3	
FUSIO	Fusio, TI	BB-3	
GEF	Geissflue, SO	SP-1	
GIF	Gisliflue, AG	SP-1	
GIMEL	Gimel, VD	BB-3	
HASLI	Hasliberg, BE	BB-3	
KAMOR	Kamor, SG	BB-3	
LKBD	Leukerbad, VS	BB-3	
LLS	Linth-Limmern, GL	SP-3, BB-3	dam site
MELS	Mels, SG	BB-3	
MMK	Mattmark, VS	SP-3, BB-3	dam site
MUO	Muotathal, SZ	SP-1, BB-3	
OSS	Ova Spin, GR	SP-1	dam site
RBF	Rickenbacherflue, BL	SP-1	
ROM	Romont, FR	SP-4	coloc. TORNY
SAX	Säntis, AI	SP-3	
SIERE	Sierre, VS	SP-4	
SLE	Schleitheim, SH	SP-3	
STG	Saint Georges, VD	SP-3	coloc. GIMEL
SULZ	Cheisacher, AG	BB-3	
TMA	Monte Tamaro, TI	SP-3	
TORNY	Torny, FR	BB-3	
VDL	Valle di Lei, GR	SP-1, BB-3	dam site
WIL	Wil, SG	SP-4	coloc. WILA
WILA	Wil, SG	BB-3	
WIMIS	Wimmis, BE	BB-3	
ZLA	Zürich-Lägern, ZH	SP-1	
ZUR	Zürich-Degenried, ZH	BB-3	
Single stations			
Code	Station name	Type	Remarks
BAS	Basel, BS	SP-3	digital (LED)
BBS	Basel-Blauen, BL	SP-1	telemetry (LED)
BERT	Bern, BE	SP-3	paper records
GNV	Geneva, GE	SP-1	paper records

The new Swiss Digital Seismic Network SDSNet

Since 1998, the configuration of the national high-gain network is undergoing a fundamental change. The analog data transmission technology of the mid-seventies, when the national telemetry network was first set up, poses severe restrictions on the dynamic range and frequency bandwidth of the recorded seismic data. With the advent of modern digital technology and broadband sensors, these restrictions can now be overcome. As a consequence, the Swiss Seismological Service has begun to modernize its entire network. The block diagram in Figure 1 shows the basic configuration of the new system. The existing short-period seismometers will be replaced by three-component STS-2 broad-band instruments. These sensors feature nearly constant sensitivity to ground velocity over the range from 120 s to 50 Hz. The signals are digitized at the remote recording sites by a three-channel Nanometrics HRD24 digitizer. The initially oversampled signals are decimated to a sampling rate of 120 Hz using a digital anti-alias filter with a low-pass corner frequency at 48 Hz, which allows the entire frequency range of the STS-2 seismometers to be exploited. Time synchronization of the digitizers is provided by a GPS receiver. The HRD24 digitizers are equipped with 4 Mb of solid state memory, which is sufficient to store 2 hours of three-channel data at the recording site. From the digitizer the signals are serially transmitted in packets of 1 to 2 seconds, depending on the compression efficiency, to a RM4 bridge. This device wraps the serial packets into UDP/IP packets, which can be sent to a maximum of four IP addresses, thus no point-to-point connection needs to be maintained. The serial link between the HRD24 and the RM4 can be either a short copper or fiber-optic cable, or a modem-modem connection via telephone or radio link. This provides great flexibility in station site selection. For most stations, the UDP/IP packets are sent to the recording site via the computer network of the Swiss federal government (BV-net), where the signals are recorded by the Nanometrics NAQS32 data acquisition software on two PC's. Both recording systems store the seismic signals locally in a 10-day circular disk buffer and continuously monitor the incoming signals with an event detection algorithm based on short-time/long-time (STA/LTA) amplitude ratios in several definable frequency bands. From these computers, which reside inside the federal government's secured computer network, the signals are retrieved by the data processing system (DPS) of the Seismological Service through firewalls operated by the Federal Office of Information Technology and Telecommunication (Bundesamt für Informatik und Telekommunikation, BIT). At the central data archiving site in Zürich, the DPS stores the continuous waveforms in 5-minute time-segments at the original sampling rate and in 24-hour blocks at 1 sample/second. Event detections of the NAQS-System are transferred immediately to the DPS, where the corresponding waveforms are automatically processed for source location and magnitude determination.

A complete list of the seismic stations in operation at the end of 2000 and an updated station map are given in Table 1 and Figure 2. Wherever possible, the new instruments are installed at the sites of the old analog stations. In some cases, because of inadequate infrastructure or unfavourable noise conditions at low frequencies, the old sites will have to be abandoned in favour of more suitable locations. The new sites have been selected on the basis of extensive test measurements with portable recorders equipped with STS-2 seismometers. In the

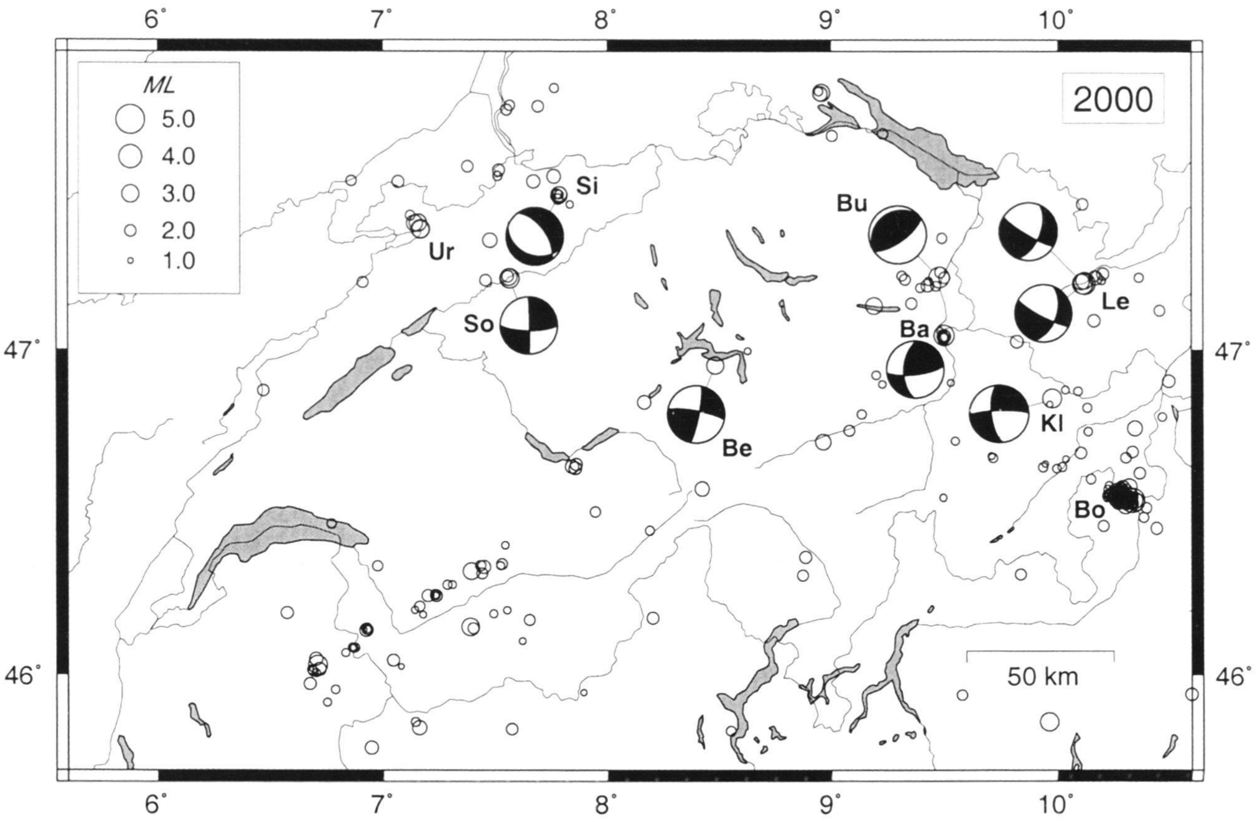

Fig. 3. Epicenters and focal mechanisms of earthquakes recorded by the Swiss Seismological Service during 2000. Epicenters of earthquakes mentioned in the text are Bad Ragaz, Feb. 22 (Ba), Beckenried, Jul. 17 (Be), Bormio, all year (Bo), Buchs, Mar. 4 (Bu), Klosters, Feb. 22 (Kl), Lech, Jun. 6 and 10 (Le), Sissach, Jun. 20 (Si), Solothurn, Jul. 10 and Nov. 13 (So) and Saint Ursanne, Mar. 28 and Apr. 6 (Ur).

course of the year 2000, four new sites have been added to the network (FUORN, MELS, TORNY and WIMIS), thus increasing the total number of broad-band stations to 24. Of the stations comprising the local network in northern Switzerland (e.g. Deichmann et al. 2000a, 2000b), TSB and ENB were closed, and CHE, which has been renamed SULZ, was converted to a broad-band station with an STS-2 seismometer and a nine-channel digitizer. The additional 6 channels are used to digitize the signals of the three-component station ACB as well as of the 3 single-component stations RBF, GEF and GIF. All nine channels are transmitted to the central recording site in Zürich along with the data from the national network. By the end of the year 2001, also station SLE will be equipped with a broad-band instrument and two new sites will be operational west of Lake Neuchâtel and at the southern tip of Canton Ticino.

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, from the Zentralanstalt für Meteorologie und Geodynamik in Vienna, from the SISMALP array operated by the Laboratoire de Géophysique Interne et Tectonophysique, Observatoire de Grenoble, from the Laboratoire de Détection et Géophysique in Bruyères-le-Châtel, from the RENASS array operated by the Ecole et Observatoire des Sciences del Terre in Strasbourg, from the Istituto Nazionale di Geofisica in Rome and from the Istituto di Geofisica, Università di Genova.

Data analysis

Preliminary hypocenter locations are determined on the basis of an automatic arrival time picker (Baer & Kradolfer 1987), but final arrival times and locations are subsequently reviewed by a seismologist. Locations are calculated either with a modified version of the widely used HYPO-71 algorithm originally developed by Lee & Lahr (1972) or with a grid search algorithm, which can use any earth model for which the travel times of seismic waves can be computed. The seismic velocity models consist of three horizontal crustal layers with constant velocities overlying a mantle half-space. The models account

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
20000.01.10 05:30:09	46.149	7.389	596/111	9	3.1	A	Euseigne, VS
20000.02.09 16:01:17	46.581	10.318	821/163	15	2.7	B	Bormio, I
20000.02.22 22:45:33	46.851	9.975	793/192	4	3.3	B	Klosters, GR
20000.02.23 04:07:07	47.044	9.501	757/212	7	3.6	A	Bad Ragaz, SG
20000.03.04 15:43:20	47.221	9.480	755/232	3	3.6	B	Buchs, SG
20000.03.26 05:13:30	46.322	7.393	596/130	10	2.9	A	Anzere, VS
20000.03.28 03:09:39	47.385	7.141	578/248	1	2.8	A	Saint Ursanne, JU
20000.03.28 05:29:50	47.386	7.157	579/248	1	3.0	A	Saint Ursanne, JU
20000.03.28 05:33:02	47.366	7.168	580/246	1	3.0	A	Saint Ursanne, JU
20000.04.03 00:28:05	46.551	10.320	821/159	14	2.9	B	Bormio, I
20000.04.06 00:43:18	47.367	7.168	580/246	1	3.2	A	Saint Ursanne, JU
20000.04.06 17:40:37	46.539	10.333	822/158	15	4.2	B	Bormio, I
20000.04.11 12:09:53	46.541	10.313	820/158	13	2.5	B	Bormio, I
20000.04.19 21:06:43	47.333	7.478	603/242	21	2.5	A	Vermes, JU
20000.05.03 19:04:11	45.833	7.160	578/ 76	10	2.5	C	Gr.S.Bernard, I
20000.05.17 05:40:38	46.537	10.323	821/158	12	2.6	B	Bormio, I
20000.05.28 11:22:20	46.534	10.348	823/158	15	3.0	B	Bormio, I
20000.06.03 15:14:10	47.202	10.122	803/231	3	3.8	B	Lech, A
20000.06.03 19:41:35	47.207	10.107	802/232	3	2.7	B	Lech, A
20000.06.09 05:06:06	46.539	10.304	820/158	15	3.2	B	Bormio, I
20000.06.10 05:51:02	47.202	10.114	803/231	3	3.6	B	Lech, A
20000.06.20 06:18:49	47.469	7.786	626/258	18	2.9	A	Sissach, BL
20000.06.20 06:25:33	47.472	7.788	626/258	18	2.6	A	Sissach, BL
20000.06.24 00:24:08	46.541	10.282	818/158	13	2.5	B	Bormio, I
20000.07.10 02:48:47	47.222	7.561	609/230	10	2.9	A	Solothurn, SO
20000.07.29 07:14:19	45.852	9.961	796/ 81	14	3.2	D	Lovere, I
20000.08.13 01:07:03	47.772	8.951	713/292	10	2.5	C	Radolfzell, D
20000.08.17 07:14:08	46.952	8.484	680/201	10	3.0	A	Beckenried, NW
20000.08.19 08:37:25	46.030	6.708	543/ 98	9	3.3	B	Haute Savoie, F
20000.08.24 04:58:57	47.775	8.957	714/293	10	3.0	C	Radolfzell, D
20000.09.09 02:02:07	47.211	10.121	803/232	3	2.9	B	Lech, A
20000.10.08 22:38:44	46.539	10.341	823/158	11	2.9	B	Bormio, I
20000.10.31 19:10:24	46.759	10.344	822/183	10	2.6	C	S'Charl, GR
20000.11.13 16:30:40	47.218	7.565	610/230	10	3.4	A	Solothurn, SO
20000.11.30 08:34:22	46.574	8.424	676/158	14	2.5	B	Furkapass, UR
20000.12.21 06:30:00	47.134	9.189	733/222	1	2.9	B	Walensee, SG
20000.12.25 10:18:02	46.717	8.963	717/175	9	2.7	B	Trun, GR

for differences between the near-surface geology in the Alps and foreland as well as, in a simplified way, for the large depth variation of the crust-mantle boundary. In addition, calculated travel times are corrected for differences in station elevation.

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

The newly installed broadband stations allow the use of state-of-the-art waveform modeling techniques to study the source parameters of some larger earthquakes in Switzerland. We invert complete three-component waveforms recorded at local to regional distances for the seismic moment tensor by minimizing the least squares misfit between observed and synthetic seismograms. Strike, dip, rake, and seismic moment follow directly from the moment tensor formulation. Earthquake depth is found by repeating the inversion for several trial depths. The inversion is performed at relatively low frequencies; thus, a simple one-dimensional velocity-depth model is sufficient to calculate synthetic discrete wavenumber seismograms (Bouchon 1982) for all stations. The model consists of a 35 km thick continental crust with an average ratio between the P- and S-wave velocities of 1.73. Using three-component data and low-frequency waveforms provides robust and stable source parameter estimates; moderate changes in the crustal model affect the moment tensor solutions only slightly. We refer to Nabelek & Xia (1995) and Braunmiller et al. (1995) for a more detailed description of the method and to Deichmann et al., 2000a for an illustration of the application to a local earthquake in Switzerland.

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

From the records of the short-period stations, magnitudes are determined from the maximum amplitudes of the vertical components of ground velocity. In order to obtain the local magnitude (M_L), these amplitude values and the corresponding period are converted to what they would be if the signals had been recorded by a standard Wood-Anderson seismograph. The broad-band signals, on the other hand, are digitally filtered to simulate the response of a Wood-Anderson seismograph, and M_L is then determined directly from the maximum amplitudes of the resulting horizontal seismograms. The attenuation with epicentral distance is accounted for by an empirically determined relation (Kradolfer & Mayer-Rosa 1988). The final magnitude corresponds to the median value of all individual station magnitudes.

Seismic activity during 2000

Overview

During 2000, the Swiss Seismological Service detected and located 256 earthquakes in the region shown in Figure 3. Based on such criteria as the time of occurrence, the location, the sig-

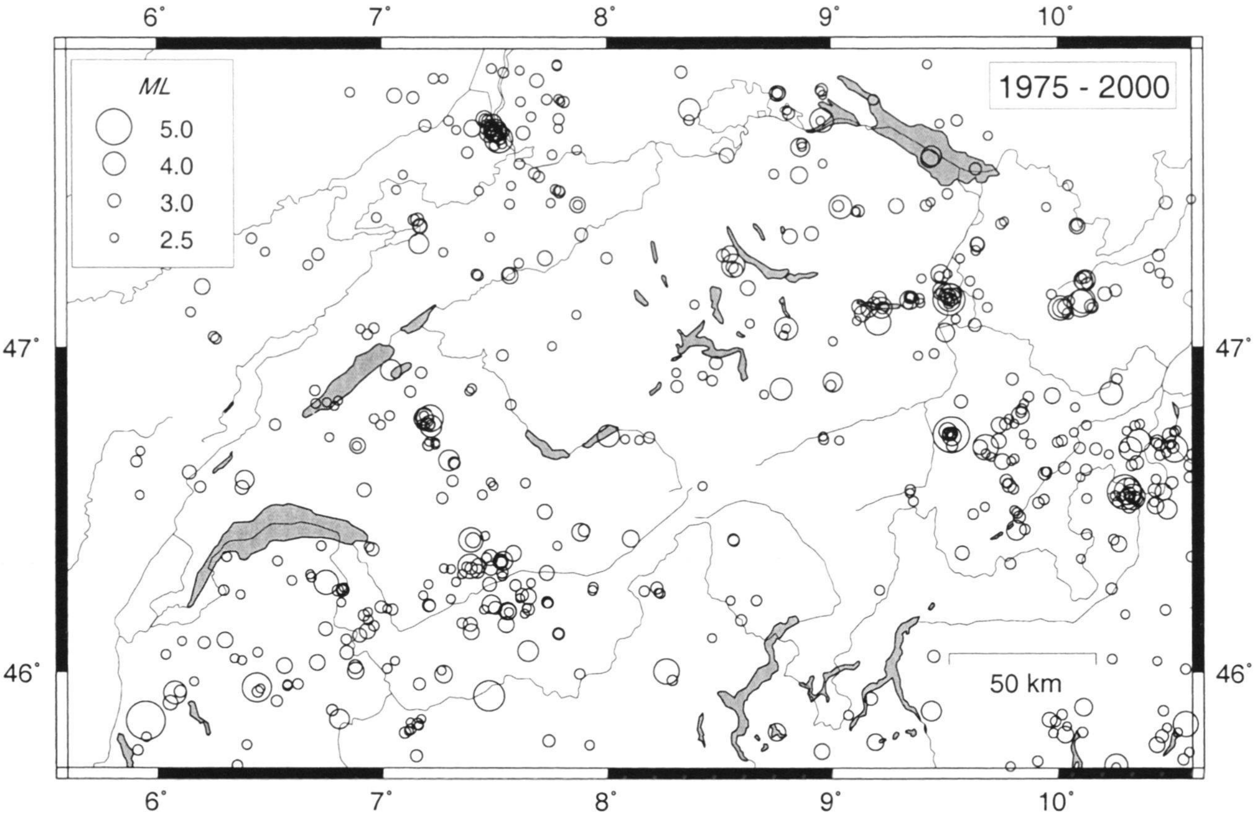

Fig. 4. Epicenters of earthquakes with Magnitudes M_L ≥ 2.5, during the period 1975–2000.

nal character or direct information, 49 additional seismic events were identified as quarry blasts.

Magnitude values of the events recorded in 2000 range between M_L = 0.8 and 4.2. The events with $M_L \geq 2.5$ and the criteria used to assign the quality rating for the given locations as well as the corresponding estimated location accuracy are listed in Tables 2 and 3. Where available, the epicentral coordinates and focal depths given in Table 2 are based on the results that include additional data from foreign networks and on 2-D ray-tracing. The locations of all earthquakes with $M_L \geq 2.5$ recorded in Switzerland and surroundings since 1975 are shown on the epicenter map in Figure 4.

The fault-plane solutions with first-motion directions are shown in Figures 5 and 6, and the corresponding parameters are listed in Table 4 together with the results of the moment tensor inversions. In what follows, we present the highlights of the seismic activity observed during 2000.

Significant earthquakes of 2000

Bormio

More than one third of all the earthquakes recorded in Switzerland and surroundings during the year 2000 are aftershocks of the M_L 4.9 earthquake that occurred on Dec. 29th 1999 on the Swiss-Italian Border between Val Müstair and Bormio. Routine locations of these 88 events cluster in an area of 12 × 10 km. Being situated at the periphery of the seismic network, the locations are poorly constrained, so that the apparent scatter is certainly larger than the area actually occupied by these events. Among these aftershocks is also an event with M_L = 4.2, that occurred on April 6th and that is the strongest event recorded in the year 2000 in Switzerland, as well as 8 other events with magnitudes between M_L = 2.5 and 3.2 (Table 2). A comprehensive analysis of the 1999 mainshock and this aftershock sequence is still underway.

Klosters

The February 22nd Klosters earthquake was the first of three events with a magnitude around 3.5 to occur within a period of only 10 days at the beginning of the year in eastern Switzerland. Its epicenter was located about 8 km east of Klosters and the earthquake reached a magnitude M_L of 3.3. The routinely calculated focal depth is 6 km, but the closest station (DAVOS) is 14 km away, so that this value is not well constrained. Travel time differences of PmP-Pg at stations in central Switzerland are matched best for a depth of 4 km. The agreement between the focal mechanism resulting from the first-motion analysis and that from the waveform inversion is not perfect. In addition, neither result is free from internal inconsistencies: three polarities near the nodal planes are mismatched in the faultplane solution and only the transverse components of the seismograms are well modeled by the theoretical waveforms. Nevertheless, a significantly different result from the strike-slip mechanism shown in Figure 5 is not compatible with the observations. Moreover, the NW-SE and NE-SW orientation of the P- and T-axes is typical for this region (Roth et al. 1992; Pavoni et al. 1997).

Bad Ragaz

Only 5 hours after the Klosters event, a magnitude M_L 3.6 earthquake occurred below the Fläscherberg, 4 km north of Bad Ragaz. It was well recorded by high-gain stations out to distances of more than 300 km and by six of the local strong-motion stations. This event was associated with one foreshock (M_L = 2.0) on January 13th and with five aftershocks ($1.2 \le M_L \le 2.2$) distributed over the following eight months. With station MELS at only 9 km from the epicenter, a dense azimuthal station coverage and a good match of the theoretical Pn travel times with the observed arrivals at stations in northern Switzerland, the focal depth of 7 km is well constrained. The impulsive signal character of both P- and S-waves and the clear records even at large distances are an additional qualitative indication that the hypocenter must be located in the crystalline basement below the thick and complex sedimentary sequence known to exist in this region (e.g. Stäuble & Pfiffner 1991). The basically strike-slip mechanism is documented by both the first-motion analysis and by the waveform inversion (Fig. 5). Its orientation is similar to that of the Klosters event.

Buchs

The last of the three earthquakes to jolt eastern Switzerland within 10 days occurred on March 4th. Its epicenter was located about 7 km north of Buchs in the Rhine Valley of Sankt Gallen and its magnitude was 3.6. Although it was possible to improve the azimuthal station coverage by using data from stations DAVA in Austria and UBR in southern Germany, the location is not optimally resolved. At most stations, S-wave travel-time residuals remain very high, so that S-arrivals were not used for the location. Thus also the focal depth is poorly constrained by the routine location procedure. However, the poor match of observed and calculated S-wave travel times suggests that the hypocenter is located in the near-surface sedimentary layers, which are laterally highly heterogeneous in this area and for which the V_p/V_s ratio differs significantly from the standard velocity model used in the location procedure. This conclusion is supported also by the surface-wave dominated signal character observed at several stations, by 2-D ray tracing and by the waveform inversions. In addition, assuming that the hypocenter was located in the crystalline basement requires take-off angles of the rays at the source which lead to an inconsistent distribution of P-wave polarities in the faultplane solution. An assumed focal depth of 2–3 km places the source more or less at mid-depth within the sedimentary sequences in the epicentral region and is consistent with all observations. The resulting focal mechanism corresponds to almost pure thrust faulting (Fig. 5). From the first-motion analysis the strike and dip of the steep nodal plane is well constrained, whereas the strike of the flat nodal plane is not. The preferred solution corresponds to an intermediate result, which also matches the waveform inversion almost perfectly. Although well-constrained thrust-fault mechanisms are rare in Switzerland, some have been found in the uppermost crust of the Helvetic domain in the region of Sarnen (Deichmann et al. 2000b) and in the Walensee area (Roth et al. 1992; Pavoni et al. 1997). The orientation of the P-axis of the Buchs mechanism agrees well with the NW-SE direction of maximum crustal shortening observed in the other focal mechanisms in Figure 5 and deduced from earlier studies (Roth et al. 1992; Pavoni et al. 1997).

Saint Ursanne

During the early morning hours of March 28th, the population of Saint Ursanne were jolted by a series of four earthquakes with magnitudes as high as 3.0. Ten days later, a fifth earthquake with M_L = 3.2 occurred at practically the same location. That all five events have almost identical hypocentral locations and focal mechanisms is evidenced by the high similarity of the observed signals. The routine location procedure results in a focal depth of 6–7 km, which corresponds to a source in the upper crystalline crust. However, the seismograms recorded at most stations in northern Switzerland and adjacent regions of France feature exceptionally strong and long-lasting surface wave codas, that are usually only observed from quarry blasts at the Earth's surface. Thus a shallow source within the Mezozoic sedimentary cover of the Jura Mountains is much more likely. Based on this argument, the focal depth given in Table 2 has been fixed to 1 km, but this needs to be verified by a more thorough analysis that is not yet completed.

Lech

Another remarkable series comprising eight earthquakes occurred between the beginning of June and the end of October near the town of Lech, north of the Arlberg Pass in Austria. The two strongest events attained magnitudes M_L of 3.6 and 3.8. Routinely calculated focal depths are poorly constrained. However, based on the same observations and arguments as cited for the Buchs event, all evidence suggests that the hypocenters must be situated in the near-surface sedimentary sequences. The strike-slip focal mechanisms of the two strongest events differ only little from each other (Fig. 5). Both the first-motion analysis and the waveform inversion give subhorizontal, ENE-WSW oriented T-axes, whereas the NNW-SSE oriented P-axes obtained from the first-motion analysis are slightly more inclined than those from the waveform inversion.

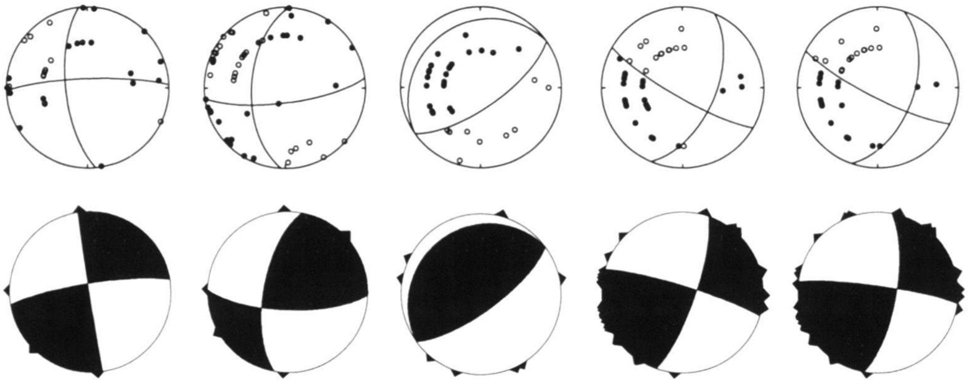

Fig. 5. Faultplane solutions based on first-motion polarities and moment tensors based on full-waveform inversions of the earthquakes in eastern Switzerland and the adjacent area of Austria (lower hemisphere, equal area projection). In the fault-plane solutions (above), solid circles correspond to compressive first motion (up) and empty circles to dilatational first motion (down); on the moment tensors (below), triangles show the station locations.

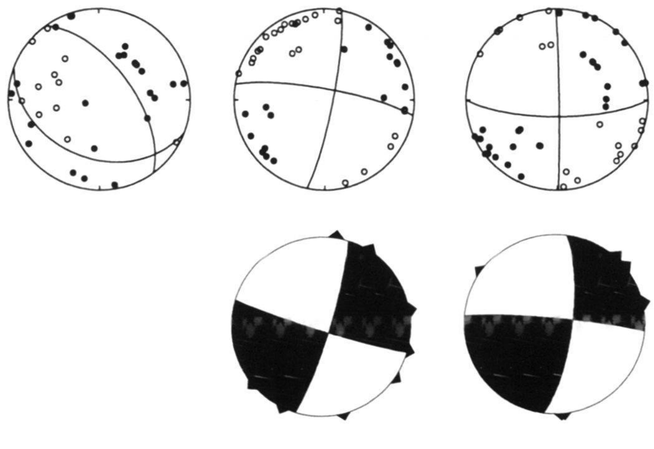

Fig. 6. Faultplane solutions based on first-motion polarities and moment tensors based on full-waveform inversions of the earthquakes in central and northern Switzerland.

Sissach

The two Sissach earthquakes listed in Table 2 are part of a sequence of five events with magnitudes M_L between 1.5 and 2.9, which occurred on June 20th within less than four hours. The focal depth of 18 km obtained from 2-D ray-tracing differs only slightly from the 16 km determined routinely and falls within the depth range of numerous other hypocenters in northwestern Switzerland.

A focal mechanism solution for the strongest event is available only from first-motion analysis and the result is not entirely free of inconsistencies: two mismatched polarities are from observations close to a nodal plane and could be due to mispicks or errors in take-off angle. The third mismatch concerns the positive first-motion polarity in the middle of the dilatational quadrant, observed at station RBF. This station is situated practically at the epicenter and the signals are completely saturated starting right at the first break. The P-onset observed at station RBF for the second event starts with a very slight downward motion before rising as impulsively as for the first event. Considering that the signals recorded at all other stations are practically identical for these two events, it is likely that the mismatched polarity at RBF is a result of instrument malfunction due to severe signal saturation. Despite these inconsistencies, the resulting normal-faulting mechanism is well constrained and the NE-SW orientation of the T-axis is typical for the focal mechanisms observed in northwestern Switzerland (e.g. Deichmann et al. 2000b).

The signals are similar enough to determine high-precision relative locations of the hypocenters based on signal cross-correlations only for the first two events. The resulting locations suggest that the SW dipping nodal plane could correspond to the active fault plane, but the results are not entirely unambiguous.

Beckenried

The hypocenter of the M_L 3.0 earthquake, which ocurred on August 17th near Beckenried on the south shore of the Vierwaldstättersee, was located at a depth of about 10–12 km. With three azimuthally well distributed stations at epicentral distances of 10–17 km and with impulsive S-wave arrivals, the location is well constrained. This focal depth places the Beckenried quake with certainty in the crystalline basement, in contrast to most other well-constrained earthquakes in central Switzerland, which are located in the overlying Helvetic Nappes (Deichmann et al. 2000b). However, the orientation of the focal mechanism (strike-slip with NW-SE oriented P-axis, Fig. 6) matches the general deformation direction deduced for central Switzerland from the shallower events (Deichmann et al. 2000b).

Solothurn

The magnitude M_L 3.4 earthquake of November 13th occurred 2.5 km north of Solothurn and was clearly felt by the

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
Klosters	2000.02.22 22:46	4	M_L3.3	174/68/-010	268/81/-158	133/22	039/09
		6	M_w3.1	171/89/-009	261/81/-179	126/07	217/06
Bad Ragaz	2000.02.23 04:07	7	M_L3.6	183/56/ 018	083/75/ 145	137/12	038/35
		6	M_w3.1	190/65/ 020	092/72/ 154	142/05	049/31
Buchs	2000.03.04 15:43	3	M_L3.6	235/20/ 090	055/70/ 090	145/25	325/65
		2	M_w3.6	234/17/ 090	054/73/ 090	144/28	324/62
Lech	2000.06.03 15:14	3	M_L3.8	023/57/-012	120/80/-146	347/31	247/15
		6	M_w3.6	019/77/ 007	287/83/ 167	334/04	243/14
Lech	2000.06.10 05:51	3	M_L3.6	019/53/-013	117/80/-142	345/33	243/18
		6	M_w3.4	010/71/ 007	278/83/ 161	326/08	233/18
Sissach	2000.06.20 06:19	18	M_L2.9	111/35/-118	324/60/-072	273/70	041/13
Beckenried	2000.08.17 07:14	10	M_L3.0	280/80/ 172	011/82/ 010	145/01	235/13
		10	M_w2.9	107/86/-172	017/82/-004	332/09	242/03
Solothurn	2000.11.13 16:31	10	M_L3.4	090/75/-178	359/88/-015	313/12	045/09
		10	M_w3.2	275/85/ 164	007/74/ 006	322/07	230/15

Tab. 4. Focal mechanism parameters based on first-motion polarities (first line with M_L) and full-waveform inversion (second line with M_w, where available).

local population. This event was the second one of almost two identical events. The first occurred 4 months earlier on July 10th and had a magnitude of 2.9. A smaller aftershock (M_L 2.0), which occurred on November 15th at the same location, produced slightly different waveforms from those of the other two. The focal depth of about 10 km is constrained by a good azimuthal station coverage and a minimal epicentral distance of only 9 km and by two-dimensional raytracing of the travel-time differences between Pg and PmP at several stations, as well as full waveform modeling. The results of the analysis of the first motion distribution and of the full waveform inversion are practically identical, giving a focal mechanism that is almost pure strike-slip with N-S and E-W oriented nodal planes and with P- and T-axes that reflect the known orientation of the stress field in northern Switzerland (Deichmann et al. 2000b). Attempts to identify the active fault plane by waveform correlations and precise relative locations failed: the hypocenters of the first two events were located practically below each other with a separation of only 50 m, so that within the remaining location uncertainties they could lie on either of the two nodal planes, and the waveforms of the third event did not match those of the previous events closely enough to obtain a sufficient number of usable correlation results.

Non-seismic events

Airplane crash near Zürich Airport

On January 10th, an airplane crashed shortly after take-off from the airport of Zürich. The impact was sufficiently violent to produce a seismic signal that was recorded clearly at station ZLA, 6.37 km away (Fig. 7). As an application of forensic seismology on behalf of the authorities investigating the cause of the accident, the exact time of the impact was determined from the arrival times of the P- and S-waves at ZLA.

Ice avalanches of Allalin Glacier

On July 30th at 7:52 local time, a massive ice avalanche broke loose from the tongue of Allalin Glacier, in the Valais. The next morning at 8:23, an even larger ice mass broke off, the debris of which reached the valley floor close to the west buttress of the Mattmark hydroelectric dam. The total volume of the two ice avalanches was estimated at more than $10^6 m^3$ (Funk & Bösch 2001). The vibrations caused by the two avalanches saturated the short-period instruments of station MMK and MMK2, installed at either side of the Mattmark dam, and were clearly recorded by the broad-band sensors located in the east buttress of the dam. These broad-band records provided useful information regarding the exact time and duration of the two events (Fig. 8).

Rupture of the pressure shaft at Cleuson-Dixence

On December 12th, shortly after shutdown of the turbines at the hydroelectric powerplant of Bieudron, the pressure shaft coming from Lac des Dix ruptured. The volume of water that escaped from the leak was sufficient to trigger a massive landslide, which demolished several cottages and killed three people near the town of Nendaz. Seismic signals associated with this accident were recorded by the seismometers installed at Grande Dixence dam. As can be seen in the seismogram recorded by the N-S component of the broad-band sensor in-

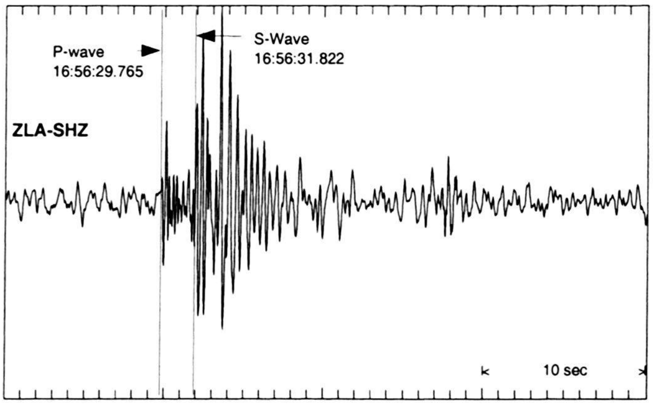

Fig. 7. Signal of the airplane crash of January 10th near Zürich airport recorded at station ZLA. Time is UTC.

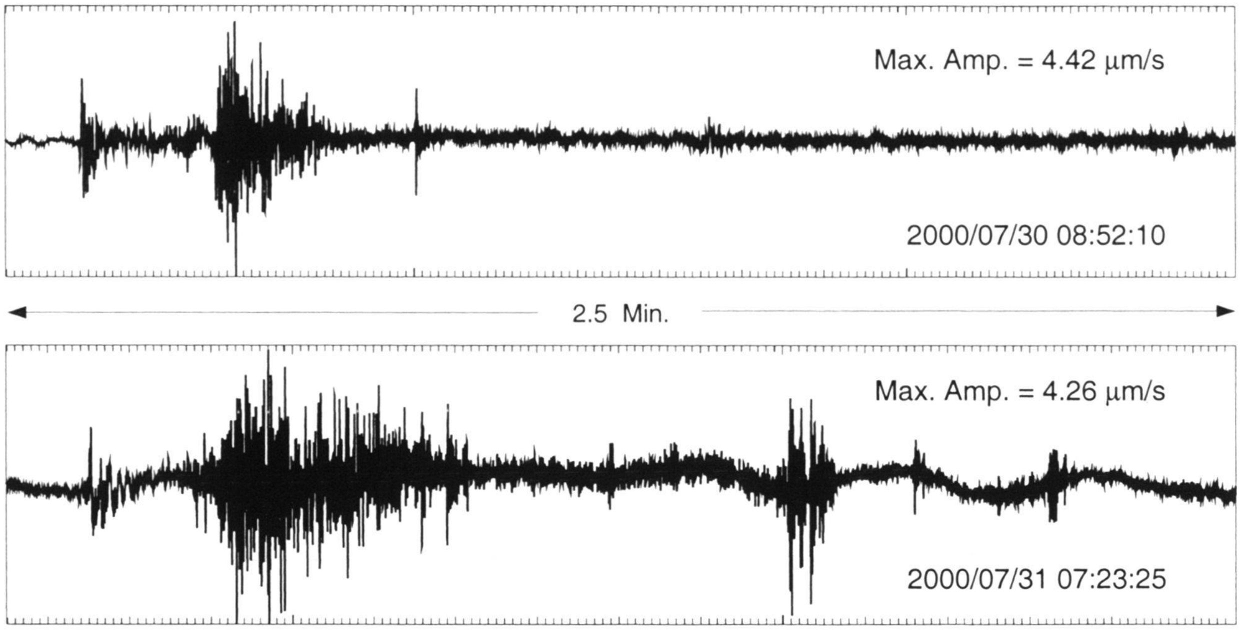

Fig. 8. Signals of the two ice avalanches from Allalin Glacier recorded by the E-W component of the broad-band sensor installed in the east buttress of the Mattmark dam (station MMK). Time is local summer time.

stalled in the west buttress of the dam (Fig. 9), the signals lasted for more than a minute and are highly monochromatic, with a dominant frequancy of 2 Hz. Given this signal character and a distance of about 15 km from the location of the rupture, the signals recorded at the Grande Dixence dam most likely correspond to the response either of the dam itself or of the hydrodynamic system to a protracted source of vibrations, rather than to the rupture itself or to the ensuing landslide.

Discussion

Figure 4 shows the epicenters of the earthquakes with $M_L \geq 2.5$, which have been recorded in Switzerland and surrounding regions over the period of 1975–2000. The chosen magnitude threshold of 2.5 ensures that the data set is complete for the given period and that the number of unidentified quarry blasts and of badly mislocated epicenters is negligible. These events represent about 10% of the total number of events detected during that time period in the same area.

Averaged over the last 26 years, the earthquakes shown in Figure 4 are equivalent to about 24 events with $M_L \geq 2.5$ and about 7 events with $M_L \geq 3$ per year. With 37 events with $M_L \geq 2.5$ and 17 events reaching $M_L \geq 3$, the seismic activity in 2000 was thus above the average over the last 26 years for earthquakes in these magnitude ranges. However, it is important to note that one third of the total number of events and

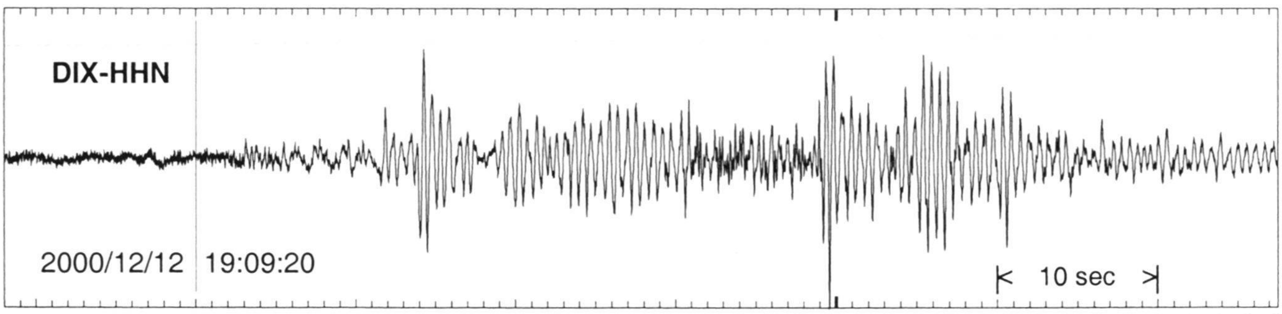

Fig. 9. Signal associated with the rupture of the Cleuson-Dixence pressure shaft on December 12th, recorded by the NS component of the broad-band seismometer installed in the east buttress of the Grand Dixence dam (station DIX). Time is UTC.

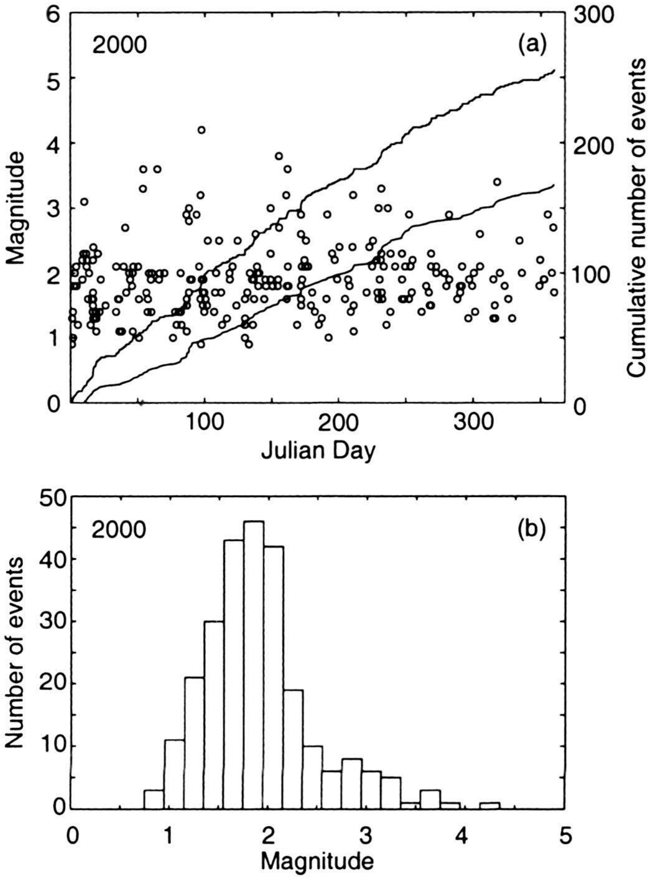

Fig. 10. Earthquake activity during 2000: magnitude of each event and cumulative number of events (a); histogram of magnitudes (b). In (a) the upper curve shows the cumulative number of all events, whereas the lower curve corresponds to the number of events without the Bormio aftershocks.

one fourth of the events with $M_L \geq 2.5$ must be attributed to the aftershock sequence of Bormio.

In addition to the Bormio aftershocks, seismic activity in the year 2000 has been particularly high in the eastern parts Switzerland. As in the past, the Valais was active as well, giving rise to a suggestive rectilinear alignment of epicenters that extends the well-known seismicity of the northern Valais (Maurer et al. 1997) towards the southwest across the Rhone Valley and into France.

Routinely calculated focal depths for the 256 earthquakes recorded in 2000 range between 1 and 23 km, but only 7 of these hypocenters are deeper than 15 km. As in the past (e.g. Deichmann et al. 2000a), these deep sources are located in the lower crust beneath the Jura Mountains and Molasse Basin of northern Switzerland.

The focal mechanisms, that could be determined for five events with magnitudes around 3.5 in eastern Switzerland and the adjacent area of Austria, complement the existing focal mechanism data in a region where previously reliable observations had been scarce.

Acknowledgements

Monitoring the seismicity in a small country is not possiblewithout international cooperation. We thank all individuals who kindly responded to our requests for information and data: W. Brüstle, S. Mellert and S. Stange of the Erdbebendienst des Landesamtes für Geologie, Rohstoffe und Bergbau Baden-Württemberg in Freiburg, D. Spallarossa, S. Solarino and E. Eva of the University of Genova, R. DiGiovambattista of the Istituto Nazionale di Geofisica, Rome, F. Thouvenot of the Observatoire de Grenoble, B. Massinon and F. Schindele of the Laboratoire de Détection et Géophysique in Bruyères-le-Châtel, and N. Horn of the Zentralanstalt für Meteorologie und Geodynamik in Vienna. We are also very grateful to our colleagues in the electronics lab, C. Bärlocher, M. Grieder, K. Kleiber, B. Rinderknecht, D. Winiger and P. Zweifel, for their relentless efforts in ensuring the continuous reliability of the data acquisition systems and to A. Blanchard for the compilation of the macroseismic data. A. Zappone reviewed and relocated all the Bormio aftershocks. Financial support from the Nationale Genossenschaft für die Lagerung radioaktiver Abfälle, Nagra, for the operation of the stations in northern and central Switzerland, from the BLS Alptransit for the operation of station LKBD near Leukerbad as well as from the Verband Schweizerischer Elektrizitätswerke, VSE, for the instrumentation of the dam sites is gratefully acknowledged.

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Manuscript received June 5, 2001