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Earthquakes in Switzerland and surrounding regions during 1999

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Key words: Earthquakes, focal depth, focal mechanisms, moment tensors, Switzerland

ABSTRACT

This report of the Swiss Seismological Service summarizes the seismic activity in Switzerland and surrounding regions during 1999. During this period, 283 earthquakes and 46 quarry blasts were detected and located in the region under consideration. With 27 events with $M_L \geq 2.5$ and with 3 events reaching $M_L > 4$, the seismic activity in 1999 was above the average over the last 25 years. As in the past, most of the earthquakes occurred in the Valais and in Graubünden. In addition, there was a concentration of activity northeast of the Walensee. The three most significant events include an M_L 4.3 earthquake on Feb. 14th near Fribourg as well as the two M_L 4.9 and 4.3 earthquakes, that occurred on Dec. 29th and 31st between Val Müstair and Bormio, Italy. Fault-plane solutions were determined for five events, which in three cases were complemented by full-waveform moment tensor inversions of local broadband data. Except for six events beneath the northern foreland, all earthquakes located in 1999 occurred in the upper 15 km of the crust. An updated compilation of focal depths from a selected dataset of the last 25 years confirms that in the northern Alpine foreland seismicity extends over the whole crust down to depths of about 30 km, while under the Alps, where the crust thickens to almost 60 km, seismicity is restricted to the uppermost 15–20 km.

ZUSAMMENFASSUNG

Dieser Bericht des Schweizerischen Erdbebendienstes stellt eine Zusammenfassung der im Vorjahr in der Schweiz und Umgebung aufgetretenen Erdbeben dar. Im Jahr 1999 wurden im erwähnten Gebiet 283 Erdbeben und 46 Sprengungen erfasst und lokalisiert. Mit 27 Beben mit Magnituden $M_L \geq 2.5$ und 3 Beben mit $M_L > 4$ war die seismische Aktivität im Jahr 1999 leicht überdurchschnittlich. Wie schon in der Vergangenheit waren die meisten Beben im Wallis und in Graubünden zu verzeichnen. Ausserdem wurde eine zusätzliche Konzentration von schwachen Beben nordöstlich des Walensees beobachtet. Dir drei bedeutendsten seismischen Ereignisse waren das Beben bei Freiburg (14. Februar, M_L 4.3) sowie die zwei Beben mit M_L 4.9 und 4.3, die sich am 29. und 31. Dezember in der Gegend zwischen Münstertal und Bormio ereigneten. Für fünf Ereignisse sind Herdflächenlösungen konstruiert worden, welche in drei Fällen durch Momenten Tensoren aus der Wellenforminversion von lokalen Breitbanddaten ergänzt werden konnten. Mit Ausnahme von sechs Ereignissen unter dem Jura und der Molasse, ereigneten sich 1999 alle Beben in den oberen 15 km der Erdkruste. Eine aufdatierte Zusammenstellung der Herdtiefen in der Schweiz, basierend auf einem ausgewählten Datensatz der letzten 25 Jahre, bestätigt, dass sich die Erdbebenherde unter dem nördlichen Alpenvorland bis fast zur Moho in rund 30 km Tiefe erstrecken, während unter den Alpen, wo die Erdkruste Mächtigkeiten von 40 bis fast 60 km aufweist, die Beben auf die oberen 15 bis maximal 20 km beschränkt sind.

RESUME

Le présent rapport du Service Sismologique Suisse résume l'activité sismique de l'année écoulée, en Suisse et dans les régions limitrophes. En 1999, 283 tremblements de terre ont été détectés et localisés dans la région considérée. De plus, 46 événements ont été identifiés comme des tirs de carrière. Avec 27 événements de magnitude $M_L > 2.5$ et avec 3 événements de $M_L > 4$, l'activité sismique de 1999 se situe au dessus de la moyenne sur les 25 dernières années. Comme par le passé, la plupart des tremblements de terre se sont produits dans le Valais et dans les Grisons. Il y a eu en plus une concentration d'activité sismique au nord-est du Walensee. Les trois événements les plus significatifs incluent un séisme de M_L 4.3 le 14 Février près de Fribourg, ainsi que deux séismes de M_L 4.9 et 4.3 qui se sont produits les 29 et 31 Décembre entre Val Müstair et Bormio, Italie. Des mécanismes au foyer ont été déterminés pour cinq événements, qui dans trois cas ont été complétés par le tenseur des moments sismiques par inversion des formes d'onde. A l'exception de six événements sous le Jura et la Molasse, tous les séismes localisés en 1999 se situent dans les 15 km supérieurs de la croûte. Une compilation mise à jour des profondeurs focales pour un ensemble de données sélectionnées pour les 25 dernières années, confirme que sous l'avant-pays alpin nord la sismicité se distribue à l'intérieur de l'ensemble de la croûte jusqu'à une profondeur d'environ 30 km, alors que sous les Alpes, où la croûte s'épaissit pour atteindre presque 60 km, la sismicité est restreinte aux 15–20 km superieurs.

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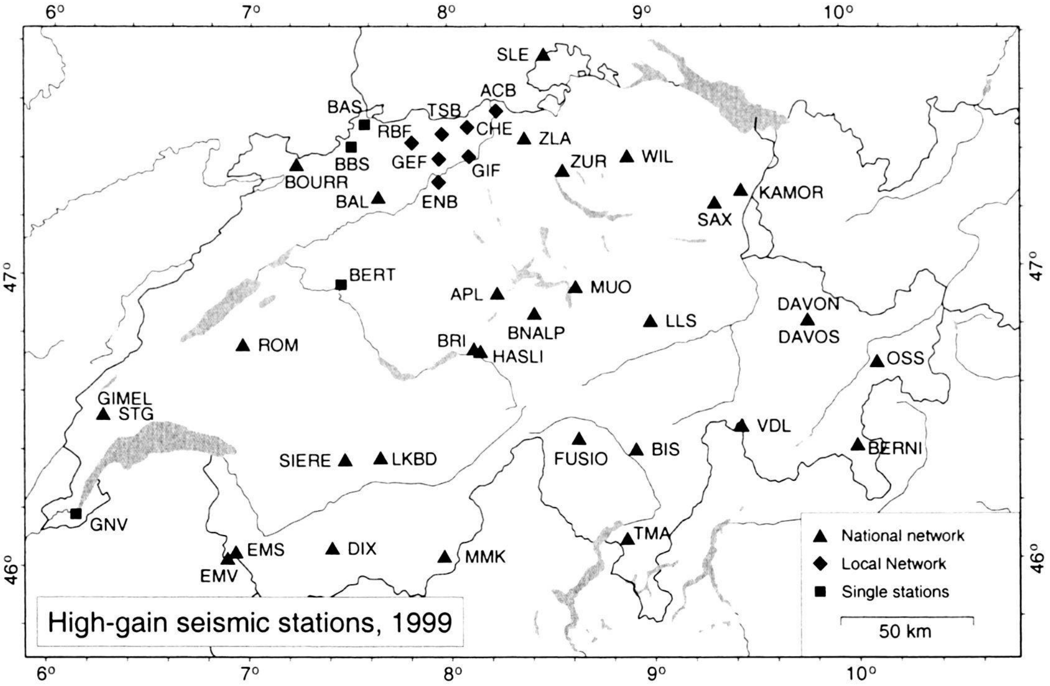

Fig. 1. Seismograph stations operational at the end of 1999.

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 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). 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 1992b; Rüttener 1995; Rüttener at al. 1996; Pavoni et al. 1997; Deichmann et al. 2000).

Seismic stations in operation during 1999

The Swiss Seismological Service operates two separate nationwide seismic networks, a high-gain seismometer network (Baer 1990) and a low-gain accelerograph network (Smit 1998). The former is designed to continuously monitor the ongoing earthquake activity down to magnitudes well below the human perception threshold, whereas the latter is principally aimed at engineering concerns and thus only records so-called strong motions. The observations presented here are based mainly on the high-sensitivity monitoring network. The data that have been collected until September 1999 by the strong-motion network is documented separately (Spühler 1999) and an additional report for the following time period is in preparation.

Since 1997, 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, which entails replacing most of the existing short-period sensors by three-component

STS-2 broad-band instruments. The signals, which are digitized at the remote recording sites, are transmitted over a nationwide INTRANET to the processing center in Zürich, where a Nanometrics NAQS32 data acquisition system has been installed. This system is designed to store ten days of seismic data and state of health information in a circular buffer. Each 24 bit digitizer is synchronized with GPS time and samples the seismic signals at 120 Hz, thus making use of the full frequency range of the STS-2 sensors up to 50 Hz. The two hour solid state data buffer of the digitizers together with the retransmit functionality of the NAQS32 system ensures high completeness of the data.

By the end of 1999, 17 broad-band stations were operational and the modernized network is expected to be completed by the end of the year 2000. In the course of these changes, a few of the old sites will be abandoned in favour of more suitable locations. A complete list of the seismic stations in operation at the end of 1999 and an updated station map are given in Table 1 and Figure 1.

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 also use data obtained from the Landeserdbebendienst in Freiburg, Germany, from the SISMALP array operated by the Laboratoire de Géophysique Interne et Tectonophysique, Observatoire de Grenoble, France, from the Laboratoire de Détection et Géophysique in Bruyères-le-Châtel, France, from the Istituto di Geofisica, Università di Genova, Italy, and from the Istituto Nationale di Geofisica in Rome, Italy.

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, 6 = all three components recorded at high and low gain.

National telemetry network recorded in Zürich			
Code	Station name	Type	Remarks
AIGLE	Aigle	BB-3	
APL	Alpnach	SP-4	
BAL	Balsthal	SP-4	
BERNI	Bernina	BB-3	
BNALP	Bannalpsee	BB-3	
BIS	Biasca	SP-3	
BOURR	Bourrignon	BB-3	
BRI	Brienz	SP-4	
DAVOS	Davos	SP-4	
DAVON	Davos	BB-3	
DIX	Grande Dixence	SP-1, BB-3	dam site
EMS	Emosson	SP-1	
EMV	Vieux Emosson	SP-1, BB-3	
FUSIO	Fusio	BB-3	
GIMEL	Gimel	BB-3	
HASLI	Hasliberg	BB-3	
KAMOR	Kamor	BB-3	
LKBD	Leukerbad	BB-3	
LLS	Linth-Limmern	SP-3, BB-3	dam site
MMK	Mattmark	SP-3, BB-3	dam site
MUO	Muotathal	SP-1, BB-3	
OSS	Ova Spin	SP-1	dam site
ROM	Romont	SP-4	
SAX	Säntis	SP-3	
SIERE	Sierre	SP-4	
SLE	Schleitheim	SP-3	
STG	Saint Georges	SP-3	
TMA	Monte Tamaro	SP-3	
VDL	Valle di Lei	SP-1, BB-3	dam site
WIL	Wil	SP-4	
ZLA	Zürich-Lägern	SP-1	
ZUR	Zürich-Degenried	BB-3	
Local telemetry network recorded at station CHE			
Code	Station name	Type	Remarks
ACB	Acheberg	SP-3	
CHE	Cheisacher	SP-6	
ENB	Engelberg	SP-1	
GEF	Geissflue	SP-1	
GIF	Gisliflue	SP-1	
RBF	Rickenbacherflue	SP-1	
TSB	Tiersteinberg	SP-1	
Single stations			
Code	Station name	Type	Remarks
BAS	Basel	SP-3	digital (LED)
BBS	Basel-Blauen	SP-1	telemetry (LED)
BERT	Bern	SP-3	paper records
GNV	Geneva	SP-1	paper records

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 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

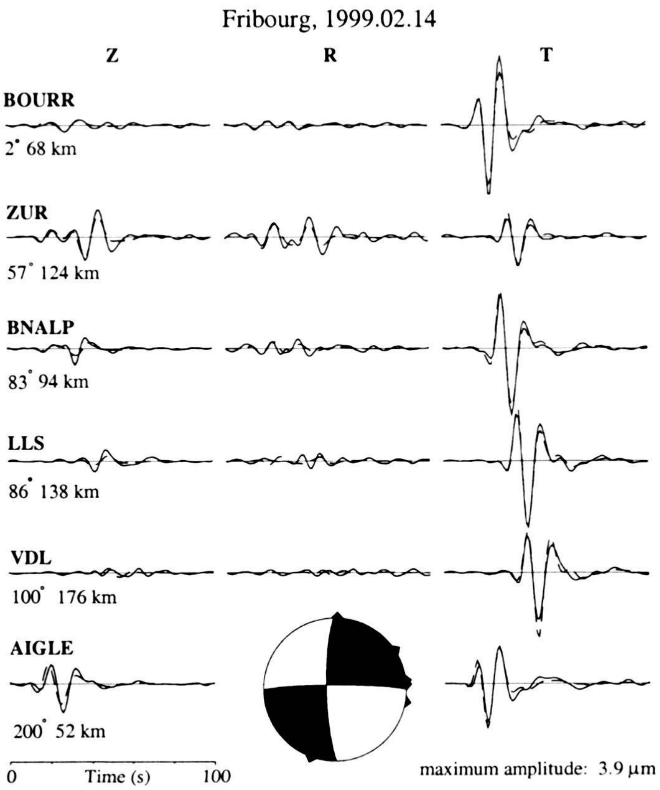

Fig. 2. Waveform fit for the Feb. 14th Fribourg earthquake. Observed (solid) and synthetic (dashed) seismograms are shown for the best-fit model in the 0.1-0.03 Hz frequency band. Z, R, T are vertical, radial, and transverse components. The stations are listed in azimuthal order; numbers beneath station codes are event-station azimuth and distance. Seismogram amplitudes are normalized to an epicentral distance of 100 km assuming cylindrical geometrical spreading. The triangles on the circumference of the fault-plane solution (lower hemisphere projection) show the station locations.

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).

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 (Fig. 2). 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.

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 1999

Overview

During 1999, the Swiss Seismological Service detected and located 283 earthquakes in the region shown in Figure 3. Based on such criteria as the time of occurrence, the location, the signal character or direct information, 46 additional seismic events were identified as quarry blasts.

Magnitude values of the events recorded in 1999 range between $M_L = 0.7$ and 4.9 (Fig. 4). The events with $M_L \geq 2.5$ and the criteria used to assign the quality rating for the locations together with the corresponding estimated location accuracy are listed in Tables 2 and 3. For several events, epicentral coordinates and focal depths in Table 2 were recalculated using additional data from foreign networks and were checked with 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 5.

The fault-plane solutions with first-motion directions are shown in Figure 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 1999.

Significant earthquakes of 1999

Fribourg

Early Sunday morning, February 14th, many inhabitants of northern Switzerland were awakened by an earthquake with epicenter near the town of Marly, 5 km southeast of the city o

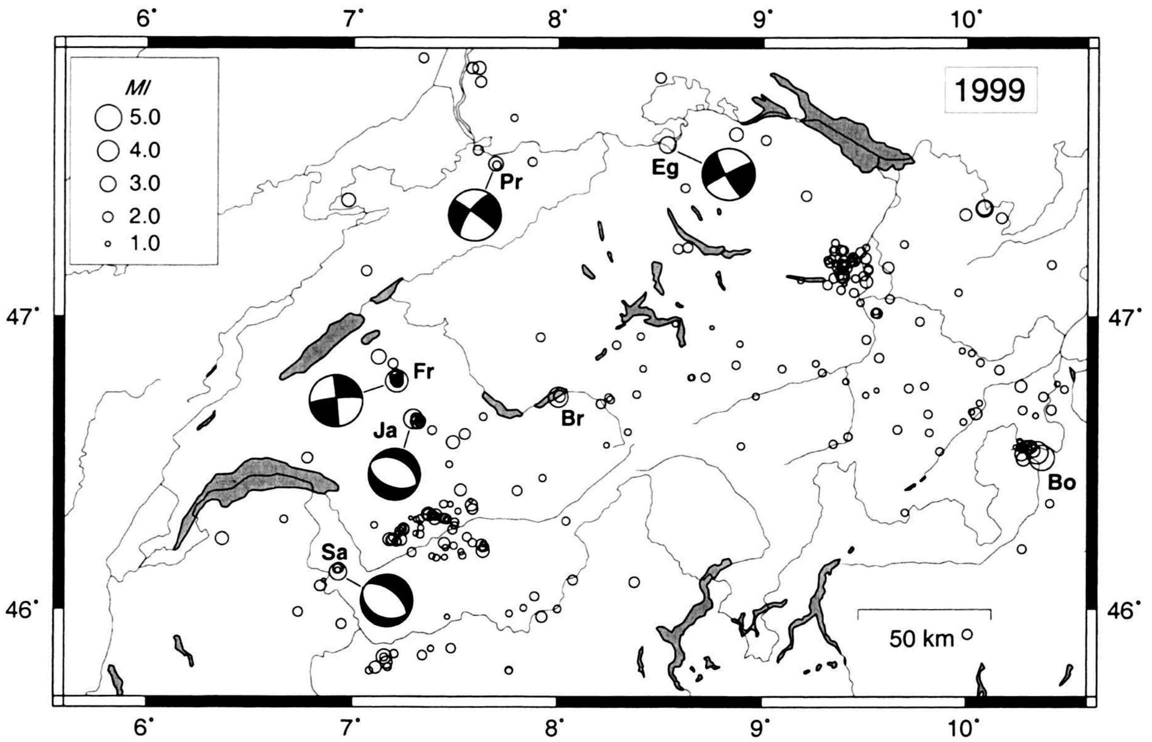

Fig. 3. Epicenters and focal mechanisms of earthquakes (based on first-motion polarities) recorded by the Swiss Seismological Service during 1999. Epicenters of earthquakes mentioned in the text are Bormio, Dec. 29 and 31 (Bo), Brienz, May 14 (Br), Eglisau, Sep. 12 (Eg), Fribourg, Feb. 14 (Fr), Jaun, May 20 (Ja), Pratteln, July 13 (Pr) and Lac de Salanfe, Dec. 29 (Sa).

Tab. 2. Earthquakes with $M_L \geq 2.5$. The focal depths of the earthquakes of Fribourg, Jaun, Pratteln, Eglisau, Lac de Salanfe and Bormio are based on 2-D ray-tracing or on additional data from foreign networks.

Location	Date & Time [UT]	Lat. [°N]	Lon. [°E]	X / Y [km]	Depth [km]	Mag. [M_L]	Q
Chevenez, JU	1999.01.02 21:01:54	47.392	6.975	565/249	13	2.6	C
Müllheim, D	1999.02.07 14:51:34	47.834	7.612	613/298	12	2.5	C
Fribourg, FR	1999.02.14 05:57:54	46.782	7.212	583/181	10	4.3	B
Courtepin, FR	1999.02.26 19:30:19	46.864	7.124	576/190	10	2.8	B
Hüttwilen, TG	1999.03.09 18:01:08	47.614	8.867	707/275	25	2.6	B
Bormio, I	1999.04.15 17:19:52	46.525	10.253	816/156	6	2.6	A
G. S. Bernard, I	1999.04.25 20:36:47	45.838	7.154	578/ 76	12	2.8	C
Zwischenflüh, BE	1999.05.14 15:21:29	46.574	7.491	604/158	6	2.5	B
Brienz, BE	1999.05.14 18:25:29	46.728	8.005	643/175	7	3.9	B
Lechtal, A	1999.05.16 10:24:06	47.473	10.649	842/263	10	2.6	D
Jaun, FR	1999.05.20 13:11:35	46.655	7.320	591/167	7	3.8	A
Jaun, FR	1999.05.20 15:48:09	46.655	7.320	591/167	7	2.7	A
Jaun, FR	1999.05.20 17:56:41	46.655	7.320	591/167	7	2.9	A
Fulfirst, SG	1999.05.23 20:53:04	47.134	9.392	748/222	2	2.5	B
Fulfirst, SG	1999.05.24 13:39:50	47.147	9.386	748/223	2	2.7	B
Chablais, F	1999.06.24 03:20:47	46.242	6.369	517/122	12	2.5	C
Arbaz, VS	1999.07.03 22:40:05	46.327	7.373	595/130	6	2.6	A
Pratteln, BL	1999.07.13 20:47:01	47.514	7.696	619/262	19	2.8	A
Chamoson, VS	1999.09.01 15:54:48	46.239	7.180	580/121	7	2.5	B
Eglisau, ZH	1999.09.12 13:25:22	47.578	8.534	682/270	2	3.2	A
Bregenzerwald, A	1999.10.14 09:33:42	47.367	10.086	800/249	3	2.8	C
Bregenzerwald, A	1999.10.28 04:54:22	47.365	10.087	800/249	3	3.3	C
Zinal, VS	1999.11.05 14:30:32	46.200	7.638	615/116	6	2.5	B
Lac de Salanfe, VS	1999.12.29 09:29:30	46.129	6.923	560/109	4	3.3	A
Bormio, I	1999.12.29 20:42:34	46.553	10.305	820/160	12	4.9	B
Bormio, I	1999.12.30 03:21:42	46.530	10.306	820/157	12	2.7	B
Bormio, I	1999.12.31 04:55:54	46.554	10.321	821/160	15	4.3	B

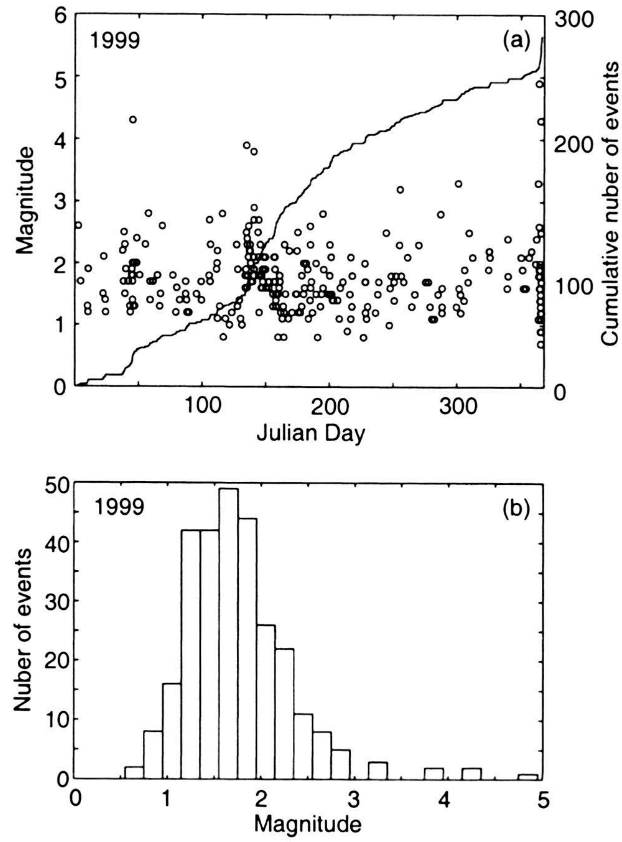

Fig. 4. Earthquake activity during 1999: magnitude of each event and cumulative number of events (a); histogram of magnitudes (b).

Fribourg. Although the magnitude, M_L, did not exceed 4.3, the macroseismic intensity in the epicentral area reached I_0 = V (Fig. 7), causing objects to fall off shelves and tables and causing plaster to crack and come off walls. The peak horizontal ground acceleration (PGA) measured by an accelerometer at a station 13 km from the epicenter (SLAE in Laupen, BE) reached 4% g (Spühler 1999). The routinely calculated focal depth (≈ 15 km) is not reliable. Based on two-dimensional raytrace modeling of PmP-Pg and Pg-Pn arrival-time differences the most likely hypocentral depth seems to be 10 km. On the other hand, the long-period waveforms modelled by the moment-tensor inversion are matched best for a focal depth of 4 km (Fig. 2), and the rapid intensity decay with epicentral distance (Fig. 7) would also suggest a shallow source. The reason for the discrepancy between these depth estimates is still unclear.

The focal mechanisms deduced from first motion polarities and from the full waveform inversion agree very well with each other despite the differences in focal depth assumed by the two methods. Both results show that the earthquake occurred as a strike slip rupture on a roughly N-S or E-W oriented fault plane. The main event was followed by a classical aftershock sequence: four events occurred within two hours of the mainshock and three more over the following 10 days; another small spurt of activity occurred in April with three events and in November with a single one. The magnitudes of these 11 aftershocks range from 1.4 to 2.4.

The 1999 events near Marly are the latest manifestation of an ongoing seismic activity that appears as a N-S trending alignment of epicenters in the region south of Fribourg (Fig. 5). This activity includes two earthquakes with M_L of 3.7 and 3.5, that occurred in the Fall of 1995 at practically the same location as the 1999 events, and an M_L 3.9 event in 1987, 3 km further to the South.

Brienz

In the evening of May 14th, the region around Brienz, in the Bernese Oberland, experienced an earthquake with M_L = 3.9. The epicenter was located below the Lake of Brienz. The routinely calculated focal depth is 7 km, but the fact that it was felt only in the immediate vicinity of the epicenter suggests that it probably was considerably shallower. A shallow source would be compatible also with the character of the observed seismograms, which feature emergent first arrivals and large surface waves even at short distances.

Jaun

The M_L 3.8 earthquake that occurred on May 20th near Jaun, FR, is the third and strongest of a swarm-like sequence of 9 events recorded between the 15th and 26th of May. Seven of these events actually occurred within a period of only 9 hours on May 20th and included two events with M_L 2.7 and 2.9 in addition to the main event. The magnitudes of the other events range from 1.6 to 2.2. The closest station is located at an epicentral distance of 31 km, so that the routinely calculated focal depths (15–19 km) are not reliable. However, in 1987, in the context of a seismic refraction study of the crustal structure below the Helvetic nappes, an explosion was set off at the Jaunpass, located about 5 km south of the epicenter of the 1999 earthquake sequence (Maurer & Ansorge 1992). Using

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

Pg and PmP arrivals at stations that recorded the 1987 explosion as well as the 1999 earthquakes, it was possible to calibrate the location algorithm and the crustal model for the 2-D ray-tracing and thus to obtain reliable hypocentral parameters (Table 2). With reference to the crustal model of Maurer & Ansorge (1992), the focal depth of 7 km puts the source of this earthquake sequence in the crystalline basement. The fault-plane solution based on first-motion polarities and the moment tensor inversion based on waveform fitting result in a normal-faulting mechanism with a NNE-SSW or NE-SW trending T-axis (Fig. 6 and Table 4).

Pratteln

In the evening of July 13th, Pratteln, near Basel, was the site of an earthquake doublet consisting of an M_L 2.8 event followed 7 minutes later by an M_L 1.6 event with almost identical signal character. The significance of this doublet lies in the fact that its epicenter coincides with the location of a cluster of earthquakes that has been intermittently active over the years between 1987 and 1993 (Deichmann et al. 2000). Contrary to the earlier earthquakes, which were located at depths of 10 and 12 km, the most recent doublet occurred at a depth of 19 km. The focal depth is well constrained by observations close to the epicenter (minimum epicentral distance 11 km) and by 2-D ray-tracing. There is thus no direct relation between the 1999 doublet and the earlier earthquake cluster. The focal mechanism corresponds to strike-slip motion on either a NW-SE or a NE-SW striking fault plane (Fig. 6). This mechanism is similar to that of two earlier events at 10 and 12 km depth (M_L = 2.4 and M_L = 1.2). It is, however, rotated by almost 45° relative to the mechanism of the majority of the 10 km deep events, which occurred as left-lateral motion on a vertical N-S striking fault (Faber et al. 1994).

Eglisau

On Sunday afternoon, September 12th, the region north of Zürich was jolted by an earthquake with an M_L of 3.1 and an epicentral intensity, I_0, of IV. The calculated epicenter is situated between Eglisau and Buchberg. This area has seen repeated earthquake activity in the past: between 1705 and 1878, there have been 9 events with $I_0 \geq$ V and, since 1879, 7 events reached an intensity of at least IV (e.g. Rüttener 1995); in addition, between 1984 and 1991, the Swiss Seismological Service detected 6 events with M_L between 1.0 and 2.1 (Deichmann et al. 2000). At stations in central Switzerland, PmP arrival times of this most recent earthquake are matched best for a focal depth of 4–5 km. On the other hand, the fact that it was felt only out to a distance of about 10 km as well as the observation

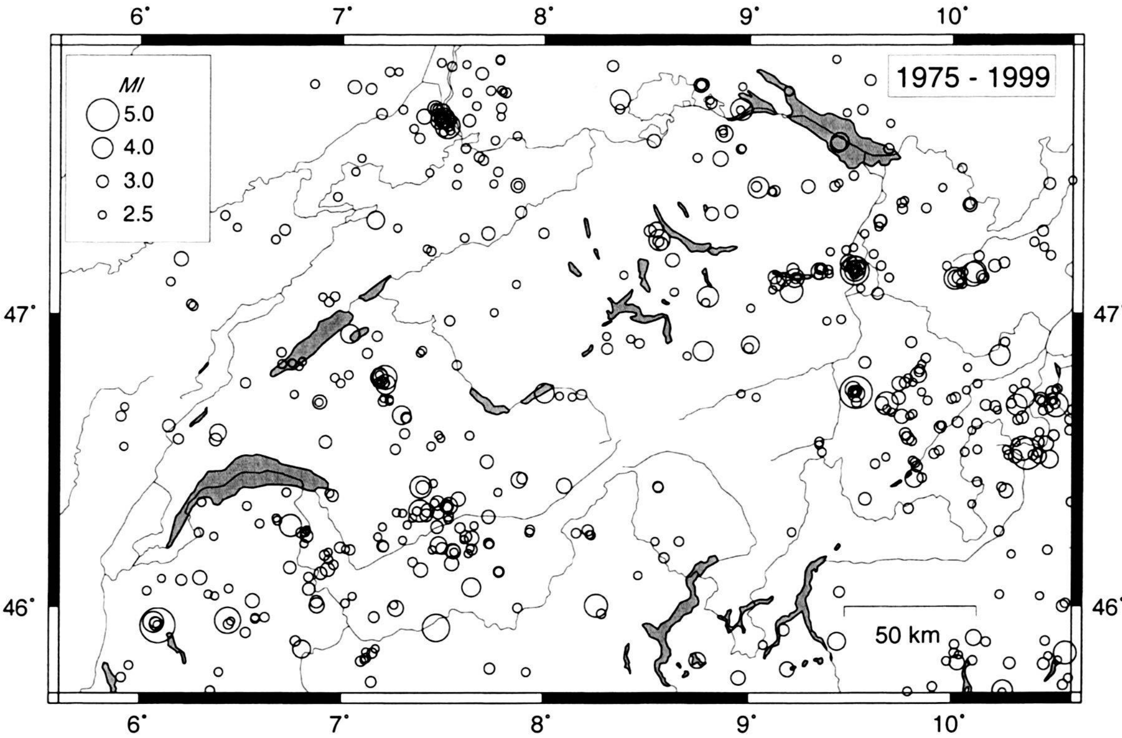

Fig. 5. Epicenters of earthquakes with Magnitudes $M_L \geq 2.5$, during the period 1975–1999.

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).

Location	Date & Time [UT]	Mag.	Depth [km]	P-Axis Az.	P-Axis Dip	T-Axis Az.	T-Axis Dip
Fribourg	1999.02.14 05:58	M_L4.3	10	129	5	219	8
		M_w4.0	4	135	10	45	3
Jaun	1999.05.20 13:11	M_L3.8	7	326	84	204	3
		M_w3.5	4	333	72	217	8
Pratteln	1999.07.13 20:47	M_L2.8	19	173	17	79	11
Eglisau	1999.09.12 13:25	M_L3.1	2	16	3	107	11
Lac de Salanfe	1999.12.31 09:29	M_L3.3	4	249	76	32	11
		M_w3.0	4	248	76	36	12

that many signals are dominated by strong surface waves and that the apparent velocity of the direct Pg wave over the first 80 km is clearly less than 6.0 km/s suggest that the source was shallower. The conclusion that the source is probably close to the surface is also supported by the fact that one of the events with very similar signal character recorded in 1984 was felt in the epicentral area, although the magnitude of that event was only 1.4 (Deichmann et al. 2000). We have therefore fixed the focal depth at 2 km (Table 2). This puts the hypocenter just below the sediment/basement transition; it is, however, equally possible that it was situated in the sedimentary rocks above. The fault-plane solution corresponds to a strike-slip mechanism (Fig. 6 and Table 4). Whereas the data leave room for variation in the dip of the nodal planes, the strike is well constrained. It is important to note that the P- and T-axes are oriented NNE-SSW and WNW-ESE, thus deviating significantly from the NNW-SSE and ENE-WSW directions usually observed in the Alpine foreland and Jura Mountains of northern Switzerland (Deichmann et al. 2000).

Lac de Salanfe

The M_L 3.3 event, which occurred in the morning of Dec. 29th near Lac de Salanfe, is particularly interesting, because its epicenter is located in the SW corner of the Valais, where seismic activity has been observed before but reliable focal mechanisms have not been available previously. The epicentral location and focal depth (4 km) are well constrained by the P- and S-arrivals observed at the accelerographs of the Emosson hydroelectric dam situated at a distance of only 7 km. The focal mechanisms based on first-motion polarities and on the full-waveform inversion are practically identical and correspond to a normal faulting mechanism with a T-axis oriented in a direction between NNE-SSW and NE-SW. Although the T-Axis is rotated somewhat compared to the usually observed N-S orientation, the normal faulting mechanism constitutes a confirmation of the presently predominant extensional deformation in the Penninic nappes of the southern Valais (Maurer et al. 1997; Eva et al. 1998).

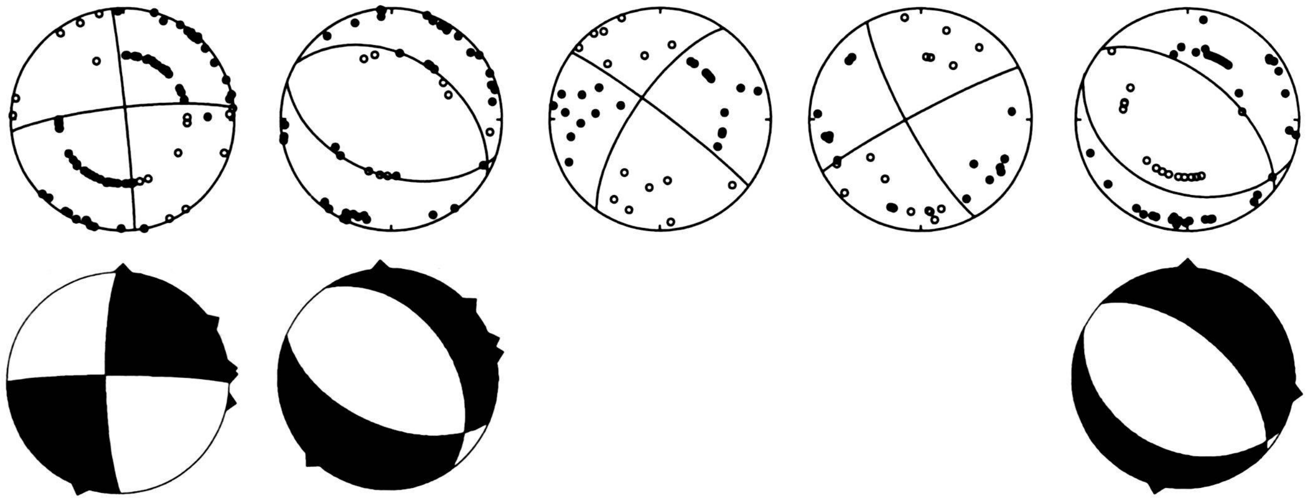

Fig. 6. Fault-plane solutions based on first-motion polarities and moment tensors based on full-waveform inversions (lower hemisphere, equal area projection). In the fault-plane solutions (above), solid circles correspond to compressive first motion (up) and empty circles to dilatational first motion (down); on the moment tensors (below), triangles show the station locations.

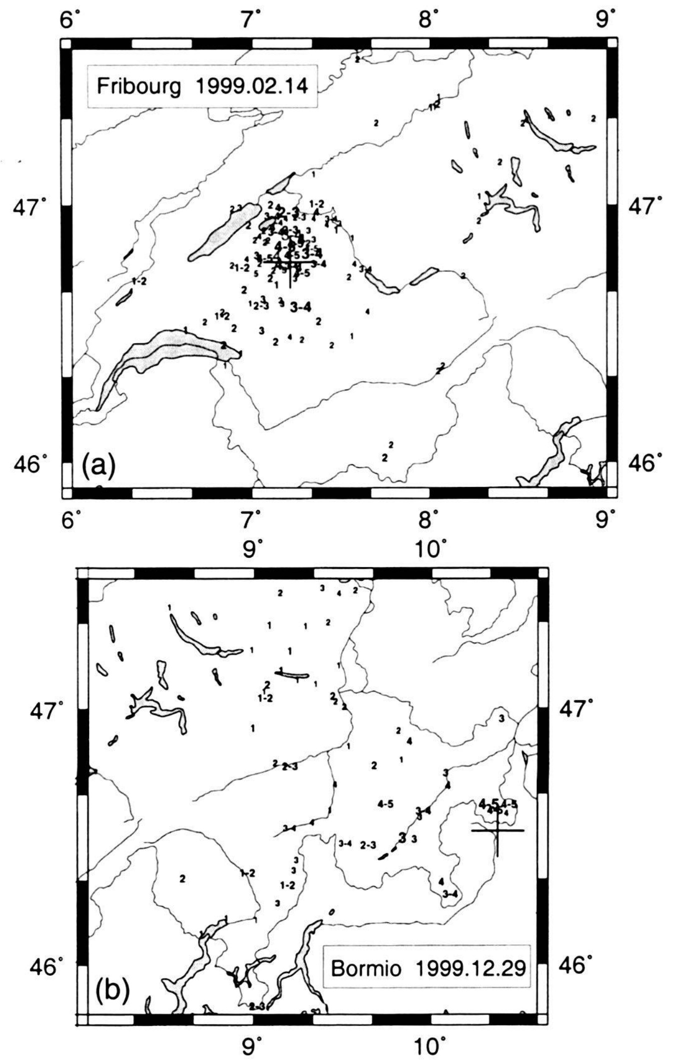

Fig. 7. Observed macroseismic intensities (EMS98) for the Feb. 14th, 1999, Fribourg (a) and the Dec. 29th, 1999, Bormio (b) earthquakes.

Bormio

The strongest earthquake of the year 1999 in and around Switzerland occurred at 21:42 local time on Dec. 29th just accross the border between Val Müstair and Bormio, Italy. With M_L = 4.9, it reached an epicentral intensity of IV-V and was felt throughout eastern Switzerland as well as in adjacent regions of Italy and Austria (Fig. 7). Peak free-field accelerations on hard rock at a distance of 11 km near the Punt dal Gall hydroelectric dam reached 1% g, while 9% g was measured at one site close to the crest of the dam. In Zernez and Scuol, on soft soil 22 and 27 km away, peak accelerations were about 2% g. This earthquake was preceded by two smaller events on April 15th (M_L = 2.6) and on Dec. 28th (M_L = 2.4) and subsequently was followed by vigorous aftershock activity, that continued for several months, with sporadic events still occurring more than half a year later. The strongest aftershock was an M_L 4.3 event in the early morning of Dec. 31st. Due to this sequence's location at the perifery of the Swiss network, routinely determined epicenters and in particular focal depths are poorly constrained. Integration of the Swiss data with those of the Italian Istituto Nazionale di Geofisica, which operates a short period station (BR9) about 10 km SW of the epicentral area, is still underway. The hypocentral parameters in Table 2 include the available arrival times from station BR9 and from the accelerographs at the Punt Dal Gall dam, but are preliminary, pending a complete analysis of all data. First results of moment tensor inversions and of first-motion fault-plane solutions indicate that this earthquake sequence occurred on a NNW-SSE striking normal fault. However, a detailed analysis of the focal mechanisms and of their relation to the relative locations of the individual earthquakes still needs to be completed.

Discussion

Making use of data from the new broad-band seismographs, it was possible for the first time to perform moment tensor inversions for some of the stronger local earthquakes in Switzerland. The agreement between the focal mechanisms determined from these full-waveform inversions and the traditional first-motion fault-plane solutions is excellent. Whether the differences between local magnitude, M_L, and moment magnitude, M_w, as seen in Table 4, are systematic can not be decided yet on the basis of the currently available data. Discrepancies remain between focal depths determined from waveform inversions and from traditional location methods or 2-D ray-tracing (Table 4), but these are likely to be resolved in the future with the use of more refined crustal models. The advantage of the waveform inversion is that fewer seismograms are needed to obtain a reliable focal mechanism, that the inversion procedure can be automated much more readily and that, with M_w or equivalently the seismic moment, M_0, it provides directly a physically meaningful measure of earthquake size.

Figure 5 shows the epicenters of the earthquakes with M_L 2.5, which have been recorded in Switzerland and surrounding regions over the period of 1975–1999. 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 25 years, the earthquakes shown in Figure 5 are equivalent to 24 events with $M_L \geq 2.5$ and about one event with $M_L \geq 4$ per year. With 27 events with $M_L \geq 2.5$ and with 3 events reaching $M_L > 4$, the seismic activity in 1999 was thus above the average over the last 25 years. The strongest events in this time span are the two magnitude 5 events of 1990 near Vaz, Graubünden, and of 1996 near Annecy, France, as well as the M_L 4.9 earthquake, which occurred near Bormio in 1999.

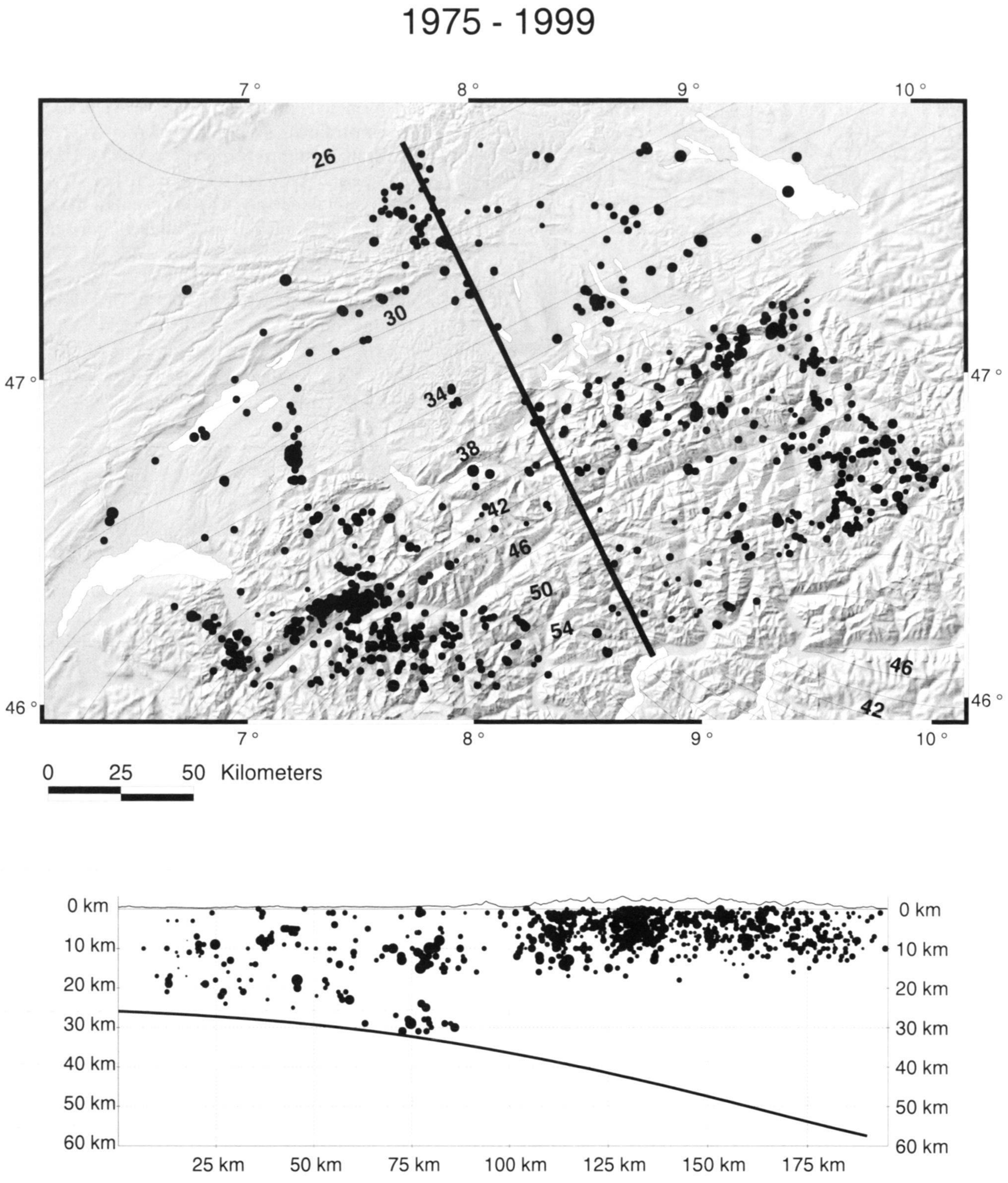

Fig. 8. Epicenter map and depth cross-section along a NNW-SSE trending profile from Basel to Locarno of all earthquakes that meet the selection criteria discussed in the text. Moho topography is from Waldhauser (1996) and Waldhauser et al. (1998). Surface topography is from the digital elevation model "RIMINI", reproduced with permission from the Swiss Federal Office of Topography (BA002892), complemented with data from the 30" elevation model (GTOPO30) of the USGS.

In agreement with long-term observations, most of the earthquakes during 1999 occurred in the Valais and in Graubünden. A concentration of activity can also be noted in northeastern Switzerland, between the Walensee and the Rhine Valley of Sankt Gallen (Fig. 3). The two M_L 2.5 and 2.7 Fulfirst earthquakes of May 23rd and 24th (Table 2) are part of this activity, most of which occurred between mid May and mid July, 1999 (Fig 4). The magnitudes of the majority of these events are in the range between 1 and 2. Consequently, their signal quality is poor and they are difficult to locate properly. It is thus very likely that in reality they cluster much more tightly than the scatter in Figure 3 implies.

Routinely calculated focal depths range between 0 and 30 km, but, of the 283 earthquakes recorded in 1999, only 6 hypocenters are deeper than 15 km. As in the past, these deep sources are located in the lower crust beneath the Jura Mountains and Molasse Basin of northern Switzerland. The hypocenters of selected earthquakes projected onto a NNW-SSE striking cross-section from Basel to Locarno are shown in Figure 8. The direction of the profile is such that it is perpendicular to the predominant trend of the Alps and of the major tectonic units. The dataset was selected from all earthquakes recorded between 1975 and 1999 according to the following criteria: largest angle between the epicenter and two adjacent stations, $GAP \leq 180°$, minimum epicentral distance, $DM \leq 30$ km, number of arrival times (P and S) used for location, $NO \geq 11$, root-mean-square of the travel-time residuals, $RMS \leq 0.4$ s. These criteria are the same as those used for an earlier compilation of focal depths (Deichmann & Baer 1990). The first condition ensures that all epicenters are located inside the station network. Since the determination of focal depths of local earthquakes using direct arrivals is only possible if the epicentral distance to the closest station is not greater than about 1.5 times the depth, the second condition ensures that all hypocenters deeper than 20 km are in principle well constrained. The third and fourth conditions reduce the probability of grossly mislocated events remaining in the dataset. Of the almost 6000 events in the original dataset, only about 20% meet the combination of these conditions. Figure 8 shows that earthquake hypocenters below the northern Alpine foreland of Switzerland are distributed throughout the entire crust from close to the surface down to the Moho at a depth of about 30 km, whereas below the central Alps, where the Moho lies at depths of 40–60 km, earthquakes are restricted to the upper 15–20 km of the crust. Thus, the focal depth distribution published earlier by Deichmann & Baer (1990) is confirmed by the additional 10 years of data shown here. With the adopted selection criteria, the hypocenters that are shallower than about 20 km are generally still poorly constrained, unless they happen to have been recorded by at least one station at an epicentral distance that is less than about 1.5 times their focal depth. However, the reliability of the computed hypocentral parameters increases with depth and consequently both the existence of the lower crustal earthquakes below the foreland and their absence beneath the Alpine mountain range are significant. In addition, there is no evidence of any seismicity in the upper mantle beneath Switzerland.

The existence of the deep hypocenters beneath the foreland and their restriction to the crust as opposed to extending into the mantle has been confirmed for numerous events by modeling of phases reflected and refracted at the Moho (e.g., Garcia-Fernandez & Mayer-Rosa 1986; Deichmann 1987; Deichmann & Rybach 1989). Moreover, the absence of lower-crustal seismicity beneath the Alps does not seem to be an artifact of the seismic velocity model used for the locations: simultaneous inversions for an optimum velocity model and hypocentral locations applied to datasets in Graubünden (Roth et al. 1992) and in the Valais (Maurer & Kradolfer 1996) also result in a seismicity cut-off between 13 and 19 km. Based on a relocated earthquake dataset using arrival times merged from several European seismic networks (Solarino et al. 1997), Schmid & Kissling (2000) published a projection of hypocenters onto two geological transects across the eastern and western Swiss Alps, which feature the same concentration of seismicity in the upper 10–15 km of the crust as is shown here in Figure 8. The few hypocenters at depths greater than 20 km below the Alps in the cross-sections of Schmid & Kissling (2000) are possibly a consequence of different selection criteria and, in the case of the western transect, of the inclusion of earthquakes from regions beyond the area covered by the Swiss station network. The chosen orientation of the profile in Figure 8 is such that the shown hypocenters are projected along lines that are parallel to the trend of both the major tectonic units and of the Moho isolines over the region covered by the selected earthquake dataset. Thus, the transition from the deeper to the shallower seismicity cut-off consists of an abrupt vertical jump of more than 10 km, that seems to coincide with the Helvetic front at the northern margin of the Alps.

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REFERENCES

BAER, M. 1990: The seismic station network of the Swiss Seismological Service. In: I. Workshop on: MEDNET, the Broad-Band Seismic Network for the Mediterranean (Ed. by E. BOSCHI, D. GIARDINI & A. MORELLI). Istituto Nazionale Geofisica, Roma, 345–350.

BAER, M. & KRADOLFER, U. 1987: An automatic phase picker for local and teleseismic events. Bull. Seis. Soc. Am. 77, 1437–1445.

BAER, M., DEICHMANN, N., FÄH, D., KRADOLFER, U., MAYER-ROSA, D., RÜTTENER, E., SCHLER, T., SELLAMI, S. & SMIT, P. 1997: Earthquakes in Switzerland and surrounding regions during 1996. Eclogae geol. Helv. 90/3, 557–567.

BAER, M., DEICHMANN, N., BALLARIN DOLFIN, D., BAY, F., DELOUIS, B., FÄH, D., GIARDINI, D., KASTRUP, U., KIND, F., KRADOLFER, U., KÜNZLE, W., RÖTHLISBERGER, S., SCHLER, T., SELLAMI, S., SMIT, P. & SPÜHLER, E. 1999: Earthquakes in Switzerland and surrounding regions during 1998. Eclogae Geol. Helv., 92/2, 265–273.

BOUCHON, M. 1982: The complete synthesis of seismic crustal phases at regional distances. J. Geophys. Res., 87, 1735–1741.

BRAUNMILLER, J., NABELEK J. L., LEITNER, B. & QAMAR, A. 1995: The 1993 Klamath Falls, Oregon, earthquake sequence: source mechanisms from regional data. Geophys. Res. Lett., 22, 105–108.

DEICHMANN, N. 1987: Focal depths of earthquakes in northern Switzerland. Annales Geophysicae 5B, 395–402.

– 1990: Seismizität der Nordschweiz, 1987–1989, und Auswertung der Erdbebenserien von Günsberg, Läufelfingen und Zeglingen. Nagra Technischer Bericht, NTB 90–46, Nagra, Baden.

DEICHMANN, N. 1992a: Structural and rheological implications of lower-crustal earthquakes below northern Switzerland. Phys. Earth Planet. Inter. 69, 270–280.

– 1992b: Recent seismicity of the northern Alpine foreland of Switzerland. Eclogae geol. Helv. 85/3, 701–705.

DEICHMANN, N. & BAER, M. 1990: Earthquake focal depths below the Alps and northern Alpine foreland of Switzerland. In: The European Geotraverse: Integrative Studies. (Ed. by R. FREEMAN, P. GIESE & ST. MUELLER). European Science Foundation, Strasbourg, France, 277–288.

DEICHMANN, N. & RYBACH, L. 1989: Earthquakes and temperatures in the lower crust below the northern Alpine foreland of Switzerland. In: Properties and Processes of the Lower Crust. (Ed. by R. F. MEREU, ST. MUELLER & D. FOUNTAIN). Am. Geophys. Union, Geophysical Monograph 51, IUGG Vol. 6, 197–213.

DEICHMANN, N., BAER, M., BALLARIN DOLFIN, D., FÄH, D., FLÜCK, P., KASTRUP, U., KRADOLFER, U., KÜNZLE, W., MAYER-ROSA, D., RÖTHLISBERGER, S., SCHLER, T., SELLAMI, S., SMIT, P. & GIARDINI, D. 1998: Earthquakes in Switzerland and surrounding regions during 1997. Eclogae geol. Helv. 91/2, 237–246.

DEICHMANN, N., BALLARIN DOLFIN, D. & KASTRUP, U. 2000: Seismizität der Nord- und Zentralschweiz. Nagra Technischer Bericht, NTB 00–05, Nagra, Wettingen.

EVA, E., PASTORE, S. & DEICHMANN, N. 1998: Evidence for ongoing extensional deformation in the western Swiss Alps and thrust-faulting in the southwestern Alpine foreland. J Geodynamics 26/1, 27–43.

FABER, S., BONJER, K.-P., BRÜSTLE, W. & DEICHMANN, N. 1994: Seismicity and structural complexity of the Dinkelberg block, southern Rhinegraben. Geophys. J. Int., 116, 393–408.

GARCIA-FERNANDEZ, M. & MAYER-ROSA, D. 1986: Improved hypocentral parameter determination using secondary regional phases. Rev. Geophysica, 42, 175–184.

KRADOLFER, U. & MAYER-ROSA, D. 1988: Attenuation of seismic waves in Switzerland. In: Recent seismological investigations in Europe. Proc. XIX Gen. Assem. Moscow, October 1–6, 1984, 481–488.

LEE, W. H. K. & LAHR, J. C. 1972: HYPO-71 a computer program for determining hypocenter, magnitude and first motion pattern of local earthquakes. U.S. Geol. Surv., Open-File Rep.

MAURER, H. & ANSORGE, J. 1992: Crustal structure beneath the northern margin of the Swiss Alps. Tectonophysics 207, 165–181.

MAURER, H. & KRADOLFER U. 1996: Hypocentral parameters and velocity estimation in the western Swiss Alps by simultaneous inversion of P- and S-wave data. Bull. Seis. Soc. Am. 86, 32–41.

MAURER, H., BURKHARD, M., DEICHMANN, N., GREEN, A. G. 1997: Active Tectonism in the Western Swiss Alps. Terra Nova, 9, 91–94.

NABELEK, J. & XIA, G. 1995: Moment-tensor analysis using regional data: application to the 25 March, 1993, Scotts Mills, Oregon earthquake. Geophys. Res. Lett., 22, 13–16.

PAVONI, N. 1977: Erdbeben im Gebiet der Schweiz. Eclogae geol. Helv. 70/2, 351–370.

– 1984: Seismotektonik Nordschweiz. Nagra Technischer Bericht, NTB 84–45, Nagra, Baden.

PAVONI, N. & ROTH, P. 1990: Seismicity and seismotectonics of the Swiss Alps. Results of microearthquake investigations 1983–1988. In: Deep Structure of the Alps. (Ed. by F. ROURE, P. HEITZMANN & R. POLINO). Mém. Soc. géol. France, N. S., 156, 129–134.

PAVONI, N., MAURER, H., ROTH, P., DEICHMANN, N. 1997: Seismicity and seismotectonics of the Swiss Alps. In: Deep structure of the Swiss Alps, results of NRP 20, Birkhäuser, Basel, 241–250.

PFISTER, M. 1990: Gemeinsame Auswertung von Erdbeben-, Refraktions- und Reflexionsdaten in der Nordschweiz. Diploma thesis, Institute of Geophysics, ETH-Zürich.

ROTH, P., PAVONI, N., DEICHMANN, N. 1992: Seismotectonics of the eastern Swiss Alps and evidence for precipitation-induced variations of seismic activity. Tectonophysics, 207, 183–197.

RÜTTENER, E. 1995: Earthquake hazard estimation for Switzerland. Matér. Géol. Suisse, Geophys. Nr. 29, Schweizerische Geophysikalische Kommission, ETH-Zürich, 106 pp.

RÜTTENER, E., EOGOZCUE, J., MAYER-ROSA, D. & MUELLER, S. 1996: Bayesian estimation of seismic hazard for two sites in Switzerland. Natural Hazards 14, 165–178.

SÄGESSER & MAYER-ROSA 1978: Erdbebengefährdung in der Schweiz. Schweizerische Bauzeitung 78/7, 3–18.

SCHMID, S. & KISSLING, E. 2000: The arc of the western Alps in the light of geophysical data on deep crustal structure. Tectonics, 19, 62–85.

SMIT, P. 1998: The Swiss National Strong Motion Network – Achievements and prospects. Proc. 11th Conference Earthquake Engineering, 6.–11. September 1998, Paris.

SOLARINO, S., KISSLING, E., SELLAMI, S., SMRIGLIO, G., THOUVENOT, F., GRANET, M., BONJER, K. & SLEIJKO, D. 1997: Compilation of a recent seismicity data base of the greater Alpine region from several seismological networks and preliminary 3D tomographic results. Ann. Geofis., 40, 161–174.

SPÜHLER, E. 1999: Swiss National Strong Motion Network: Strong motion bulletin, June 1998 – September 1999. Publ. Series of the Swiss Seismological Service, Nr. 112, ETH-Zürich.

WALDHAUSER, F. 1996: A parametrized three-dimensional Alpine crustal model and its application to teleseismic wavefront scattering. Ph.D. Thesis Nr. 11940, ETH-Zürich, 137 pp.

WALDHAUSER, F., KISSLING, E., ANSORGE, J., MUELLER, ST. 1998: Three-dimensional Interface Modeling with two-dimensional Seismic Data: the Alpine Crust-Mantle boundary. Geoph. J. Int., 135, 264–278.

YAN, Q. Z. & MECHIE, J. 1989: A fine structural section through the crust and lower lithosphere along the axial region of the Alps. Geophys. J. Int. 98, 465–488.

YE, S., ANSORGE, J., KISSLING, E. & MUELLER, S. 1995: Crustal structure beneath the eastern Swiss Alps derived from seismic refraction data. Tectonophysics 242, 199–221.

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