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Earthquakes in Switzerland and surrounding regions during 2001

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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 2001. During this period, 382 earthquakes and 48 quarry blasts were detected and located in the region under consideration. With 44 events with $M_L \geq 2.5$, the seismic activity in the year 2001 was above the average over the last 27 years. However, more than 30% of the total seismic activity of 2001 is associated with three earthquake sequences near Martigny, Bormio and Val Baone (N. Italy). The strongest event with M_L 4.1 was part of the Bormio sequence. The sequence of 27 events near Martigny, in the lower Valais, activated a 2 km long segment of a SW-NE trending strike-slip fault at a depth of about 6 km. A moderate M_L 3.8 earthquake just below Linthal, GL, produced a peak ground acceleration of 20% g, which is unusually high for an earthquake of this magnitude. Except for six events beneath the northern foreland and one noteworthy event below the southern margin of the Alps, all reliably located earthquakes of the year 2001 occurred in the upper 15 km of the crust. Fault-plane solutions were determined for seven events, which in five cases were complemented by full-waveform moment tensor inversions of local broad-band data.

ZUSAMMENFASSUNG

Dieser Bericht des Schweizerischen Erdbebendienstes stellt eine Zusammenfassung der im Vorjahr in der Schweiz und Umgebung aufgetretenen Erdbeben dar. Im Jahr 2001 wurden im erwähnten Gebiet 382 Erdbeben sowie 48 Sprengungen erfasst und lokalisiert. Mit 44 Beben mit Magnituden $M_L \geq 2.5$ war die seismische Aktivität überdurchschnittlich. Mehr als 30% aller Ereignisse sind jedoch drei Erdbebenserien bei Martigny, Bormio und Val Baone (Norditalien) zuzuschreiben. Das stärkste Ereignis mit M_L 4.1 war Teil der Serie von Bormio. Die Serie von 27 Beben bei Martigny im Unterwallis hat ein 2 km langes Segment einer SW-NE streichenden Blattverwerfung in rund 6 km Tiefe aktiviert. Ein mittelstarkes M_L 3.8 Beben ganz in der Nähe von Linthal, GL, hat dort eine maximale Bodenbeschleunigung von 20% g verursacht, was für ein Beben dieser Magnitude ungewöhnlich hoch ist. Mit Ausnahme von sechs Ereignissen unter dem Jura und der Molasse, sowie von einem bemerkenswerten Beben am Südrand der Alpen, ereigneten sich alle Beben, deren Herdtiefe mit genügender Sicherheit bestimmbar sind, in den oberen 15 km der Erdkruste. Für sieben Ereignisse sind Herdflächenlösungen konstruiert worden, welche in fünf Fällen durch Momenten-Tensoren aus der Wellenforminversion von lokalen Breitbanddaten ergänzt werden konnten.

RESUMÉ

Le présent rapport du Service Sismologique Suisse résume l'activité sismique de l'année écoulée, en Suisse et dans les régions limitrophes. En 2001, 382 tremblements de terre ont été détectés et localisés dans la région considérée. De plus, 48 événements ont été identifiés comme des tirs de carrière. Avec 44 événements de magnitude $M_L \geq 2.5$ l'activité sismique de l'année 2001 se situe au dessus de la moyenne sur les 27 dernières années. Cependent plus de 30% de l'activité sismique de l'année 2001 est associée à trois séquences de tremblement de terre près de Martigny, Bormio et Val Baone (Italie du Nord). L' événement le plus fort, qui atteint une magnitude de M_L 4.1, fait partie de la série de Bormio. Les 27 événements de la série près de Martigny dans le Bas Valais s'alignent, sur 2 km, le long d'un segment de faille de direction SO-NE. Cette faille de type décrochement se trouve à une profondeur de 6 km environ. Un séisme de magnitude modérée, M_L 3.8, près de Linthal, GL, a produit une acceleration de 20% de g, ce qui est inabituel pour un événement de cette magnitude. En dehors de six événements sous l'avantpays nord, et d'un séisme particulier à la limite méridionale des Alpes, tous les séismes localisés de manière fiable durant l'année 2001 sont situés dans les 15 premiers kilomètres de la croûte. Des mécanismes au foyer ont été déterminés pour sept événements, qui dans cinq cas ont été complétés par l'inversion du tenseur du moment sismique avec modélisation d'enregistrements locaux à large-bande.

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

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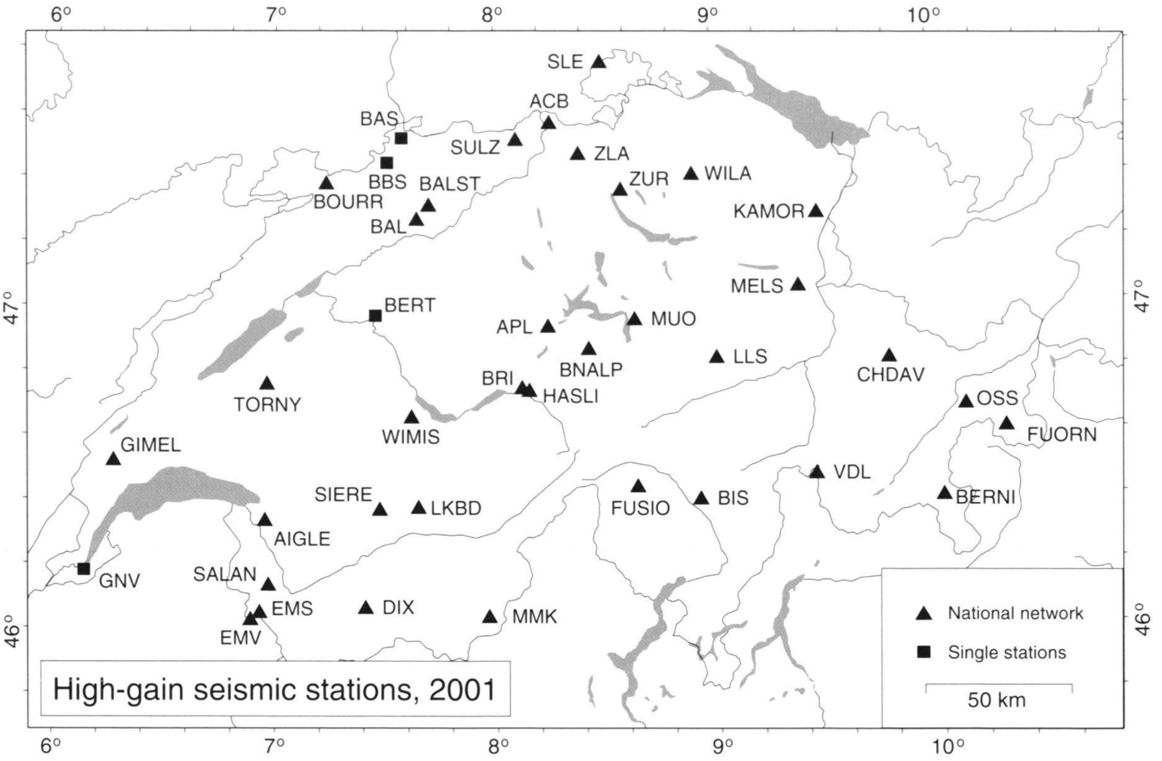

Fig. 1. Seismograph stations in Switzerland operational at the end of 2001.

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, 1999, 2001; Deichmann et al. 1998, 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 2001

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 during 2001 by the strong-motion network is documented separately (Wyss 2002).

Since 1998, the configuration of the national high-gain network is undergoing a transformation from a short-period analog telemetry system to a digital high-dynamic-range network equipped almost entirely with broadband STS-2 sensors. For a detailed description of the new data acquisition system, see Baer et al. (2001). By the end of 2001, the installation of the new network was almost completed (Table 1 and Figure 1) and the two systems were operating in parallel. In the course of the year 2001, two additional sites have been equipped with the new system (SLE and SALAN), thus increasing the total number of digital stations to 26 (BB and EB in Table 1). Of the stations that were part of the local network operating since the end of 1983 in northern Switzerland (e.g. Deichmann et al. 2000a, 2000b), only two were still operational by the end of 2001: ACB and SULZ (the latter was formerly called CHE and has been converted to a broad-band station). By the middle of the year 2002, three new digital sites will be operational west of Lake Neuchâtel, near the Sanetsch Pass (between the Bernese Oberland and the Valais) and at the southern tip of Canton Ticino.

Tab. 1. Seismograph stations operational at the end of 2001. Instrument types: SP = 1 - 2 seconds, EB = 5 seconds, BB = broad band, 1 = vertical component only, 3 = vertical and horizontal components, 4 = additional low-gain vertical component channel.

National high-gain 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	
CHDAV	Davos, GR	BB-3	temporary
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	
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
ROM	Romont, FR	SP-4	coloc. TORNY
SALAN	Lac de Salanfe, VS	EB-3	
SIERE	Sierre, VS	SP-4	
SLE	Schleitheim, SH	SP-3, BB-3	
STG	Saint Georges, VD	SP-3	coloc. GIMEL
SULZ	Cheisacher, AG	BB-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, BI	SP-1	telemetry (LED)
BERT	Bern, BE	SP-3	paper records
GNV	Geneva, GE	SP-1	paper records

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 de la 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, that can use any Earth model for which 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 in a simplified way account for differences between the near-surface geology in the Alps and foreland as well as for the large depth variation of the crust-mantle boundary. In addition, calculated travel times are corrected for differences in station elevation.

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; Roth et al. 1992; 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 frequen-

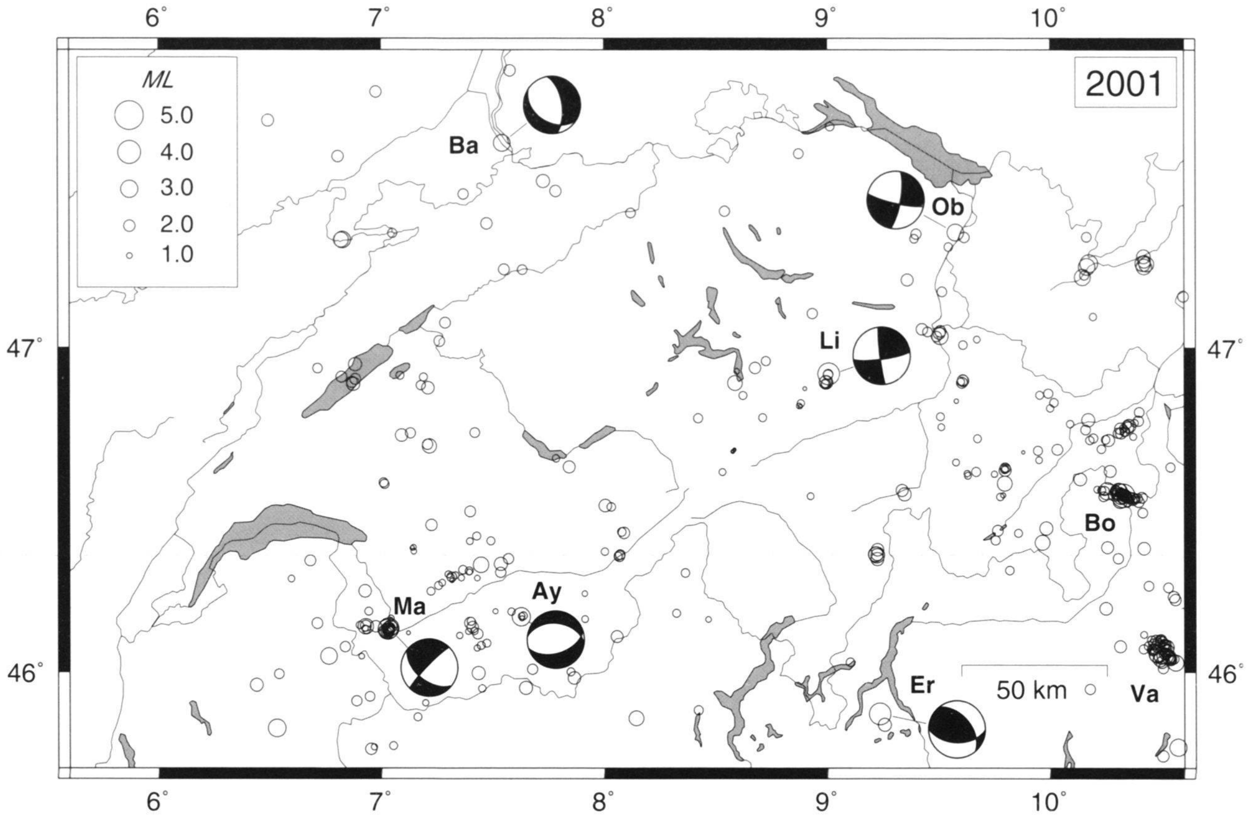

Fig. 2. Epicenters and focal mechanisms of earthquakes recorded by the Swiss Seismological Service during 2001. Epicenters of earthquakes mentioned in the text are Ayer (Ay), Basel-St.Louis (Ba), Bormio (Bo), Erba (Er), Linthal (Li), Martigny (Ma), Oberriet (Ob), Val Baone (Va). In the case of Martigny, only one of the two focal mechanisms is shown.

cies; thus, a simple one-dimensional velocity-depth model is suficient 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.

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 the equivalent amplitudes of signals recorded by a standard Wood-Anderson seismograph. The broadband 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 2001

Overview

During 2001, the Swiss Seismological Service detected and located 382 earthquakes in the region shown in Figure 2. Based on such criteria as the time of occurrence, the location, the signal character or on direct information, 48 additional seismic events were identified as quarry blasts.

Magnitude values of the events recorded in 2001 range between $M_L = 0.4$ and 4.1. 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 $M_L \geq 2.5$

Date & Time UTC	Lat. [°N]	Lon. [°E]	X / Y [km]	Depth [km]	Mag. [M_L]	Q	Location
2001.01.20 15:49:10	45.856	8.142	655/ 78	13	2.6	C	Val Sesia, I
2001.01.25 02:17:15	46.050	6.764	548/100	7	2.9	B	Sixt, F
2001.01.30 03:24:21	47.035	9.506	757/211	9	2.9	A	Bad Ragaz, SG
2001.02.23 22:19:41	46.136	7.031	568/109	6	3.6	A	Martigny, VS
2001.02.25 01:22:30	46.133	7.028	568/109	6	3.5	A	Martigny, VS
2001.02.25 02:07:57	46.136	7.038	568/109	6	2.7	A	Martigny, VS
2001.02.28 09:26:27	46.126	7.021	568/109	6	2.6	A	Martigny, VS
2001.03.14 10:37:18	47.350	9.576	761/246	30	2.9	A	Oberriet, SG
2001.03.16 05:40:36	47.214	10.145	805/233	5	2.8	C	Lech, A
2001.03.17 00:29:59	46.920	9.006	719/198	3	3.8	A	Linthal, GL
2001.03.19 00:31:17	47.308	6.087	498/240	7	2.8	D	Besancon, F
2001.03.19 14:12:13	46.402	9.965	794/142	8	2.6	A	Lago Bianco, GR
2001.03.28 03:42:27	46.333	7.447	601/131	10	2.7	A	Tseuzier, VS
2001.04.06 02:22:52	45.870	9.234	739/ 81	22	3.8	C	Erba, I
2001.04.07 08:11:44	46.142	6.929	561/110	6	2.7	A	Lac Salanfe, VS
2001.04.12 07:06:43	47.620	7.543	608/274	8	2.9	A	Basel-St.Louis, F
2001.05.30 22:43:50	45.825	6.530	529/ 75	10	3.1	C	Haute Savoie, F
2001.06.02 08:12:04	46.892	8.586	687/194	6	2.6	A	Seedorf, UR
2001.06.12 14:54:25	46.364	9.220	737/136	12	2.8	B	San Bernardino, GR
2001.06.12 14:58:31	46.366	9.216	737/136	9	2.6	B	San Bernardino, GR
2001.07.09 22:50:02	46.172	7.626	614/113	6	3.2	B	Ayer, VS
2001.07.17 22:30:16	47.328	6.821	553/242	1	2.6	A	St. Hippolyte, F
2001.07.17 23:20:03	47.328	6.827	554/242	1	2.9	A	St. Hippolyte, F
2001.07.30 17:49:34	46.584	9.796	781/162	9	2.6	B	Albulapass, GR
2001.08.03 03:05:00	46.543	10.318	821/159	6	2.6	B	Bormio, I
2001.08.05 06:04:54	46.078	10.521	838/107	10	2.5	C	Val Baone, I
2001.08.07 21:55:40	47.254	10.432	826/238	10	2.6	C	Lechtal, A
2001.08.15 16:26:24	46.051	10.512	838/104	10	2.8	C	Val Baone, I
2001.08.24 14:37:59	46.056	10.479	835/105	10	3.0	C	Val Baone, I
2001.08.30 02:44:48	46.054	10.475	835/105	10	2.5	C	Val Baone, I
2001.09.04 14:30:05	46.029	10.560	842/102	11	2.8	C	Val Baone, I
2001.09.07 20:57:31	47.246	10.421	826/237	8	2.7	C	Lechtal, A
2001.09.07 21:52:18	47.256	10.416	825/238	10	2.7	C	Lechtal, A
2001.09.22 10:57:04	46.041	10.492	836/103	10	2.6	C	Val Baone, I
2001.10.01 06:36:22	46.547	10.327	821/159	10	4.1	B	Bormio, I
2001.10.01 06:41:22	46.561	10.306	820/161	8	2.8	B	Bormio, I
2001.10.01 07:27:01	46.559	10.309	820/160	8	2.9	B	Bormio, I
2001.10.11 22:47:46	46.699	7.216	583/172	13	2.5	B	Montevraz, FR
2001.10.28 00:09:29	45.765	10.571	844/ 73	10	3.0	D	Lago d'Idro, I
2001.10.30 17:30:22	47.256	10.174	807/237	10	3.1	C	Lech, A
2001.10.30 17:31:32	47.246	10.164	806/236	10	2.9	C	Lech, A
2001.11.05 22:01:26	46.563	10.312	820/161	8	2.5	B	Bormio, I
2001.11.24 18:05:49	46.561	10.255	816/160	7	3.0	B	Bormio, I
2001.12.14 09:52:41	46.530	10.313	820/157	5	2.5	B	Bormio, I

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.

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

recorded in Switzerland and surroundings since 1975 are shown on the epicenter map in Figure 3.

The fault-plane solutions with first-motion directions are shown in Figure 4, 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 2001.

Significant earthquakes of 2001

Martigny

Between January and October 2001, the high-gain networt recorded a sequence of 27 events located in the vicinity of

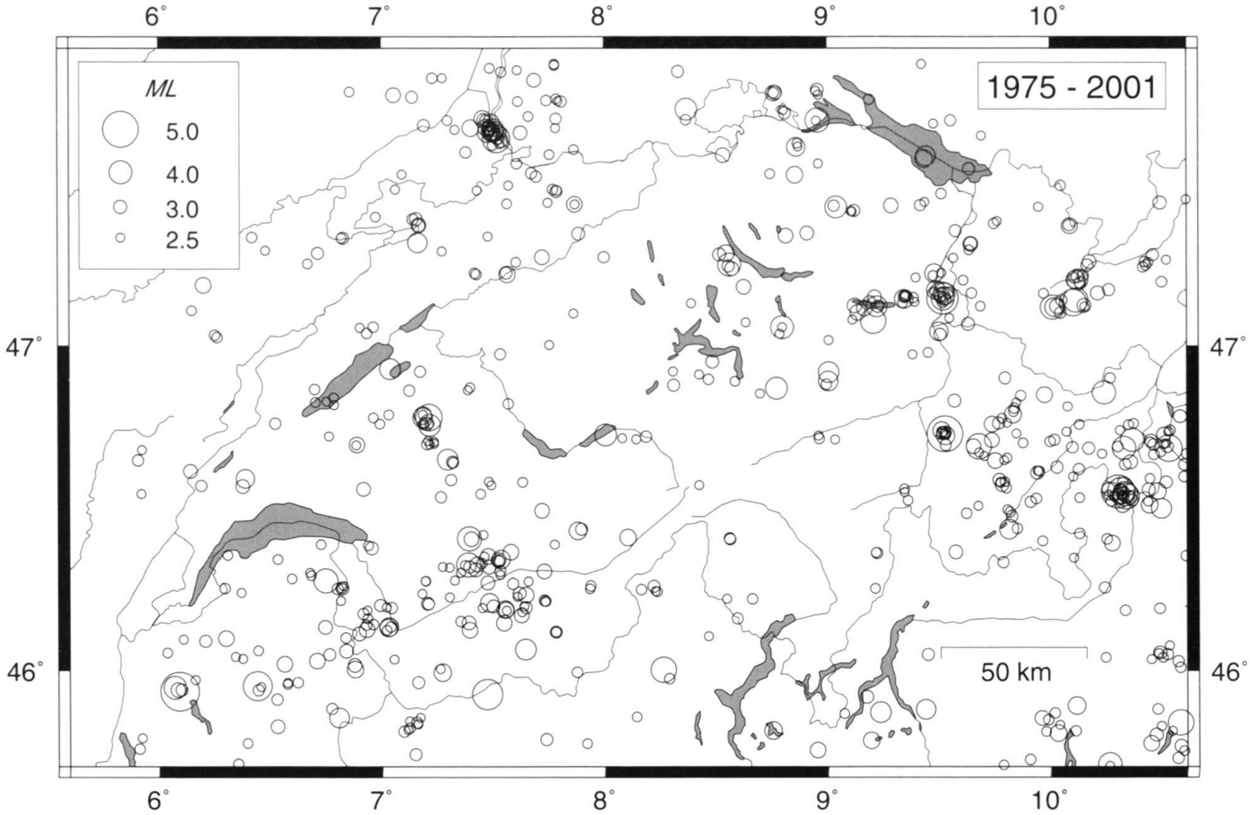

Fig. 3. Epicenters of earthquakes with Magnitudes $M_L \geq 2.5$, during the period 1975–2001.

Martigny, in the lower Valais. A detailed analysis of this earthquake sequence, which includes two events with magnitudes greater than 3, is presented in the Appendix of this report.

Oberriet

This M_L 2.9 event, which occurred on March 14th near the northern end of the Rhine Valley of St. Gallen, is of particular interest, because of its focal depth of 30 km. The location is well constrained by a station distribution with a maximum azimuthal gap of 108° and by three stations at epicentral distances closer than 25 km. The Moho at this location is at a depth of 36 km (Waldhauser et al. 1998). Thus this earthquake provides evidence for the eastward continuation of the well-known lower-crustal seismicity of the northern Alpine foreland of Switzerland (e.g. Deichmann et al. 2000a). Although we do not have any observations in the SE quadrant, the fault-plane solution is constrained to within less than ±10° and corresponds to a strike-slip mechanism with an orientation typical for the earthquakes in this region (Deichmann et al. 2000b).

Linthal

This event, which occurred at 1:30 in the morning (local time) of March 17th below the town of Linthal, Canton Glarus, is remarkable: although its magnitude is moderate (M_L = 3.8 and M_w = 3.4), the free-field strongmotion station in Linthal, at an epicentral distance of 1 km, recorded a peak horizontal acceleration of 20% g (Wyss 2002). The reasons for such a high acceleration are probably the shallow focal depth (3 km maximum, constrained by an S-P time of less than 0.5 s at the strong-motion station) and the amplifying effect of the soft alluvial fill of the valley floor. The effect of the shallow source can also be seen in the macroseismic observations shown in Figure 5: several intensity values of V are concentrated in the epicentral area and the intensity fall-off with distance is rapid. In the subsequent four days, this earthquake was followed by two small aftershocks with M_L < 2, and in the first half of August four additional events with M_L between 1.4 and 2.4 occurred about 3 km further south. The strike-slip focal mechanism with N-S and E-W striking nodal planes is optimally constrained by both the first-motion fault-plane solution and the full-waveform inversion.

In November of 1990, the area just south of Linthal was already the site of a sequence of earthquakes that included a M_L 3.6 event. This earlier event also features a strike-slip mechanism, but its nodal planes strike NNW-SSE and ENE-WSW (Kastrup 2002). The rough N-S alignment of the routine epicenter locations in this region would suggest that the N-S and

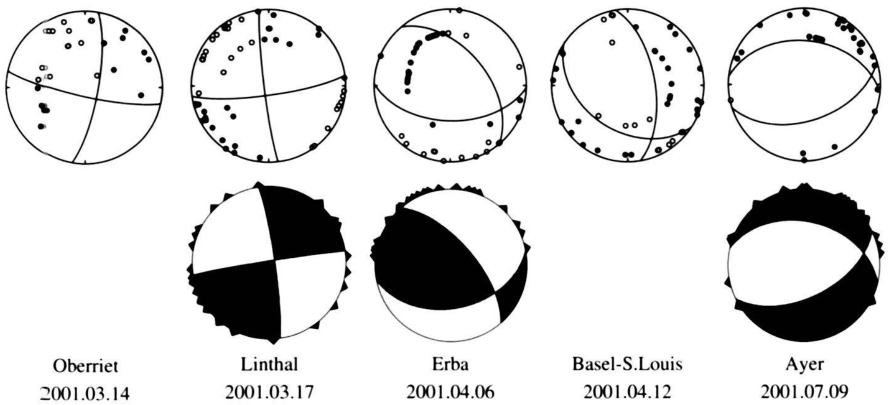

Fig. 4. Fault-plane solutions based on first-motion polarities and moment tensors based on full-waveform inversions (lower hemisphere, equal area projection). In the fault-plane solutions (above), solid circles correspond to compressive first motion (up) and empty circles to dilatational first motion (down); on the moment tensors (below), triangles show the station locations. The focal mechanisms of the Martigny events are given in the Appendix.

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
Martigny	2001.02.23 22:20	6	M_L 3.6	129/52/-009	224/83/-142	093/31	350/20
		6	M_w 3.6	123/48/-026	231/71/-136	096/44	352/14
Martigny	2001.02.25 01:23	6	M_L 3.5	138/56/-011	234/81/-146	101/30	002/16
		9	M_w 3.3	132/51/-009	228/83/-141	098/32	354/21
Oberriet	2001.03.14 10:37	30	M_L 2.9	010/76/-010	102/80/-166	327/17	236/03
Linthal	2001.03.17 00:30	3	M_L 3.8	082/80/ 175	173/85/ 010	307/03	038/11
		4	M_w 3.4	261/88/ 174	352/84/ 002	307/03	216/06
Erba	2001.04.06 02:23	22	M_L 3.8	320/50/ 126	091/52/ 055	205/01	297/63
		24	M_w 3.5	319/65/ 126	079/43/ 039	024/13	275/55
Basel-S.Louis	2001.04.12 07:07	8	M_L 2.9	123/40/-130	351/61/-062	308/63	061/11
Ayer	2001.07.09 22:50	6	M_L 3.2	276/42/-072	072/50/-106	283/77	173/04
		6	M_w 3.1	283/42/-059	064/55/-115	279/69	171/07

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).

NNW-SSE trending nodal plane constitute parts of an active fault in this area. However this needs to be confirmed by a more detailed analysis.

Erba

The epicenter of this event (M_L 3.8 and M_w 3.5), that occurred on April 6th, is located between Como and Lecco at the southern margin of the Alps. The full-waveform inversion for this event results in a thrust faulting mechanism at a depth of 24 km. Within the limits imposed by our imperfect model of the complex crustal structure in this region, this focal depth can be matched by 2-D ray tracing and the moment tensor is in good agreement with the faultplane solution derived from the first-motion polarities (Table 4 and Fig. 4). This event is particularly interesting for two reasons: firstly, it confirms earlier reports about the existence of lower-crustal earthquakes beneath the southern margin of the Alps (e.g. Deichmann & Baer 1990) and secondly, it provides a focal mechanism in a region where well-constrained mechanisms are sparse.

Basel-St.Louis

The epicenter of this M_L 2.9 event was located near the airport of Mulhouse, NW of Basel. Based on a station distribution with an azimuthal gap of only 87° and a minimum epicentral distance of 9 km, the routinely determined focal depth lies between 7 and 10 km, and two-dimensional ray-tracing gives a best fit for a depth of 8 km. The normal faulting mechanism is well constrained with a ENE-WSW striking T-axis (Fig. 4 and Table 4).

Ayer

This event with M_L = 3.2 and M_w = 3.1 occurred on July 9th near the town of Ayer, in the southern Valais. With a minimum epicentral distance of about 20 km, routine locations do not constrain the focal depth. The full-waveform inversion exhibits a best fit for a focal depth of 6 km; raytracing suggests a depth closer to 9 km, but, because the modelling results are not entirely satisfactory, we have retained the result of the moment tensor inversion. By itself the fault-plane solution based on first-motion polarities is not optimally constrained, but together with the moment tensor inversion the result is reliable. The normal-faulting mechanism with a practically N-S trending T-axis is similar to mechanisms of past earthquakes in this region: Vissoie 1986 (Eva et al. 1998), Vissoie 1990 (Maurer et al. 1997) and Grimentz 1998 (Baer et al. 1999). These earthquakes are

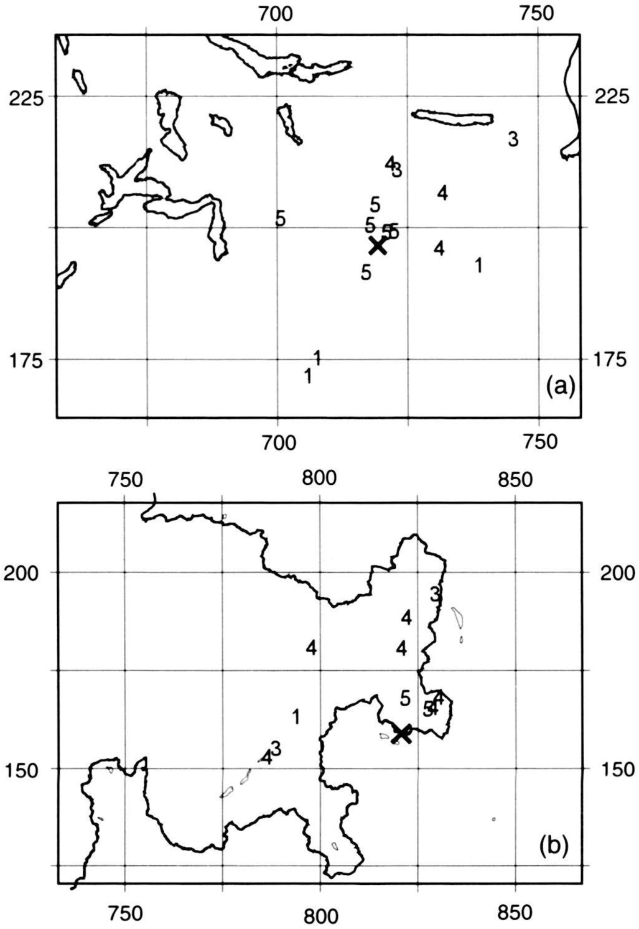

Fig. 5. Macroseismic observations of the Linthal event of 2001/03/17 (a) and of the Bormio event of 2001/10/01 (b). Each value represents the macroseismic intensity (EMS-98) assigned to a single postal code zone. The X corresponds to the instrumental epicenter. The Swiss cartesian coordinate grid is labeled in km.

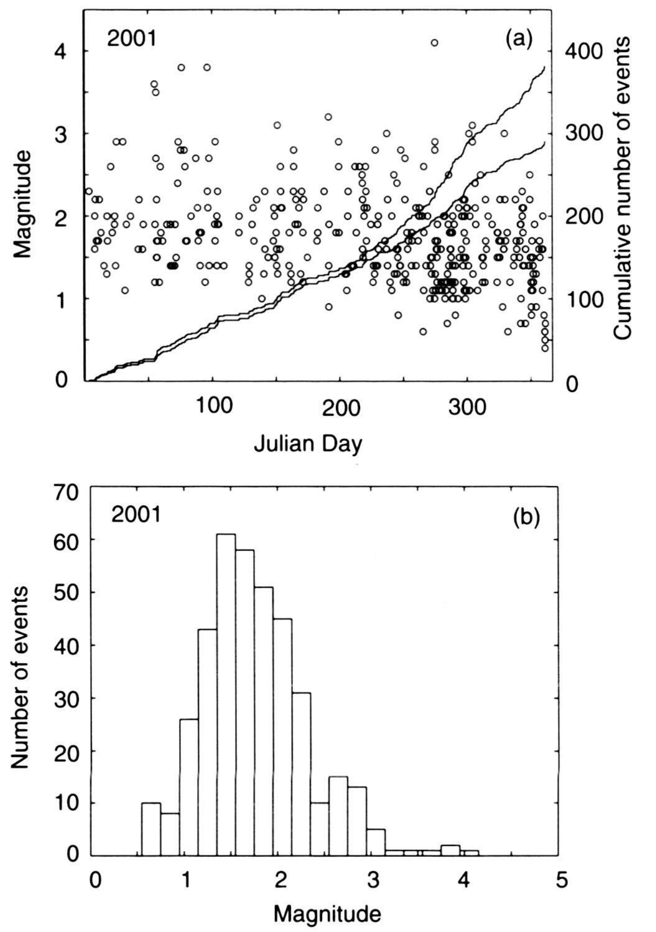

Fig. 6. Earthquake activity during 2001: magnitude of each event and cumulative number of events (a); histogram of magnitudes (b). In (a) the upper curve shows the cumulative number of all events, whereas the lower curve corresponds to the number of events without the Bormio aftershocks and the Val Baone events.

evidence of the typical extensional deformation presently active in the Penninic Nappes of the southern Valais (e.g. Maurer et al. 1997).

Val Baone

In the second half of 2001, an earthquake swarm with epicenter in Val Baone near the Tonale Pass in northern Italy became active (Fig. 2). The Swiss high-gain network detected 42 events that are associated with this cluster; the strongest event reached M_L 3.0.

Bormio

The strongest earthquake during 2001 in Switzerland and its immediate surroundings was the M_L 4.1 event of October 1st with epicenter between Bormio and Val Müstair. In the epicentral region this quake produced shaking of intensity V (Fig. 5). This event, together with 48 other weaker ones, represents continuing activity in the epicentral region of the M_L 4.9 Bormio earthquake of Dec. 29th, 1999.

Discussion

Figure 3 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 – 2001. 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 12 % of the total number of events detected during that time period in the same area.

Averaged over the last 27 years, the earthquakes shown in Figure 3 are equivalent to about 25 events with $M_L \geq 2.5$ and about 8 events with $M_L \geq 3$ per year. With 44 events with $M_L \geq$

2.5 and 11 events reaching $M_L \geq 3$, the seismic activity in 2001 was thus above the average over the last 27 years for earthquakes in these magnitude ranges. However, 17 of the 44 events with $M_L \geq 2.5$ are part of the sequences of Martigny, Val Baone and Bormio.

Figure 6 shows the temporal evolution of seismicity. Even after subtracting the events of the Bormio and Val Baone sequences, activity seems to increase towards the end of the year. This is due to the fact that, as of August 27th 2001, the event detection algorithms operate on the broadband signals instead of on the old short-period data. With this change, the frequency band is extended to higher frequencies, with the result that the network has become more sensitive to low-magnitude events.

In addition to the Bormio aftershocks, seismic activity in the year 2001 has been particularly high in Canton Graubünden. As in the past, the Valais was active as well, in particular with the sequence of Martigny.

Routinely calculated focal depths for the 382 earthquakes recorded in 2001 range between 1 and 30 km, but only 7 of these hypocenters are deeper than 15 km. As in the past (e.g. Deichmann et al. 2000a), almost all these deep sources are located in the lower crust beneath the Jura Mountains and Molasse Basin of northern Switzerland. The only exception is the source of the Erba event at a depth of more than 20 km beneath the southern margin of the Alps.

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Appendix:

The earthquake sequence of Martigny

At 23:20 local time on February 23rd and at 02:22 on February 25th, 2001, the lower Valais was shaken by two earthquakes that reached maximum intensity values of V (EMS-98) and that caused some concern among the local population. The macroseismic observations shown in Figure 7 seem to indicate that the first event was stronger then the second one. However, the macroseismic field of the second event is not complete: the second event occurred later in the night and thus was not felt as consciously by as many people as the first one, and in addition, many of those who responded to the requests for information referred only to the first event. In fact, with M_L 3.6 and 3.5 their magnitudes do not differ by much. Moreover, peak horizontal ground accelerations of the two events recorded by the free-field strong-motion stations in the epicentral area differ by less than 10% (Wyss 2002).

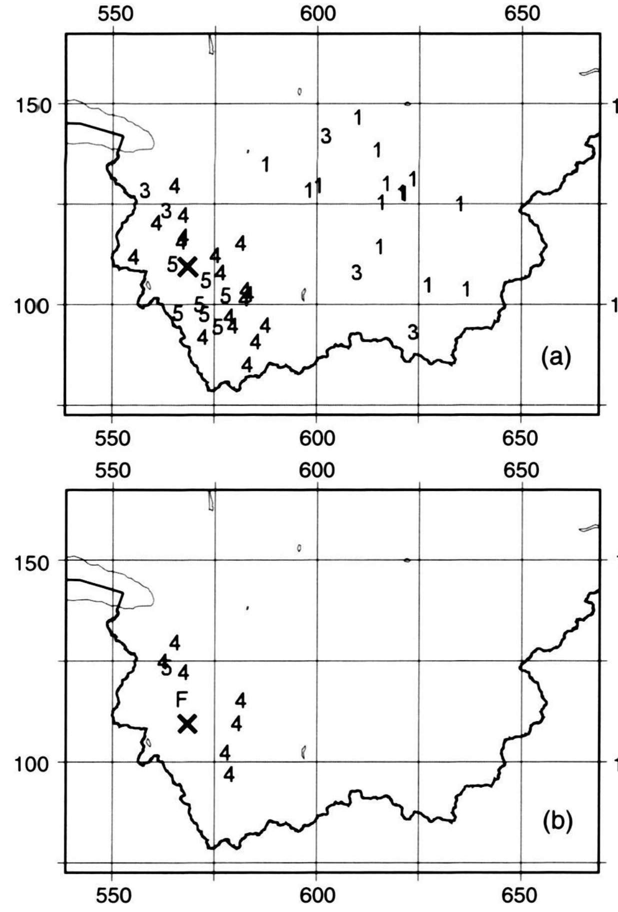

Fig. 7. Macroseismic observations of the two strongest Martigny events: (a) 2001/02/23 23:19 local time and (b) 2001/02/25 02:22 local time. Each value represents the macroseismic intensity (EMS-98) assigned to a single postal code zone. The X corresponds to the instrumental epicenter. The Swiss cartesian coordinate grid is labeled in km.

Both events were part of a sequence of 27 events that occurred between January 8th and October 24th, 2001 (Table 5). The seismograms of all events are very similar to each other (Figure 8), implying that their hypocenters must be located close together and that their focal mechanisms must be practically

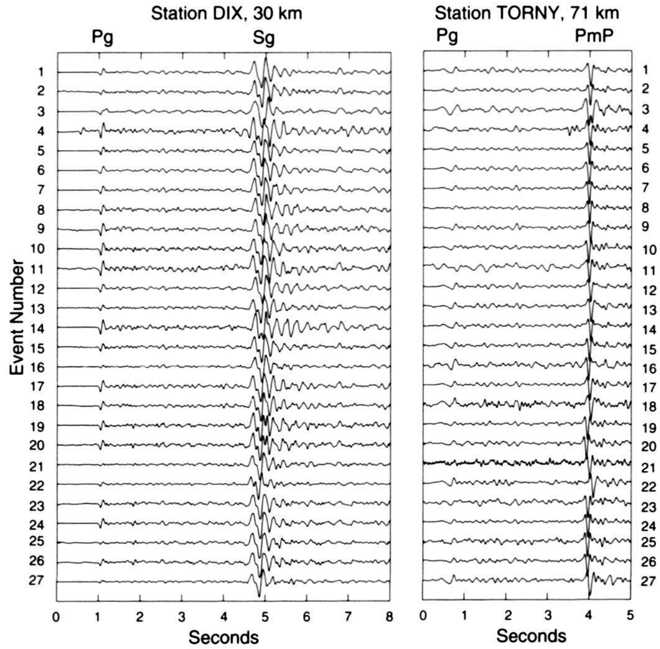

Fig. 8. Seismograms of the Martigny events recorded at stations DIX and TORNY. The signals at DIX are aligned on the Pg arrivals and bandpass filtered between 0.5 and 16 Hz; the signals at TORNY are bandpass filtered between 1 and 10 Hz and aligned on the Pg arrivals at station AIGLE, which features more impulsive onsets and which is located in practically the same direction as TORNY. The clearly visible shift between the PmP of events 20 and 22 implies that event 20 must be deeper and event 22 shallower.

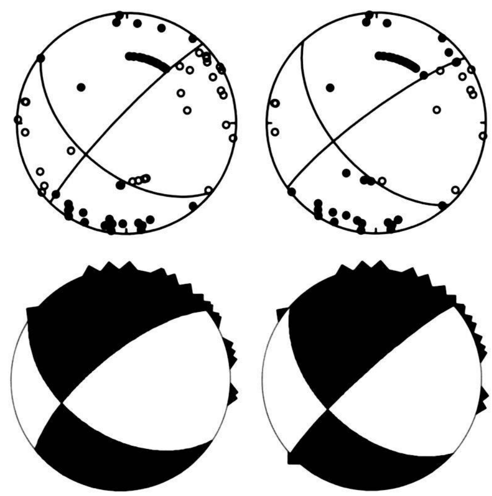

Fig. 9. Focal mechanisms of the two strongest events of the Martigny cluster, based on first-motion polarities (above) and full-waveform inversion (below). The focal mechanism parameters are listed in Table 4. (Symbols as in Figure 4.)

identical. The event with the best-constrained absolute location occurred on September 16th at 7:49 UTC. Although it only reached M_L 2.1, it triggered the strong-motion station at Martigny and in addition, was also recorded by the newly installed high-gain station at Lac de Salanfe, situated only 4.3 km from the epicenter. To reduce errors due to unmodelled lateral velocity hetorogeneities, we located the event using only stations within a distance radius of 50 km; despite this restriction, the azimuthal station gap amounted to only 94°. The resulting location places the epicenter 6 km NW of Martigny, at the SE side of the Rhone Valley, and gives a focal depth of 6 km. The location uncertainty is estimated to be ±1 km horizontally and ±2 km in depth.

Focal mechanisms for the two strongest events, based both on first-motion fault-plane solutions and on full-waveform inversion, are shown in Figure 9. The results of both techniques are well constrained by the data and are largely consistent with each other. The mechanisms of the two events correspond to strike-slip faulting with only small differences in the orientation of the nodal planes.

To resolve the source geometry and to identify the active fault plane of such an earthquake cluster, it is necessary to determine high-precision relative hypocenter locations of the individual events, and thus to determine relative arrival times at sub-sample precision. Such a high timing precision was obtained by exploiting the similarity among the signals and applying a time-domain cross-correlation technique (Deichmann & Garcia-Fernandez 1992). With the high-precision relative arrival times we then made use of a master-event location algorithm proposed by Console & DiGiovambattista (1987) to obtain relative location uncertainties on the order of a few tens of meters. Of the 27 events only event number 3, the strongest one, could not be included in the relative location procedure because of insufficient signal similarity. The difference in signal character of this event relative to the others is due to a longer

Tab. 5. List of events belonging to the cluster of Martigny.

Nr.	Date & Time (UTC)	M_L
1	2001.01.08 09:29:02	2.2
2	2001.01.15 04:14:14	1.4
3	2001.02.23 22:19:42	3.6
4	2001.02.23 23:45:56	1.2
5	2001.02.24 06:17:49	1.9
6	2001.02.25 01:22:31	3.5
7	2001.02.25 02:07:57	2.7
8	2001.02.25 09:01:19	1.5
9	2001.02.25 16:06:43	1.5
10	2001.02.26 09:14:42	1.7
11	2001.02.27 10:36:45	1.2
12	2001.02.28 09:26:28	2.6
13	2001.03.02 01:56:39	1.7
14	2001.03.05 09:41:58	1.9
15	2001.03.09 16:39:08	1.4
16	2001.03.12 13:24:51	1.5
17	2001.03.13 22:20:17	2.4
18	2001.03.31 07:41:43	1.4
19	2001.05.28 19:55:05	1.5
20	2001.05.30 03:57:23	1.4
21	2001.05.30 23:17:51	1.3
22	2001.06.30 23:14:41	1.7
23	2001.09.16 07:43:01	1.4
24	2001.09.16 07:49:51	2.1
25	2001.09.22 04:07:58	1.1
26	2001.10.13 03:03:57	1.2
27	2001.10.24 14:59:50	2.2

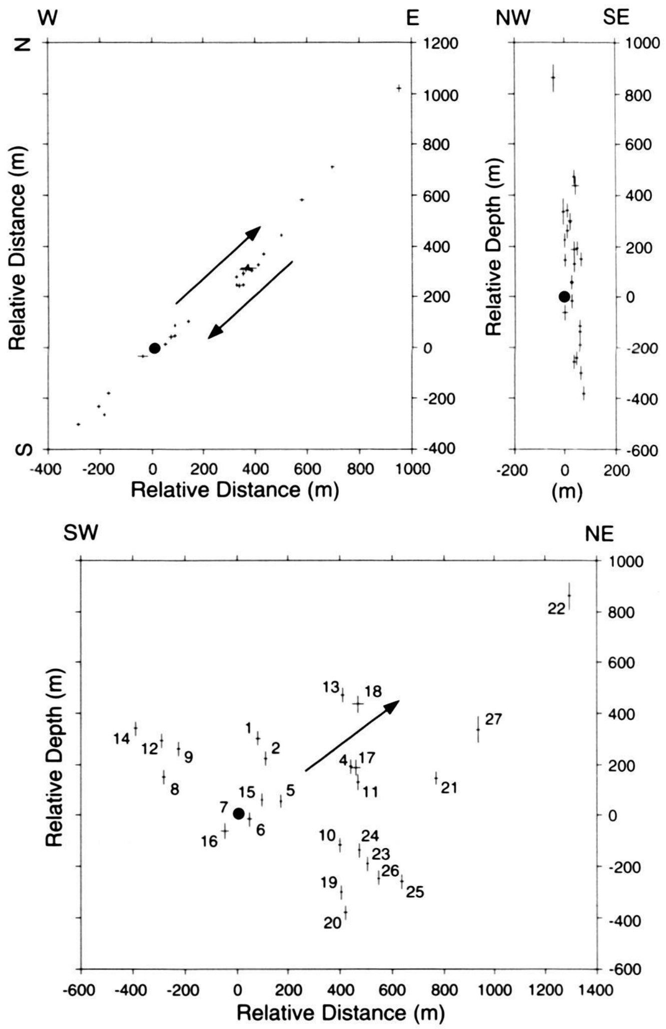

Fig. 10. Relative locations of the Martigny events: epicenter map (a) and depth section perpendicular (b) and parallel (c) to the inferred fault plane. The numbers in (c) refer to Table 5. The black dot shows the location of event Nr. 7, which we chose as master event. Event Nr. 3 is missing, because its signals could not be correlated with the others (see text). The size of the crosses corresponds to the computed relative location uncertainty (1σ) of each event. The pair of arrows in (a) shows the sense of dislocation along the inferred fault and the arrow in (c) corresponds to the slip vector of the hanging wall.

source-time function, that consists of two distinct subevents. This can be seen best by comparing the PmP waveforms at station TORNY, shown in Figure 8: instead of the simple wavelet with a single strong downward swing seen in all other seismograms, the downward pulse of event number 3 is two-pronged, corresponding to two subevents within a time interval of less than 0.1 s.

Event number 4 is also a doublet, but in this case, the seismograms correspond to two separate events that occurred 0.4 s apart. Thus effectively, the total number of events in the Martigny sequence detected by the high-gain network is 28. However, since the hypocenter of the first and weaker event of this doublet can not be located, we have not included it in our analysis.

For the cross-correlation and subsequently as input for the relative location algorithm we used the Pg and Sg arrivals at stations EMV, DIX and AIGLE as well as the PmP phase at station TORNY (Fig. 1). These stations are well distributed around the epicenter (gap = 129°), therefore the three P and the three S arrivals together with the downgoing raypath of the PmP at TORNY provide excellent constraints on both the horizontal and vertical coordinates of the relative locations. The hypocenters define an almost vertical SW-NE striking plane, that extends roughly 2 km horizontally and more than 1 km vertically (Figure 10). A comparison with the focal mechanisms (Fig. 9) shows that this plane closely matches one of the nodal planes and thus constitutes the active fault of the Martigny sequence. The dislocation on this fault corresponds to dextral strike-slip motion with a significant vertical component.

At the 2σ level of the location uncertainty, it is possible to fit a single fault plane through almost all hypocenters. However, in addition to the finite width of the hypocenter distribution suggested by Figure 10, two additional observations favour the view of a fault zone consisting of several individual subfaults, rather than of a single planar fault: (1) the structure imaged by the relative hypocenter locations dips slightly to the SE, whereas in the focal mechanisms of both of the strongest events (Fig. 9), the active fault planes dip slightly towards the NW; (2) variations in the amplitude ratios of P- to S-phases seen in the seismograms recorded at station DIX (Fig. 8) together with the observation that P-wave polarities at station EMS, situated exactly SW of the epicenters, are opposite to each other for about 50% of the events are evidence for differences in the strike of individual fault planes.

Figure 11 shows the location of the Martigny cluster superimposed on a digital elevation model. The epicenters are aligned parallel to the strike of the main geomorphic features of the region and to the strike of pre-Alpine internal structures of the Aiguilles Rouges Massif, such as the Miéville mylonite zone and the Carboniferous Salvan-Dorénaz graben. The location of the earthquakes coincides exactly with the center of this graben structure, which extends from the area of Vallorcine in the SW to below the Dents de Morcles NE of the Rhone Valley (Carte Tectonique, 1999). Although it is unlikely that the sedimentary graben fill extends down to a depth of 6 km (Pilloud 1991), it is probable that the earthquakes reactivated a boundary fault of this late hercynian structure (Burkhard, personal communication): late Alpine, post Morcles nappe em-

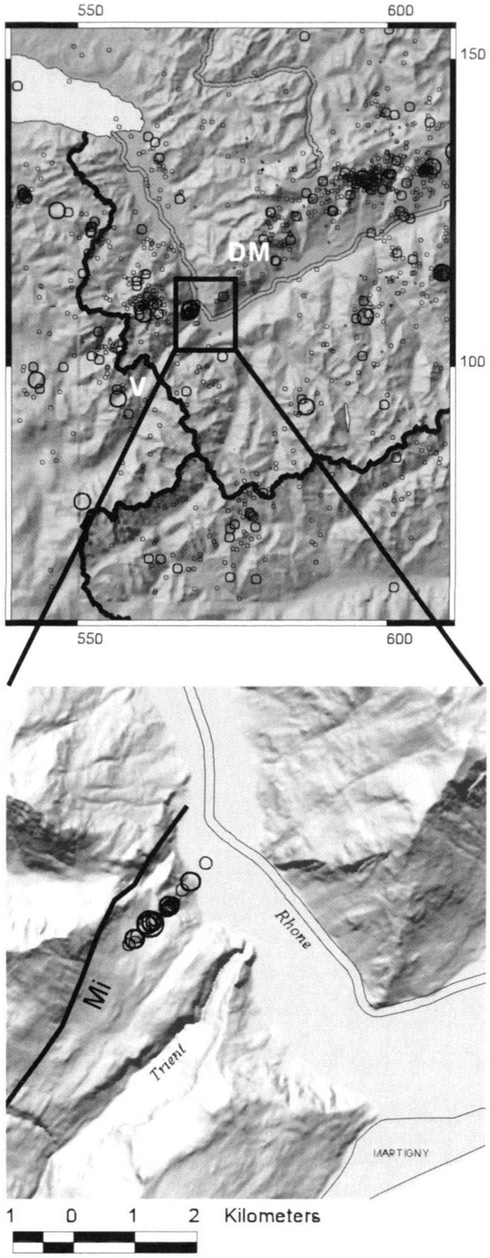

Fig. 11. Top: epicenters of all events with $M_L \geq 1$ over the period 1984-2001 (DM = Dent de Morcles, V = Vallorcine). Some of the events along the Rhone Valley might correspond to unidentified quarry blasts. Bottom: the Martigny cluster, fixed to the absolute location of event Nr. 24 (Mi = mylonite zone of Miéville). The SW-NE striking Carboniferous wedge of Salvan-Dorénaz lies between the Trient valley and the mylonites of Miéville. Digital elevation models RIMINI and DHM25 reproduced with permission from the Swiss Federal Office of Topography (BA024517).

placement reactivation and inversion of this graben has been shown to be responsible for the "synformal" shape and internal folding (Pilloud 1991; Badertscher & Burkhard 1998). Considering that both the mylonites of Miéville and the Carboniferous wedge extend over more than 20 km with practically the same strike as that of the fault patch imaged at depth by the earthquake sequence of 2001, it is conceivable that at some time a single earthquake could rupture a significantly larger portion of this fault zone. Note, however, that the strike of the fault delineated by the Martigny cluster differs by about 15° from the strike of the suggestive rectilinear alignment of epicenters that extends from the northern Valais towards the southwest across the Rhone Valley into France (Fig. 11 and Baer et al. 2001, Fig. 3).