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Earthquakes in Switzerland and surrounding regions during 1996[1]

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Key Words: Earthquakes, landslides, focal mechanisms, Switzerland

This article is dedicated to Professor Stephan Müller, former director of the Swiss Seismological Service. He died on February 17th, 1997. Stephan Müller initiated the idea of a modern seismic network in Switzerland, when he accepted the chair at the Institute of Geophysics of the ETH-Zürich in 1971.

ABSTRACT

With this contribution, the Swiss Seismological Service renews a tradition of annual reports summarizing the seismic activity in Switzerland and surrounding regions during the previous year. During 1996, 329 seismic events were detected and located in the region under consideration. Of these events, 34 were identified as quarry blasts and 5 as landslides. The magnitudes (M_L) of the detected earthquakes range between 0.9 and 5.1. The strongest earthquake, which occurred on July 15th near Annecy, France, reached an epicentral intensity of VII–VIII (MSK) and caused damages totalling about 300 million French Francs. On March 31st, a magnitude 4.6 event occurred on the border between the Valais and the Aosta Valley, triggering the strong motion arrays in the Grande Dixence and Mauvoisin dams but causing no damage, and, on August 24th, a magnitude 4.0 event with a focal depth of close to 30 km was clearly felt throughout northeastern Switzerland. The highest earthquake activity, both in terms of number of events and in terms of their size, occurred once again in the Valais. Most of the seismicity was restricted to the upper 15 km of the crust. Moreover, in agreement with previous observations, the 11 hypocenters with depths between 19 and 31 km are all located below the Jura Mountains and Molasse Basin of northern Switzerland. The focal mechanisms of the two events in the Valais and the two events in northern Switzerland analysed in this report are typical of the tectonic deformation in the respective regions: extensional deformation at a high angle to the strike of the Alpine chain in the southern Valais, a strike-slip mechanism with NW-SE oriented crustal shortening in the northern Valais and normal faulting with ENE-WSW extension below the northern Alpine foreland.

ZUSAMMENFASSUNG

Mit diesem Beitrag knüpft der Schweizerische Erdbebendienst an eine vergangene Tradition an, über die im Vorjahr in der Schweiz und Umgebung aufgetretenen Erdbeben zu berichten. Im Jahr 1996 wurden im erwähnten Gebiet 329 seismische Ereignisse erfasst und lokalisiert. Davon waren 34 Sprengungen und 5 Bergstürze. Die Magnituden (M_L) der erfassten Erdbeben liegen zwischen 0.9 und 5.1. Das stärkste Beben, das sich am 15. Juli in der Nähe von Annecy in Frankreich ereignet hat, hat eine Epizentralintensität von VII bis VIII (MSK) erreicht und Schäden von insgesamt etwa 300 Millionen französischen Francs verursacht. Im weiteren fand am 31. März im Grenzgebiet zwischen Wallis und Aostatal ein Erdbeben der Magnitude 4.6 statt, welches von den Starkbebenmessgeräten in den Stauanlagen von Grande Dixence und Mauvoisin aufgezeichnet wurde, ohne jedoch Schäden zu verursachen. Ausserdem wurde am 24. August ein Beben der Magnitude 4 mit einer Herdtiefe von fast 30 km in der ganzen Nordostschweiz gespürt. Die höchste Aktivität, sowohl bezüglich der Anzahl Ereignisse als auch ihrer Stärke, war wiederum im Wallis zu verzeichnen. In Einklang mit früheren Beobachtungen war der grösste Teil der Seismizität auf die obere Kruste beschränkt, und die 11 Erdbeben mit Herdtiefen zwischen 19 und 31 km ereigneten sich alle unter dem Jura und dem Nordschweizer Molassebecken. Die im Rahmen dieses Berichtes untersuchten Herdmechanismen der zwei Erdbeben im Wallis sowie der zwei Beben in der Nordschweiz sind repräsentativ für die tektonische Deformation in den jeweiligen Gebieten: Eine fast N-S gerichtete Extension im südlichen Wallis, eine Lateralverschiebung mit NW-SO orientierter Einengung sowie Abschiebungen mit ONO-WSW gerichteter Extension im nördlichen Alpenvorland.

RESUME

Avec la présente contribution, la service sismologique suisse renoue une tradition de présenter un rapport annuel qui résume l'activité sismique de l'année écoulée, en Suisse et dans les régions limitrophes. En 1996, 329 événements sismiques ont été détectés et localisés dans la région considérée. Parmi ces événements, 34 ont été identifiés comme des tirs de carrière et 5 comme des glissements de terrain. Les magnitudes (M_L) des tremblements de terre détectés s'étalent entre 0.9 et 5.1. L'événement le plus fort a eu lieu près d'Annecy, en France. Il a atteint une intensité épicentrale de VII–VIII (MSK) et a causé des dommages d'un montant d'environ 300 M de francs français. Un autre événement important, de magnitude 4.6, a eu lieu à la frontière entre le Valais et la vallée d'Aoste. Il a déclenché les accéléromètres des barrages de Mauvoisin et de la Grande Dixence sans toutefois causer de dommages. Un troisième événement de magnitude 4.0 et de profondeur de 30 km, a été également nettement ressenti au Nord Est de la Suisse. L'activité la plus importante, en terme de nombre d'événements et de leur taille, a eu lieu en Valais. La plupart de l'activité est limitée dans la partie supérieure de la croûte. De plus, 11 hypocentres avec des profondeurs focales de 19 à 31 km sont situés sous les monts du Jura et le bassin molassique du Nord de la Suisse, corroborant de précédentes observations. Les mécanismes focaux des 2 événements du Valais et des 2 événements dans le Nord de la Suisse sont représentatifs des déformations tectoniques dans ces régions: déformation en extension quasi N-S dans le Valais du Sud, un décrochement avec un raccourcissement crustal orienté NO-SE dans le Valais du Nord et une déformation en extension ENE-OSO dans le Plateau, au Nord des Alpes.

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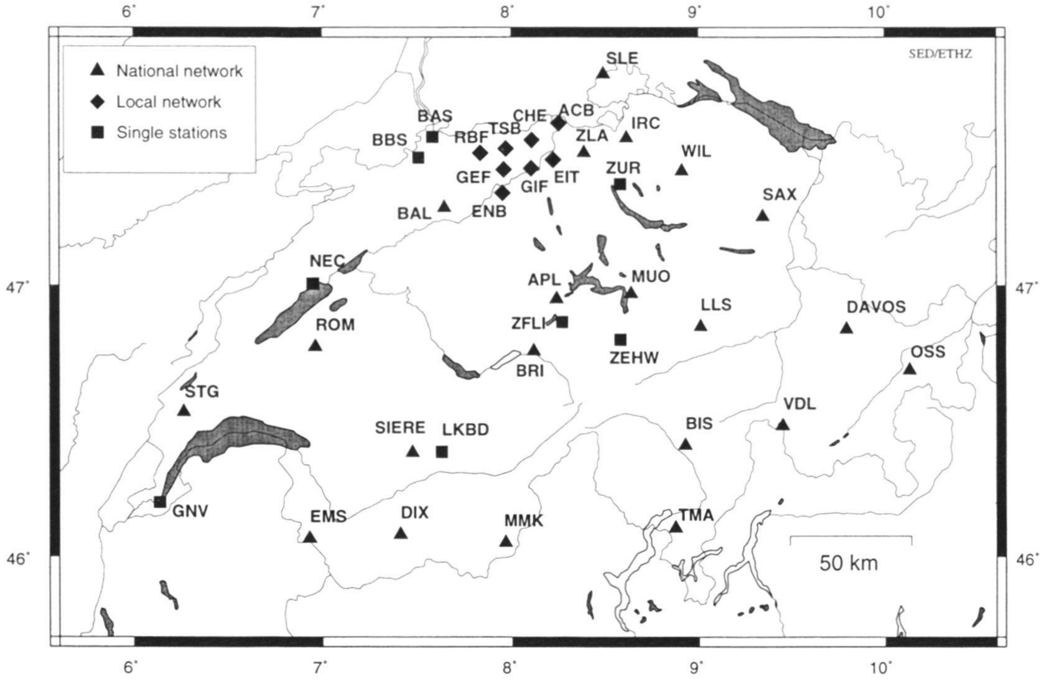


Fig. 1. Seismograph stations operational in Switzerland during 1996.

Introduction

The earthquake activity in and around Switzerland has been documented by the Swiss Seismological Service 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 furnished the basis for the first seismic hazard map of Switzerland (Sägesser & Mayer-Rosa 1978). Since then, the Swiss Seismological Service has installed and operated a dense network of highly sensitive seismic stations distributed across the whole territory of Switzerland. With the advent of routine data processing by computer, the wealth of data acquired by this network has been regularly documented in bulletins with detailed lists of all recorded events *(Monthly Bulletin of the Swiss Seismological Service)*. In addition, numerous studies covering different aspects of the recent seismicity of Switzerland have been published in the scientific literature (for an overview and additional references see, e.g. Deichmann & Baer 1990; Pavoni & Roth 1990; Deichmann 1992; Rüttener 1995; Rüttener et al. 1996; Pavoni et al. 1997).

With the present contribution, the Swiss Seismological Service renews the past tradition of annual reports summarizing the seismic activity in Switzerland and surrounding regions during the previous year.

Seismic stations in operation during 1996

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 earth-quake 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 solely on the high-sensitivity monitoring network. The data that has been collected by the strong-motion network is documented in a separate report (Smit 1997).

Figure 1 shows the distribution of the high-gain seismograph stations in Switzerland that were operational at the end of 1996. As listed in Table 1, the data from most of the stations are telemetered continously to the recording center in Zürich, where the signals are digitized and processed by computer (Baer 1990). Preliminary locations are computed on the basis of an automatic arrival time picker (Baer & Kradolfer 1987), but final arrival times and locations are subsequently reviewed by a seismologist. To overcome the limitations imposed by the low dynamic range of the analog telemetry system, selected stations feature an additional low-gain channel for the vertical component of ground motion, which extends the range of on-scale recordings for local earthquakes to a magnitude of about 4.5. Except for station ZUR, which is a broadband station, all

Tab. 1. Seismograph stations operational in Switzerland during 1996.

National telemetry network recorded in Zürich			
Code	Station name	Components	Remarks
APL	Alpnach	V + H	with low-gain channel
BAL	Balsthal	V + H	with low-gain channel
BIS	Biasca	V + H	
BRI	Brienz	V + H	with low-gain channel
DAVOS	Davos	V + H	with low-gain channel
DIX	Grande Dixence	V	dam site
EMS	Emosson	V	dam site
IRC	Irchel	V	
LLS	Linth-Limmern	V + H	dam site
MMK	Mattmark	V + H	dam site
MUO	Muotathal	V	
OSS	Ova Spin	V	dam site
ROM	Romont	V + H	with low-gain channel
SAX	Säntis	V + H	
SIERE	Sierre	V + H	with low-gain channel
SLE	Schleitheim	V + H	
STG	Saint Georges	V + H	
TMA	Monte Tamaro	V + H	
VDL	Valle di Lei	V	dam site
WIL	Wil	V + H	with low-gain channel
ZLA	Zürich-Lägern	V	
Local telemetry network recorded at station CHE			
Code	Station name	Components	Remarks
ACB	Acheberg	V + H	
CHE	Cheisacher	V + H	with low-gain channels
EIT	Eiteberg	V	
ENB	Engelberg	V	
GEF	Geissflue	V	
GIF	Gisliflue	V	
RBF	Rickenbacherflue	V	
TSB	Tiersteinberg	V	
Single stations recorded on site			
Code	Station name	Components	Remarks
BAS	Basel	V + H	digital
BBS	Basel-Blauen	V	paper records
GNV	Geneva	V	paper records
LKBD	Leukerbad	V + H	digital
NEC	Neuchatel	V	paper records
ZEHW	Erstfeld	V	analog magnetic tape
ZFLI	Flüheli	V	analog magnetic tape
ZUR	Zürich	V + H	digital broad-band

sites are equipped with a short-period seismometer with a natural period of 1 or 2 seconds. For enhanced monitoring capabilities in the vicinity of some of the large hydroelectric reservoirs in the Swiss Alps, the stations marked as dam sites in Table 1 are equipped with an additional vertical component seismometer within about 1 km of the main site.

All stations are operated by the Swiss Seismological Service, except for GNV, which is operated by the University of Geneva, and station BAS, which is part of a network of locally recording instruments operated by the Landeserdbebendienst in Freiburg, Germany. In addition to the paper records recorded locally, the signals of station BBS are telemetered also to station BAS and to Freiburg, where they are recorded in digital form.

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 foreign 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, and from the Istituto di Geofisica, Università di Genova, Italy.

Data analysis

Routine hypocenter locations are determined with a modified version of the widely used HYPO-71 algorithm originally developed by Lee & Lahr 1972. 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 twice 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 modelling 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 were 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 was based on the results of Waldhauser (1996), thus accounting more realistically for the known crustal heterogeneity. The same ray-tracing technique was also employed to help in correctly identifying the first arrivals and to estimate the take-off angles of the rays at the source, which are used for constructing the focal mechanisms (e.g. Eva et al. 1997).

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 are converted to what they would be if the signals had been recorded by a standard Wood-Anderson seismograph, and 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. In the case of the events with $M_L > 3$, for which most signals are clipped, the final magnitude is based only on the stations with low-gain channels.

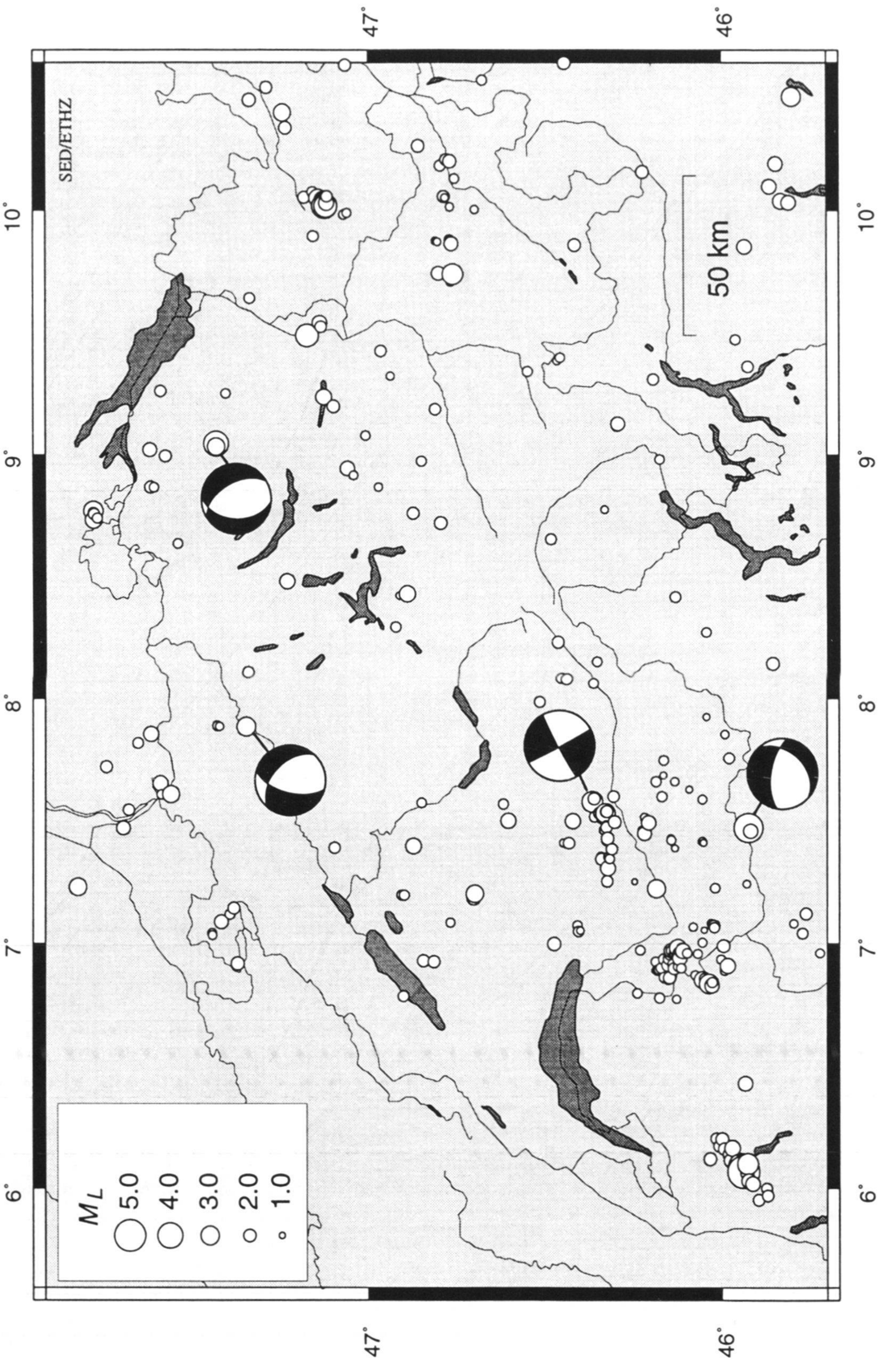


Fig. 2. Epicenters and focal mechanisms of earthquakes recorded by the Swiss Seismological Service during 1996.

Tab. 2. Earthquakes with $M_L \geq 2.5$.

Location	Date & Time [UT]	Lat. [°N]	Lon. [°E]	X / Y [km]	Depth [km]	Mag. [M_L]
Niederscherli (BE)	1996.01.16 07:00:20	46.873	7.398	597/191	20	2.5
Leukerbad (VS)	1996.02.21 18:57:28	46.368	7.579	611/135	5	3.3
Le Luisin (VS)	1996.03.06 14:16:29	46.125	6.981	565/108	1	2.7
Valpelline (I)	1996.03.31 06:08:01	45.925	7.472	603/ 86	4	4.6
Basel (BS)	1996.04.24 09:36:56	47.552	7.610	613/267	15	2.7
Arlberg (A)	1996.04.27 06:59:59	47.121	10.032	797/222	10	3.2
Bagolino (I)	1996.05.15 15:05:51	45.815	10.435	833/ 78	5	3.0
Buchs (SG)	1996.05.17 09:30:59	47.170	9.488	755/226	1	3.6
Mulhouse (F)	1996.06.04 05:05:23	47.810	7.230	584/295	10	2.8
Arlberg (A)	1996.06.15 21:40:09	47.118	10.019	796/222	10	3.6
La Berra (FR)	1996.06.27 22:40:00	46.700	7.202	582/172	10	2.8
Gottmadingen (D)	1996.06.28 03:43:10	47.767	8.768	700/291	10	3.1
Arlberg (A)	1996.06.28 09:57:48	47.121	10.019	796/222	10	3.9
Annecy (F)	1996.07.15 00:13:29	45.935	6.092	495/ 88	3	5.1
Annecy (F)	1996.07.15 05:46:13	45.940	6.084	495/ 88	3	3.3
Annecy (F)	1996.07.20 22:04:34	45.946	6.080	496/ 88	3	2.9
Annecy (F)	1996.07.23 02:50:32	45.937	6.090	495/ 88	3	2.5
Annecy (F)	1996.07.23 04:08:41	45.947	6.071	496/ 88	2	4.0
Crans (VS)	1996.07.31 16:26:44	46.335	7.529	607/131	3	2.7
Crans (VS)	1996.08.03 10:48:28	46.333	7.529	607/131	1	2.8
Thayngen (SH)	1996.08.10 13:57:45	47.766	8.732	697/291	10	2.7
Crans (VS)	1996.08.14 04:37:45	46.331	7.532	607/131	1	3.1
Arlberg (A)	1996.08.20 04:59:56	47.139	10.051	798/224	10	2.8
Arosa (GR)	1996.08.23 13:27:46	46.761	9.739	776/181	1	3.3
Kirchberg (SG)	1996.08.24 02:38:22	47.425	9.044	721/254	29	4.0
Kirchberg (SG)	1996.08.24 02:42:24	47.425	9.032	720/254	29	2.8
Le Buet (F)	1996.09.14 22:54:52	46.037	6.833	553/ 98	13	3.1
Le Buet (F)	1996.09.20 17:37:27	46.055	6.849	554/100	9	2.7
Walensee (SG)	1996.10.11 07:43:24	47.124	9.236	736/221	1	2.5
Lago d'Iseo (I)	1996.11.21 18:56:56	45.831	10.039	802/ 79	10	2.5
Stockach (A)	1996.11.21 23:08:13	47.238	10.397	824/236	10	2.7
Oberrickenbach (NW)	1996.12.07 05:34:29	46.913	8.425	675/196	2	2.5
Olten (SO)	1996.12.15 04:49:08	47.338	7.894	634/243	20	3.0
Chamoson (VS)	1996.12.25 12:39:25	46.186	7.223	583/115	10	2.9

Seismic activity during 1996

Overview

During 1996, the Swiss Seismological Service detected and located 329 seismic events in the region shown in Figure 2. Based on such criteria as the time of occurrence, the location, the signal character or direct information, 34 of these events were identified as quarry blasts. In some cases, we applied other detection methods for identifying explosions, which are based on signal cross-correlation, multivariate statistical analysis or on full waveform inversion, but which are not yet implemented as a routine procedure (Campus & Fäh 1997). As discussed in more detail below, 5 events were landslides. Of the remaining events, 5 were located both outside of the available station configuration and with a root-mean-square traveltime residual larger than 0.5 seconds so that their locations were judged to be too unreliable for further considerations. The epicenters of the remaining earthquakes are shown in Figure 2.

Focal depths range between 0 and 31 km, but only 11 hypocenters are located at depths greater than 15 km. Clearly, the depths of many of the shallow events are poorly constrained. With increasing depth, however, focal depth determinations become more reliable. Indeed, a critical review of the location of each of these 11 events as well as ray-trace modelling of three of them show that their focal depths are well constrained. Moreover, because of the greater reliability of larger focal depths, it is unlikely that many of those events that have been located in the upper crust actually occurred at significantly greater depths. Thus, the results indicate that most of the seismic activity in 1996 was restricted to the upper part of the crust and that less than 5% of all earthquakes occurred below about 15 km. Moreover, all of these deeper hypocenters are located below the Jura Mountains and Molasse Basin of northern Switzerland.

Magnitude values of the events recorded in 1996 range between M_L 0.9 and 5.1. The events with $M_L \geq 2.5$ are listed in Table 2. Macroseismic observations are available for 4 events and are displayed in Figure 3. In what follows, we shall briefly discuss the most significant of these events as well as the observed landslides.

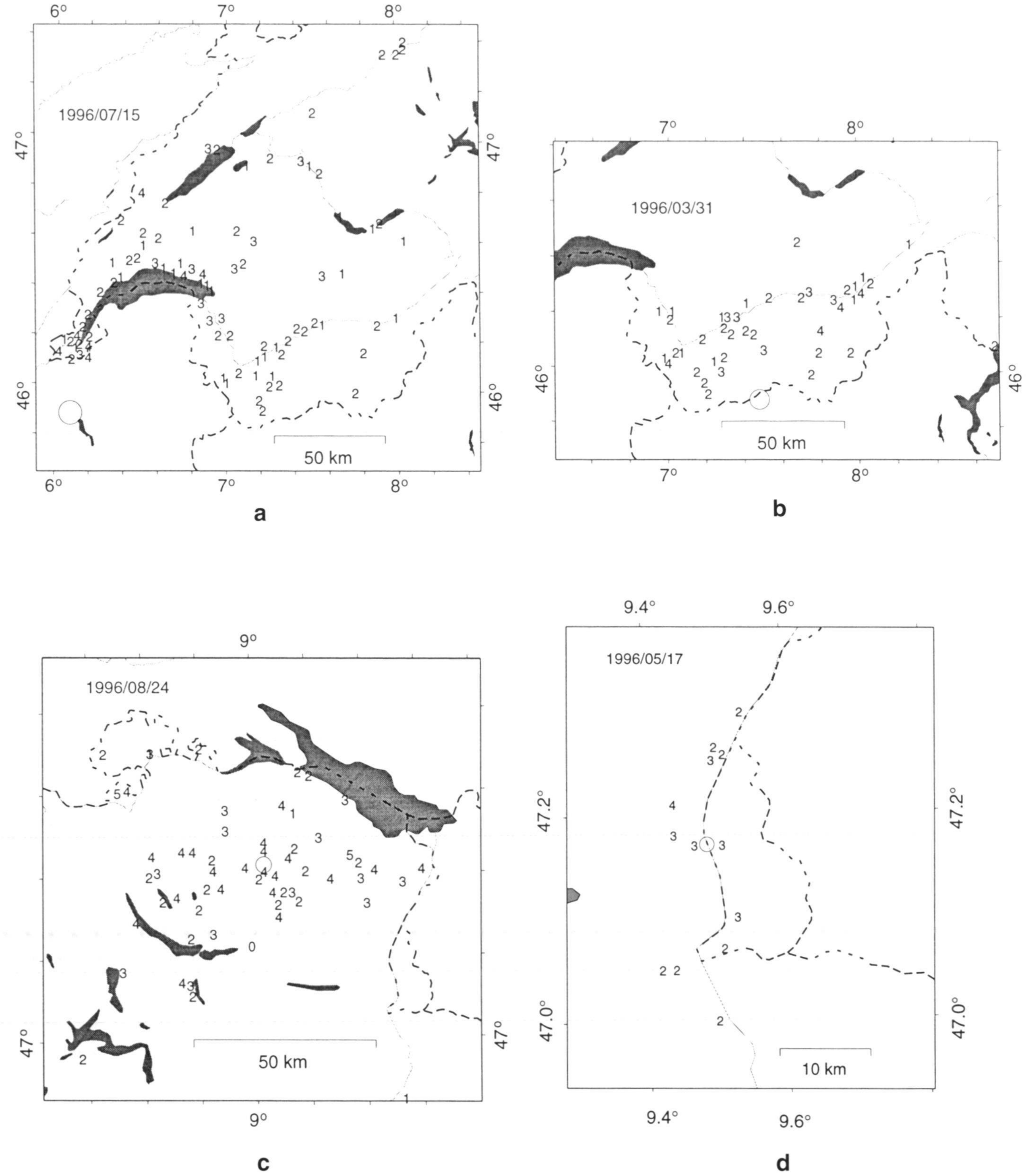


Fig. 3. Macroseismic observations of 4 earthquakes (a = Annecy, b = Valpelline, c = Kirchberg, d = Buchs).

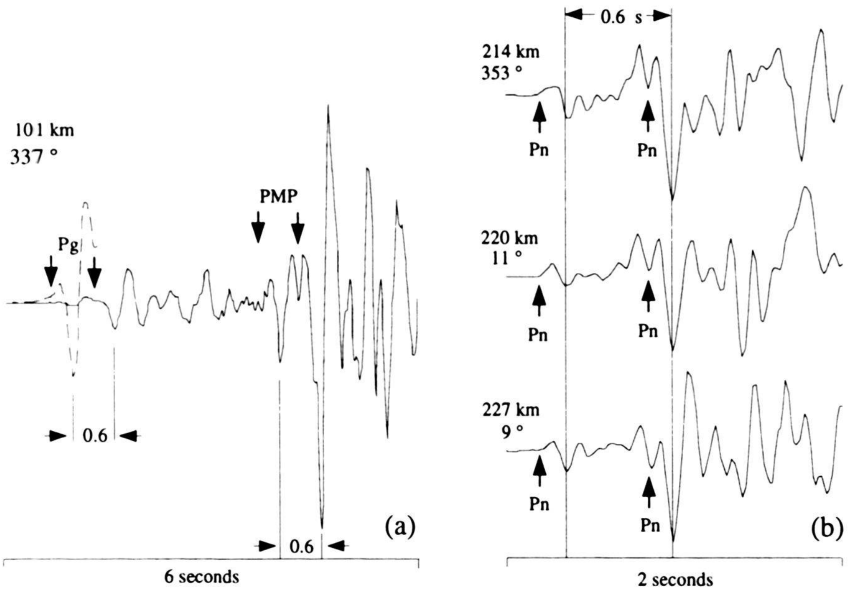


Fig. 4. Seismogram examples which show that the Valpelline quake consisted of two subevents 0.6 seconds apart. Epicentral distance and azimuth are indicated for each signal. (a) Pg and PMP recorded by the low-gain channel of station ROM (continuous trace) and the onset of the first subevent as recorded by the high-gain channel (dashed trace, magnified 20 times). (b) Pn arrivals recorded by three stations in the Vosges Mountains, France, and Black Forest, Germany.

Significant seismic events in 1996

Annecy

The most significant earthquake to have occurred in Switzerland or the surrounding areas in 1996 struck the town of Annecy, France, at 02:13 local time of Juli 15th. Its epicenter was located near Epagny, 4 km NW of Annecy. With a magnitude of 5.1 (the Observatoire de Grenoble reports a value of 5.3) and with a focal depth of about 3 km, the epicentral intensity reached a value of VII to VIII on the MSK scale (Bisch 1996). The shaking toppled chimneys and caused significant damage to several buildings in and around Annecy. A four-story apartment building in Meythet suffered such severe structural damage that it had to be evacuated (Davidovici 1996).

Immeditely after the main shock, the Observatoire de Grenoble installed a temporary seismograph network to monitor the aftershock activity. About 400 aftershocks were detected over a period of one and a half months (F. Thouvenot, INSU/CNRS, pers. comm.). Twenty of these aftershocks, ranging in magnitude between 1.7 and 4.0 were also recorded by the national network of the Swiss Seismological Service. Their epicenters form an oblique line in the southwestern corner of Figure 2. However, because of mislocations due to the unfavorable station coverage and poor signal quality of the weaker events, this apparent alignement is an artifact. Therefore, in Table 2 we report the locations determined by the Observatoire de Grenoble (J. Fréchet, pers. comm.).

Based on the fault plane solution, on the distribution of aftershocks and on the tectonic setting, it is clear that the Annecy earthquake was caused by left-lateral slip on the steaply dipping, NW-SE striking Vuache fault, which has been seismically active in the past (Thouvenot 1996; Sambeth & Pavoni 1988).

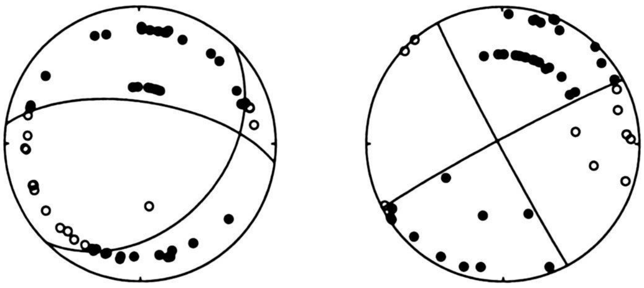
Valpelline

At 08:08 local time of March 31st, a magnitude 4.6 earthquake was felt throughout the Valais. Its epicenter was located in a relatively remote area near the border with the Aosta Valley, Italy. Ray-trace modelling indicates that its focal depth hardly exceeded 5 km. The strength was sufficient to trigger the accelerograph arrays in the Mauvoisin and Grande Dixence dams, as well as several other accelerographs out to a distance of 40 km (Smit 1997). The peak ground acceleration measured by the free-field station at Grande Dixence, situated at an epicentral distance of 18 km, reached 6 cm/s^2. However, for an earthquake of that strength, most of the recorded seismograms are characterized by relatively weak and emergent onsets. Detailed analysis of the observed signals shows that the source process actually consisted of two subevents 0.6 s apart, and that the first subevent was smaller by about one magnitude unit (Fig. 4).

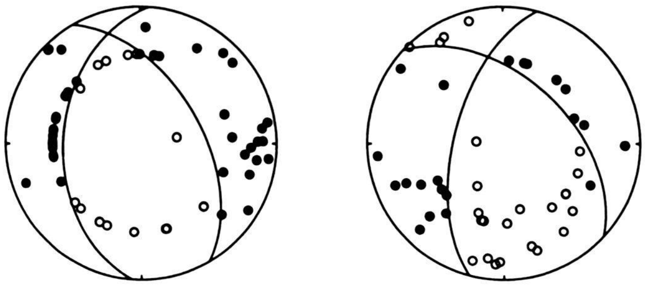
The focal mechanism determined from the first-motion polarities of the first subevent corresponds to a normal fault with a N-S trending T-axis (Fig. 5 and Tab. 3). The resulting extensional deformation oriented at a high angle to the strike of the Alpine mountain range is consistent with other focal mechanisms observed in that area and is a typical feature of the tectonic regime of the southern Valais (Eva et al. 1997; Maurer et al. 1997).

Leukerbad

Another interesting earthquake to have occurred in the Valais during 1996 is the magnitude 3.3 event of February 21st, 19:57 local time. Its epicenter is located 4 km SW of Leukerbad, at the eastern end of the prominent WSW-ENE striking epicenter alignment, which has been identified north of the Rhone



Valpelline 31.03.96 Leukerbad 21.02.96



Kirchberg 24.08.96 Olten 15.12.96

Fig. 5. Fault-plane solutions (lower hemisphere, equal area projection) of selected earthquakes. Solid circles, compressive first motion (up) and empty circles, dilatational first motion (down).

Tab. 3. Focal mechanism parameters.

Location	Mag.	Date & Time [UT]	Depth [km]	P-Axis		T-Axis	
				Az.	Dip	Az.	Dip
Leukerbad	3.3	1996.02.21 18:57	5	107	4	197	1
Valpelline	4.6	1996.03.31 06:08	4	231	59	347	15
Kirchberg	4.0	1996.08.24 02:38	29	183	72	75	6
Olten	3.0	1996.12.15 04:49	20	158	53	256	6

Tab. 4. Landslides detected south of Linthal, Canton Glarus. The energy ratios were calculated from the integral of the square of the recorded ground velocities.

Date	Time [UT]	Time (local)	Mag. [M_L]	Energy ratio	Location
96.01.24	08:00	09:00	2.6	1/2	Zuetribistock
96.03.03	18:30	19:30	2.8	1/1	Zuetribistock
96.05.19	19:35	21:35	1.6	1/700	unknown
96.09.04	02:42	04:42	1.9	1/46	Zuetribistock
96.10.05	04:39	06:39	1.6	1/43	Ochsenstock

Valley by previous studies (Maurer & Deichmann 1995; Maurer & Kradolfer 1996; Pavoni et al. 1997). Thanks to the on-scale recording of both P- and S-waves at station LKBD, which is situated only 4 km from the epicenter, the focal depth of 5 km is well constrained.

The fault plane solution corresponds to a strike-slip mechanism (Fig. 5 and Tab. 3), which is typical for the predominant focal mechanism type observed in the northern Valais (Maurer et al. 1997). The two nodal planes strike NNW-SSE with left-lateral slip and WSW-ENE with right-lateral slip. The stress field, which was derived from an inversion of focal mechanisms further west in the northern Valais, is characterized by a NW-SE oriented maximum compressive stress (Maurer et al. 1997). If this stress field is also responsible for the Leukerbad event, then the NNW-SSE striking nodal plane is oriented more favorably relative to the directions of principal stress and is thus likely to have been the active fault plane.

Kirchberg (SG)

The magnitude 4.0 event, which occurred in the early morning hours of August 24th, was located at a depth of 29 km below the town of Kirchberg, in the Untertoggenburg. The unusually large focal depth for an earthquake of this size in Switzerland is well constrained both by the nearby recording of station WIL and by 2-D ray-tracing. Because of its large focal depth, it was felt throughout all of northeastern Switzerland, even though the epicentral intensity was not more than IV (MSK) (Fig. 3). Several strong-motion stations were triggered: in Buchs (SG), at an epicentral distance of 44 km, peak ground acceleration reached a value of 6 cm/s^2 (Smit 1997).

The faultplane solution corresponds to an almost pure normal faulting mechanism (Fig. 5 and Tab. 3). The orientation of the T-axis is typical for the ENE-WSW oriented extension of the northern Swiss Molasse Basin as derived from earlier focal mechanism studies (e.g. Pavoni 1987; Deichmann 1992b).

The mainshock was followed 4 minutes later by a magnitude 2.8 aftershock, which, judging from the high degree of similarity between the seismograms of the two events, must have occurred nearby and on the same fault.

Olten

The hypocenter of the magnitude 3.0 event, which occurred in the early morning of December 15th, was located at a depth of 20 km below the town of Olten, at the southern margin of the Jura Mountains. Both the focal depth and the faultplane solution are well constrained by the high station density in northern Switzerland and southern Germany. Although the focal mechanism has a much stronger strike-slip component than that of the Kirchberg event, the ENE-WSW trend of the nearly horizontal T-axis is practically the same for both events (Fig. 5 and Tab. 3).

Landslides

Based on their signal character, five events detected by the national network during 1996 were judged to correspond to large landslides in the vicinity of station LLS (Fig. 1 and Tab. 1). In fact, as listed in Table 4, four of these events can be associated

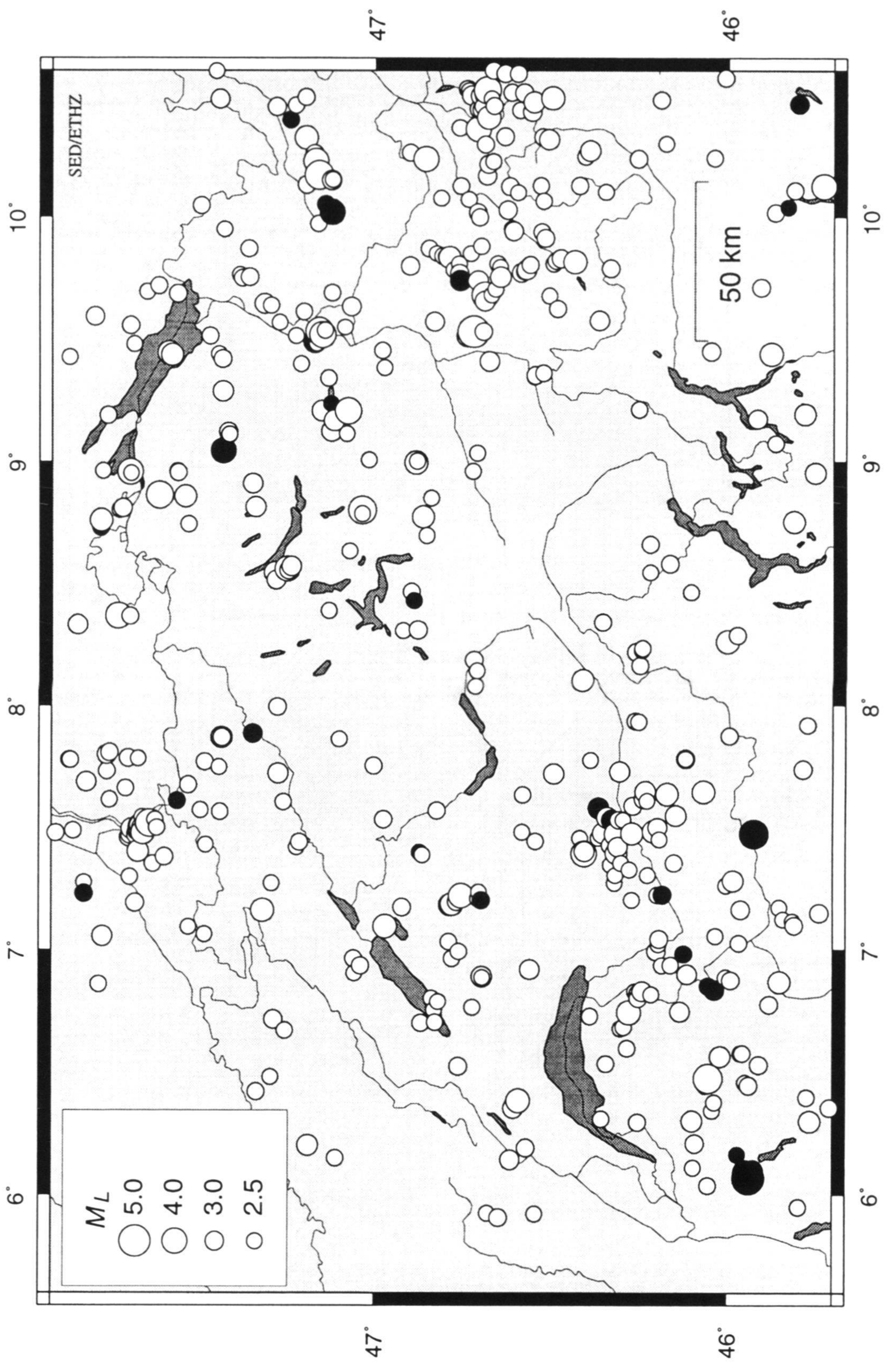


Fig. 6. Epicenters of earthquakes with Magnitudes $M_L \geq 2.5$, during the period 1975–1996. The solid circles denote the corresponding events of 1996.

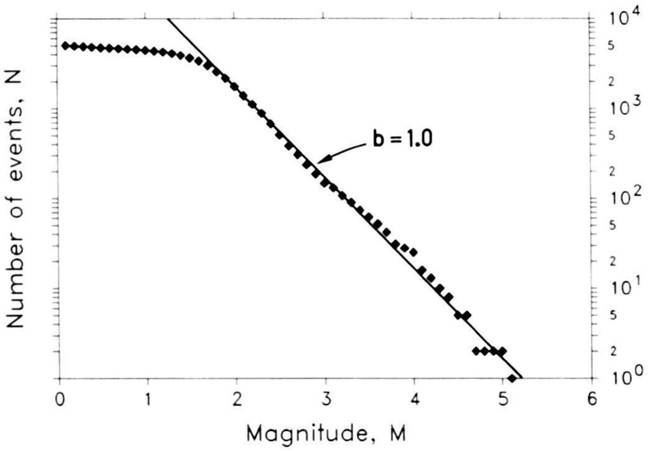


Fig. 7. Plot of N (= number of events with magnitude ≥ M) as a function of M (= M_L) for the time period 1975–1996. For $M \geq 2$, the data follow the Gutenberg-Richter relation, $\log N = a - bM$, with $b = 1.0$. However, for $M < 2.5$, the data set is likely to include an unknown number of unidentified quarry blasts.

with landslides that fell onto Sandalp, south of Linthal, Canton Glarus (K. Stüssi, Kraftwerke Linth-Limmern, AG, personal communication). The nature of the event which occurred on May 19th and which was considerably smaller than the others has not been confirmed. However, the similarity of the signals with those of the other landslides strongly suggests that this event was due to the same cause.

For landslides occurring in the same place, the equivalent earthquake magnitudes, calculated from the maximum amplitudes of the recorded signals, give a rough indication of the relative size of the individual events. A more reliable estimate of the combined effect of the total rock mass and the corresponding impact velocity can be obtained from the cumulative seismic energy radiated by each event. Thus, the ratios between the time integrals of the square of the ground velocity recorded at various stations suggest that the landslide of March 3rd on the flanks of Zuetribistock was about twice as energetic as the one of January 24th and 40 to 50 times more energetic than the one that occurred on September 4th (Tab. 4).

Discussion

Figure 6 shows the epicenters of the 507 earthquakes with $M_L \geq 2.5$, which have been recorded in Switzerland and surrounding regions over the period of 1975–1996. These events represent about 10% of the total number of events detected during that time period in the same area (Fig. 7). 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.

If we compare the epicenter map for 1996 (Fig. 2) with the epicentral distribution observed between 1975 and 1996 (Fig. 6), we note that the seismic activity in 1996 was representative of what has been observed over a longer time span. In particular, the highest earthquake activity, both in terms of number of events and in terms of their size, occurred once again in the Valais. The only noteworthy exception to this overall agreement is the almost total lack of activity during 1996 along the easternmost border of Switzerland, where there has been a striking concentration of events over the previous 21 years.

The regional variation of maximum focal depths, exemplified by the Kirchberg event in the lower crust below the Molasse Basin and by the complete lack of earthquakes below about 15 km in the Alps, is representative of the long-term focal depth distribution (Deichmann & Baer 1990; Deichmann 1992a).

The four focal mechanisms presented in this report are typical for the tectonic deformation in the respective regions. The extensional deformation at a high angle to the strike of the Alpine mountain chain, exemplified by the Valpelline earthquake, has been observed in several previous earthquakes in the penninic nappes of the southern Valais (Eva et al. 1997; Maurer et al. 1997) and to a lesser degree also in parts of Graubünden (Roth et al. 1992). In contrast, the style of deformation in the Valais north of the Rhone Valley is dominated by strike-slip mechanisms with a NW-SE oriented P-Axis, of which the Leukerbad event is an excellent example (Maurer et al. 1997; Pavoni et al. 1997). The ENE-WSW orientation of the T-axis of the focal mechanisms of the Kirchberg and Olten events is additional evidence for the homogeneity of the deformation and presumably also of the corresponding stress field of the crust below northern Switzerland, apparent from previous studies (Pavoni 1987; Deichmann 1990, 1992b).

The Annecy earthquake with a magnitude of 5.1 or 5.3 was only slightly stronger than the Grand-Bornand earthquake, which occurred only about 40 km ENE of Annecy on December 14th, 1994 (Fréchet et al. 1996) and the November 21st, 1991, earthquake of Vaz, Graubünden. In fact, earthquakes of this size are not uncommon in the Alps and larger ones must be expected as well (Sägesser & Mayer-Rosa 1978; Rüttener 1995). Although the individual damages caused by the Annecy earthquake were not overwhelming, the total financial loss has been estimated at 300 million French Francs (Davidovici 1996). This shows once again that even moderate earthquakes, when they occur in densely populated industrialized areas, can have significant economic impact.

The frequency of occurrence over the past 22 years, represented by the Gutenberg-Richter graph in Figure 7, shows a remarkable linearity over the magnitude range from about 2 to 5, with a slope that corresponds to a b-value of 1.0. The linearity of the graph up to magnitude 5 again indicates that this value can not be considered as a saturation value and that larger magnitudes must be taken into consideration as well.

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