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SEISMOTECTONICS AND SEISMIC HAZARD OF GERMANY IN THE EUROPEAN CONTEXT

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ABSTRACT

Although Central Europe is a rather stable continental platform area it is not void of seismic activity. Its crust has mainly been consolidated and internally structured by Hercynian folding and subsequent block-faulting in connection with the collision of Africa and Europe and the related Alpine orogeny in the south. Dominating later fault tectonic features in Germany are the Upper and Lower Rhinegraben in the west and the Hercynian striking Franconian Line and the Central German Main faults in the center and the east, respectively, as well as several N-NNE striking, obviously older and deeper rooted fault zones both on the Franconian platform in the southwest (the 9°-E zone) and in northeast Germany (12°-E zone). The seismic activity is related to this structural inventory and more or less concentrated in some shear-zones which are currently active under the recent orientation of the stress field in Central Europe. Focal mechanisms are chiefly horizontal strike-slip and normal faulting. Composition and heat flow controlled crustal rheology limit the focal depth to a maximum of about 22 km, normally between about 5 and 15 km. The Benioff-graphs of the various active regions in Germany show generally episodes of increased and reduced activity with different time constants and patterns hinting to different stress loading and relaxation histories and related crustal rheologies. Geodetically determined recent crustal movements, young tectonic deformations and the history of earthquake activity in Germany make it unlikely that events with magnitudes above 6 and epicentral intensities above 8.5° MSK will occur. The largest mining induced seismic events in Germany were almost of the same order. The paper discusses the seismic activity and its peculiarities in the main seismic regions of Germany, the unique swarm earthquakes in the Vogtland/Western Bohemia in particular.

Damages incurred in connection with the strongest tectonic earthquakes in recent years, i.e. the 1978 earthquake in the Swabian Alb and the Roermond earthquake of 1992 near the German-Dutch border, are compared with that of the probably strongest mining-induced event in the history of mankind in 1989 at Völkershausen (M = 5.5; I_{max} = 9° MSK). The current German hazard maps as derived by various authors both on the basis of probabilistic considerations and actual repeated macroseismic observations are shown and related to the seismic zoning and building regulations which are currently applied.

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1. INTRODUCTION INTO THE REGIONAL CONTEXT

The paper intends to review essential features of the seismotectonics and seismic hazard of Germany in its wider context as a case study for active consolidated continental platforms. It dwells on the findings of many authors and tries to compile and coherently discuss them in a synoptic view. The paper was presented as an invited annual lecture at the meeting of the Indian Society of Earthquake Technology in November 1993. It was to provide, therefore, a rather comprehensive account on how seismologists in Germany, who work in a younger but seismotectonically - to some extent - similar platform environment as their Indian colleagues, are tackling the problem of investigating the causes and peculiarities of their seismicity and which major results have been achieved so far.

Central Europe, and Germany as part of it, are situated towards SW and W of the Precambrian Baltic shield and the East European platform. They belong to the younger West European platform, an area which was folded and consolidated during Paleozoic orogenies (Caledonian, Hercynian) and subsequently block-faulted in conjunction with the collision of Africa and Europe and the related younger Alpine orogeny in the south (late Mesozoic to Cenozoic times). The overall tectonic situation of Central Europe in its wider context is depicted in Fig. 1. The insert shows that this area is currently deformed under a dominatingly NNW oriented compressional stress field. The overall shortening, as derived from satellite laser ranging at the four stations depicted in Fig. 1, is according to Gendt et al. (1993a) $< 3 \times 10^{-9}$ per year. This deformation is caused by the relative motions from the North Atlantic ridge in the NW and W, the African plate in the S and the "stumbling block" of the East European platform in the E with respect to Europe (Fig. 2). But a generalization of all currently available stress data as derived from fault plane solutions, in-situ stress measurements, neotectonics and fault indications by Grünthal and Stromeyer (1992, 1993) yielded a more detailed pattern of the trajectories of maximum horizontal stress $S_{H\,max}$ (cf. Fig. 3) which is also consistent with the stress pattern calculated by the same authors on the basis of a finite element modelling of the plate motion scheme shown in Fig. 2. Interestingly, the trajectories of current $S_{H\,max}$ ran roughly perpendicular both to the trend of the outer front and the internal structural alignment of the Hercynides as well as to the fast directions of S-wave anisotropy in the lithosphere/asthenosphere underneath Central Europe (cf. Figs. q and 3) and thus subparallel to both the directions of paleo and recent crustal shortening (Bormann et al. 1993, Vinnik et al. 1994). On the other hand they are roughly suborthogonal to the direction of actual absolute plate motion (Fig. 3). The latter amounts to about 2-3 cm/year. This is one to two orders larger than the current rates of crustal deformation in Central Europe which increase towards south (cf. Fig. 8).

None the less the rates of crustal deformation are sufficient to cause seismic activity along preexisting faults. As seen from Fig. 4, seismicity is significantly larger in the Alpine area, not only by the number of events but also with respect to maximum observed intensities ($I_0 \geq 9°$ MSK)[1] while north of the Alps in the Hercynian consolidated area no intensities $I_0 > 8°$ MSK have become known in historical times. Contrary to the Alpine seismicity, which is that of an active collisional belt, the seismicity of Central Europe belongs to that of stable continental platforms. According to Johnston (1994), the latter account for only 0.5 % of the global seismic energy release and 90 % of the events in such regions occur in platform areas with on-going rifting processes.

[1] All intensity values given in this paper are based on the use of the Medvedev-Sponheuer-Karnik Scale, MSK 64, or its updated version of 1980 (Report on the Ad-hoc Panel Meeting of Experts on Updating of the MSK-64 Seismic Intensity Scale, Jena, 10-14 March 1980, Gerlands Beitr. Geophys., 90, pp. 261-268).

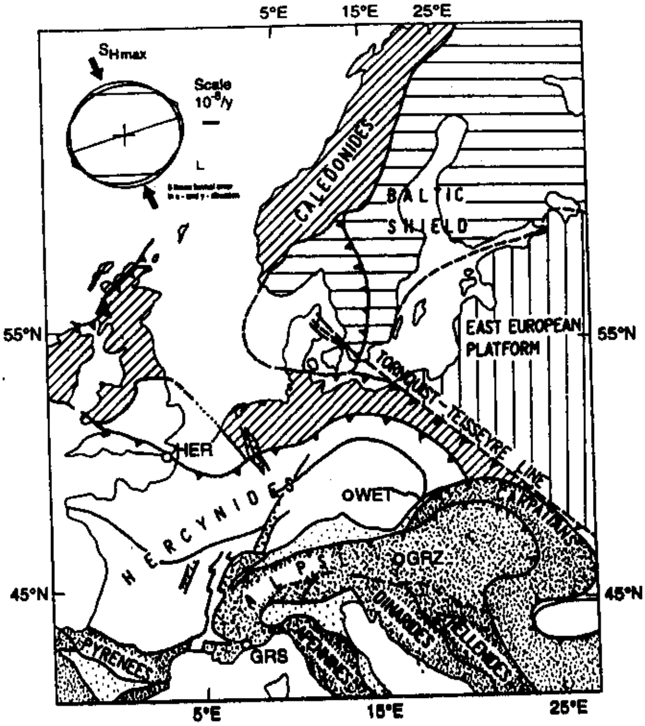


Fig. 1 Major tectonic units in Central Europe and adjacent areas. The open circles give the positions of four stations for precision satellite laser ranging (HER - Herstmonceaux, GRZ - Graz, GRS - Grasse, WET - Wettzell). From observations at these stations the deformation ellipse shown in the insert (upper left) has been derived by Gendt et al. (1993a).

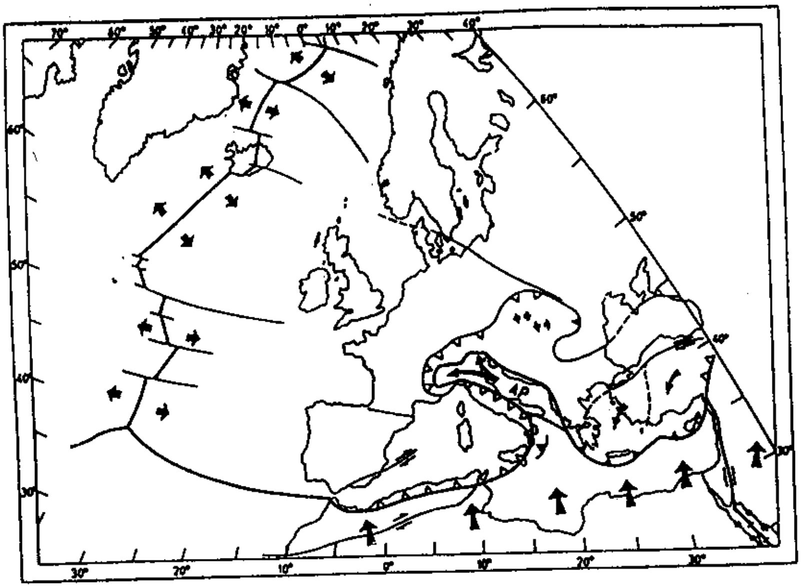


Fig. 2 Plate tectonic scheme of the western part of the Eurasian plate with the direction vectors of motion relative to Europe; AP-Adriatic promontory (from Grünthal and Stromeyer 1993).

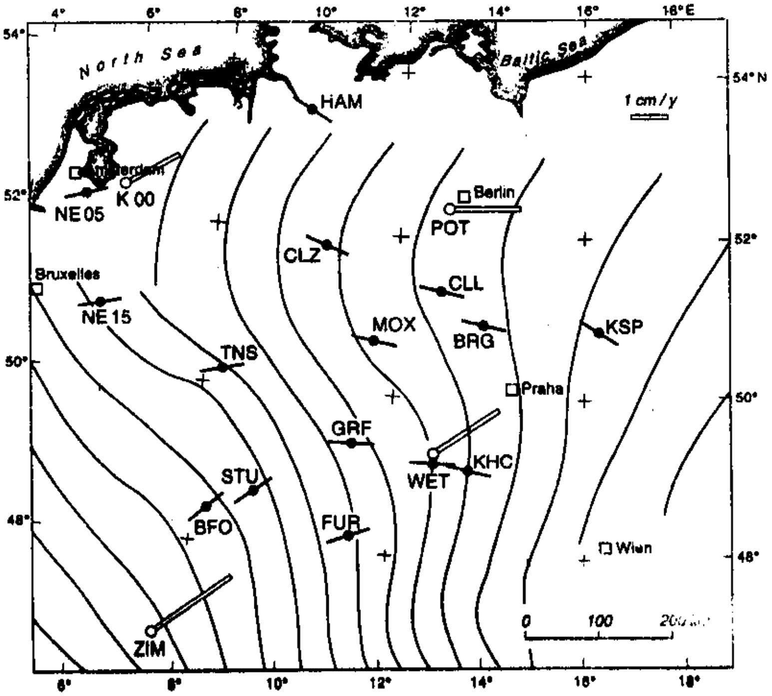


Fig. 3 Trajectories of the direction of maximum horizontal stress SH max according to Grünthal and Stromeyer (1992) (solid lines), the directions of polarization of the fast split S-wave due to anisotropy of the lithosphere/astenosphere underneath Central Europe (from Bormann et al. 1992 and Vinnik et al. 1994) (full dots and bars) and the directions and amounts of absolute plate motions as derived by Gendt et al. (1993b) for four satellite laser ranging stations in Central Europe (open circles and bars; KOO - Kootwijk, POT - Potsdam, WET - Wettzell, ZIM - Zimmerwald).

2. OVERVIEW OF SEISMICITY, SEISMOTECTONICS AND SEISMIC MONITORING IN GERMANY

Seismicity in Germany is clearly related to tectonic features of rifting or shearing such as the Upper and Lower Rhinegraben in the west, the Hercynian striking Franconian Line in the SE to center, the Central German Main Faults and Elbe river zone in the center and east and several N striking, obviously older and deeper rooted shear zones such as the 9°-E zone in southwest Germany and the 12°-E zone in northeastern Germany (Fig. 5). These rift and shear zones are at present more or less seismically active under the currently dominating NNW oriented maximum horizontal compressional stress field. The focal mechanisms of German earthquakes are chiefly horizontal strike slip and normal faulting (Fig. 6, cf. also section 5.). Crustal rheology as controlled by crustal composition (in the area considered dominatingly acid to intermediate) and heat flow (varying in Germany between some 60 and 110 mW/m^2 according to Čermak and Hurtig (1979)) limits the focal depth of German earthquakes to a maximum of about 24 km but normally it ranges between about 5 and 15 km (Bonjer et al. 1984, Bormann et al. 1986, Fuchs et al. 1987, Meissner and Kusznir 1987, Turnovsky 1981, Scholz 1988).

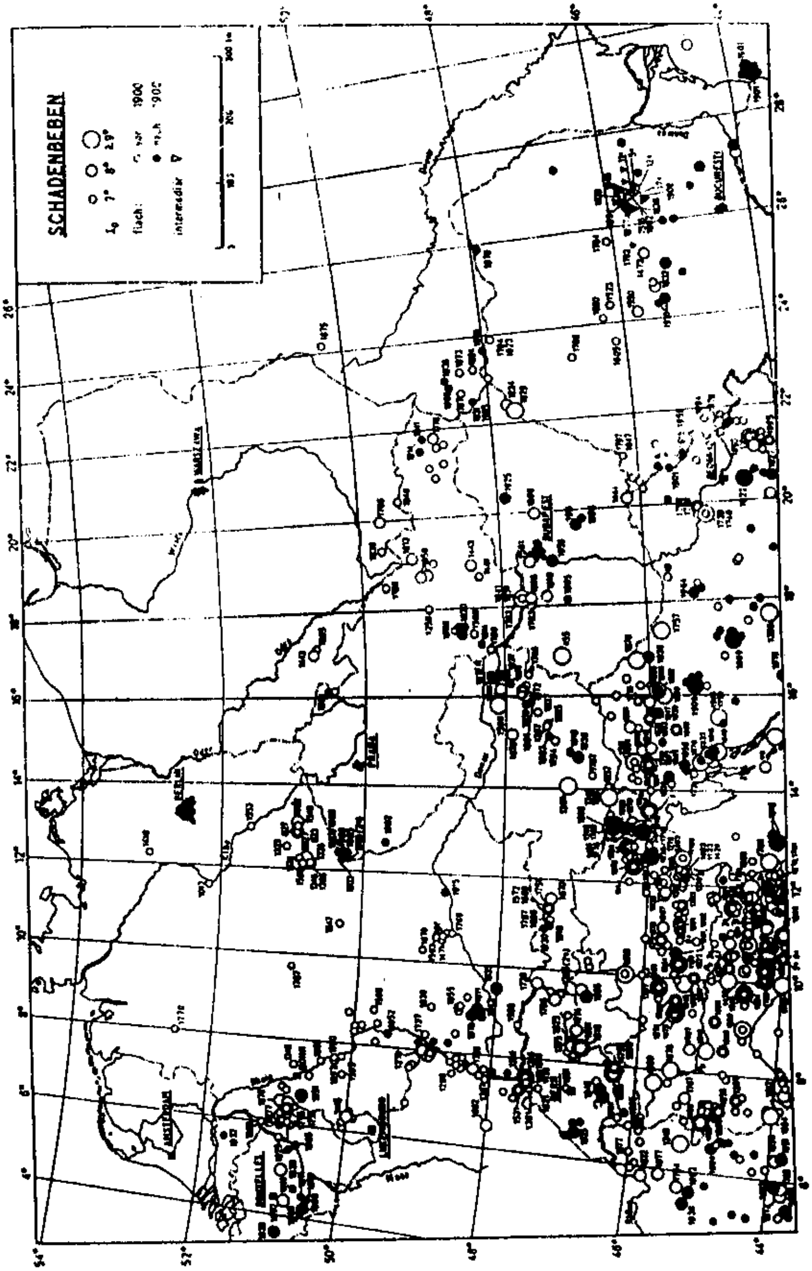


Fig. 4 Epicenters of known or catalogued damaging earthquakes in wider Central Europe (I0 ≥ 7° MSK). Open circles: before 1900, full dots: after 1900 (from Grünthal 1991).

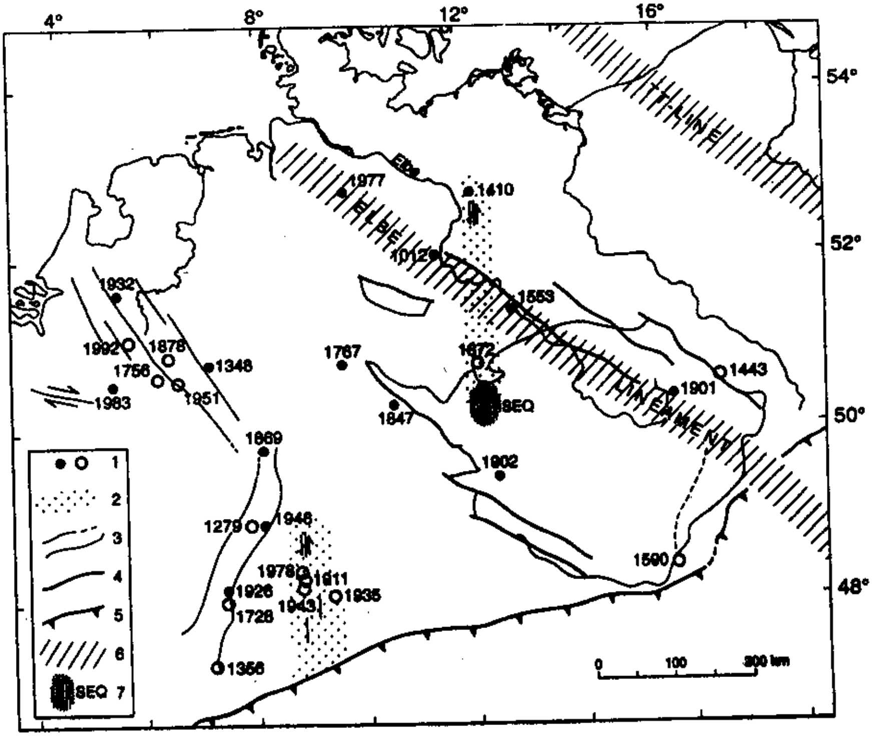


Fig. 5 Major seismological features and tectonic elements in the Central European Hercynides, 1 - selected epicenters of strong seismic events (full dots: M < 5, open circles: M > 5); 2 - areas of the 9° E (Swabian Alb) and 12° E seismic zones according to Schneider (1992); 3 - boundaries of the Lower and Upper Rhinegraben; 4 - main faults with Hercynian (NW-SE) strike; 5 - Alpine thrust front; 6 - Elbe zone and Tornquist-Teisseyre line (TTL); 7 - area of the Vogtland-Western Bohemia swarm earthquakes.

Significant regional differences in heat flow and structural control do not only affect the depth distribution of seismicity but also the stress loading and discharge histories. This is examplified by the Benioff-graphs of various seismically active regions of Germany (Fig. 7). They show episodes of increased and reduced activity with different time scales and patterns of seismic energy release. Correspondingly, also the Gutenberg-Richter relationships or related probabilistic relationships between earthquake magnitude or intensity and the frequency or probability of earthquake occurrence vary strongly within the various seismically active zones or provinces in Germany (see Fig. 17). This has a significant bearing on the seismic hazard assessment in the different areas (cf. section 7).

In order to estimate maximum possible magnitudes, seismic moments and epicentral *intensities for central European earthquakes Schneider (1993) compared deformation* velocities as derived from geodetically determined recent crustal movements with indications of young tectonic deformations and the history of earthquake deformation release on the basis of a rheological model. He found that the observed maximum earthquake displacement in conjunction with the related return periods t for major events in Central Europe was in good agreement with the range of observed crustal deformation velocities (Fig. 8). The latter vary between some 0.1 and 1 mm/year. From this he con-

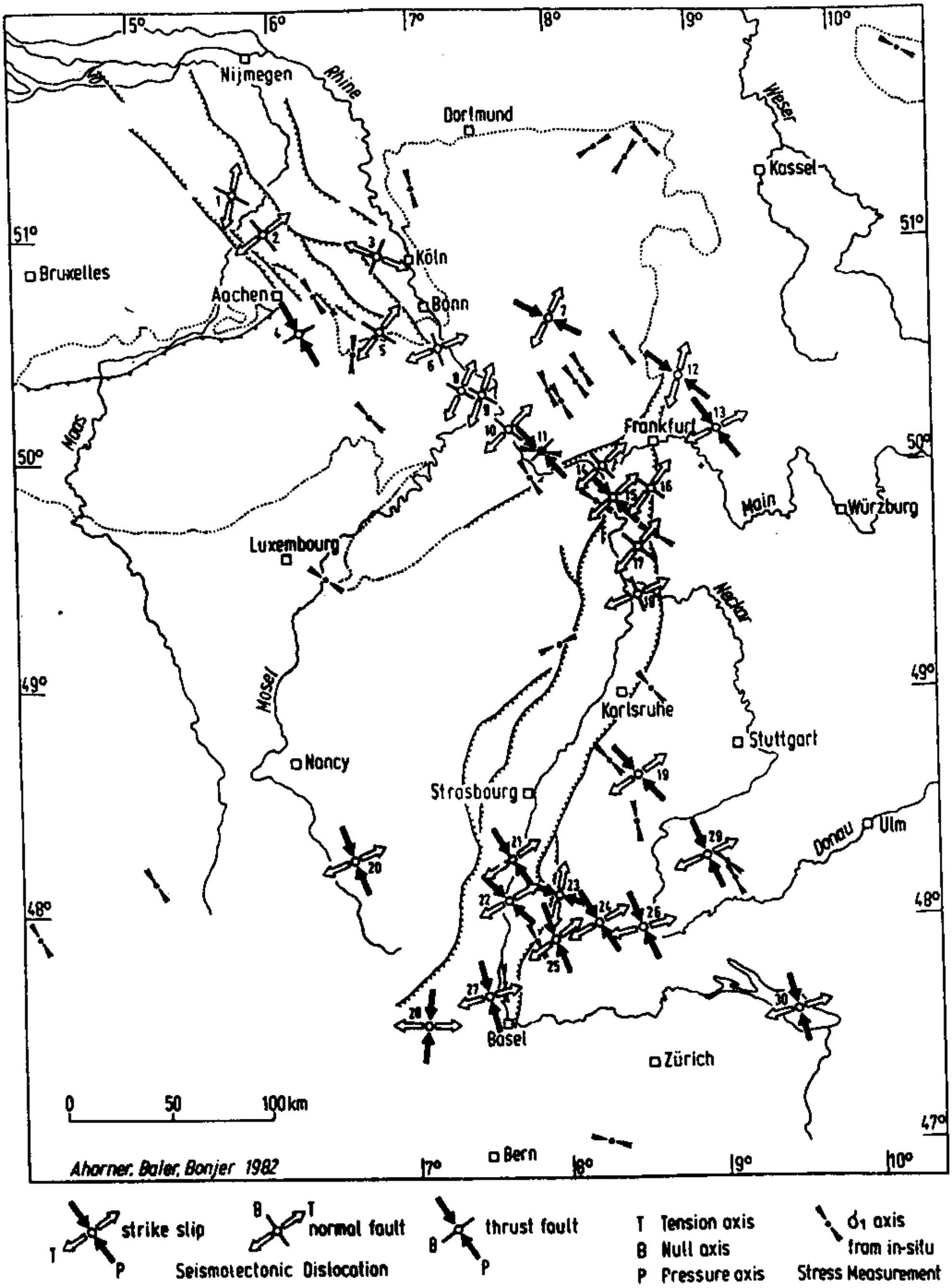


Fig. 6 Fault plane solutions of earthquakes between 1975 and 1982 in western Central Europe together with some results of in-situ stress measurements (from Ahorner et al. 1983a).

cluded that it is rather unlikely that in Germany events with magnitudes above 6 and epicentral intensities above 8.5° will occur. This is in good agreement with various independent estimates by Grünthal (1991) for East Germany (M_{max} = 5.66, cf. Fig. 7, and $I_{0\,max}$ = 8.32°, cf. Fig. 15).

Considering the low rate of relative deformation according to Gendt et al. (1993a) as derived from laser ranging data ($\leq 3 \times 10^{-9}$/year) and taking into account that relative shear deformations in the order of 10^{-6} - 10^{-7} are required for failure of preexisting and prestressed faults, then the long return periods of stronger Central European earthquakes become plausible. According to Figs. 7c and 8 they vary between about 200 and more than 2000 years, with some local exceptions, e.g. in the only recently active Swabian Alb (cf. Fig. 7a and section 3).

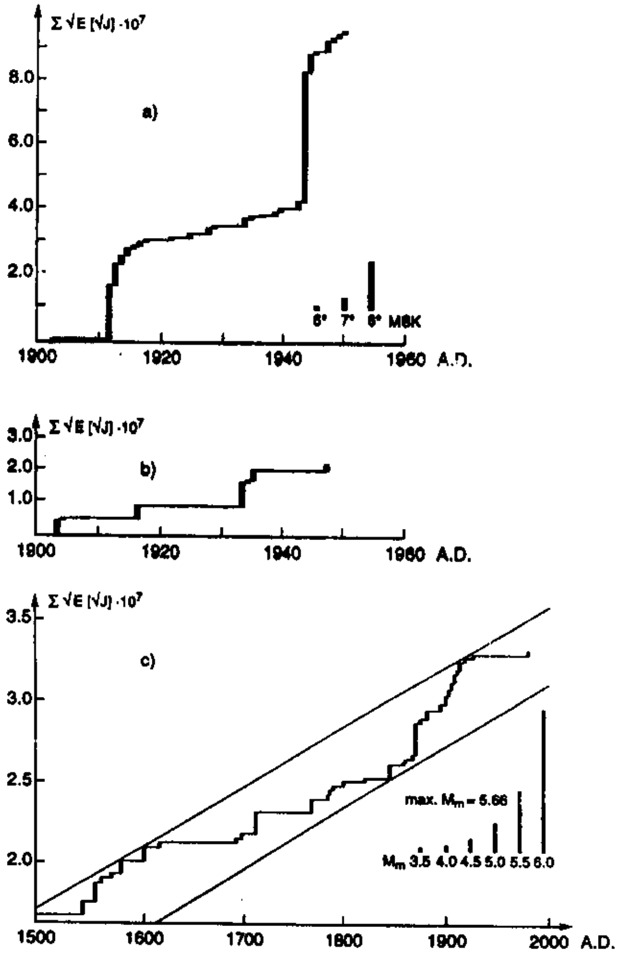


Fig. 7 Benioff-graphs of cumulative seismic energy release in a) the Swabian Alb, b) the Upper Rhinegraben (both redrawn and rescaled from Sponheuer 1962) and c) the Saxo-Thuringian earthquake province of East Germany (without swarm earthquakes) - (redrawn from Grünthal 1991; M_m - macroseismic magnitude).

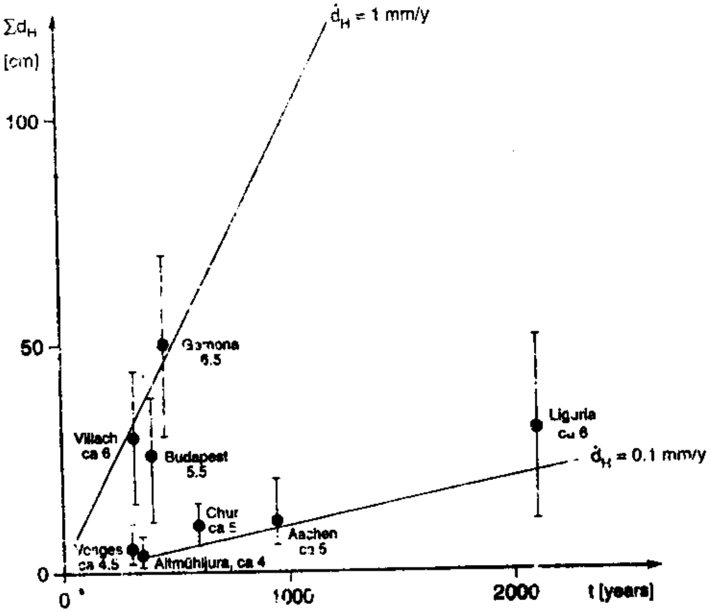


Fig. 8 Comparison of the cumulative horizontal crustal deformation Σd_H as a function of time and deformation velocity $\dot{d}_H$ with the displacement released by selected strong earthquakes in wider Central Europe over their average return periods. The bars for each earthquake give the range of uncertainty of displacement estimates. The numbers at each bar are the respective earthquake magnitude (redrawn according to Schneider 1993).

In the following, some more details will be given about seismic activity and seismotectonics in the main active regions of Germany, amongst them many results based on extensive instrumental observations. Germany avails of more than 100 seismic stations, meanwhile most of them with digital recordings, about two dozens equipped even with broad- and very broad-band high resolution digital seismographs such as stations of the nationwide German Regional Broadband Seismic Network (GRN, Hanka 1991) and the Gräfenberg Array, respectively (Buttkus 1986). In the former GDR there existed another large aperture digital station network with centralized real-time recordings of several short-period and one broadband seismometer (Bormann et al. 1992) besides local seismic networks in the Vogtland swarm earthquake region (Klinge and Teupser 1988, Neunhöfer and Güth 1989). In other seismically active regions rather dense local seismic networks have been installed as well. Most of them are administered by universities, e.g. in the Lower Rhinegraben and Rhenish Massif by the University of Cologne (Ahorner 1983b), in the Upper Rhinegraben by the University of Karlsruhe (Bonjer and Fuchs 1974; Faber et al. 1994), in the Swabian Alb by the University of Stuttgart and the Landeserdbebendienst Baden-Württemberg, in Nordrhein-Westfalen by the University of Bochum, and in Bavaria by the University of Munich. Besides this there exist several local networks and seismic arrays run by industry or governmental institutions aimed at monitoring of mining activities, sites of waste disposal, underground nuclear test explosions, seimic activities around hydroelectric or nuclear power stations. Some of the latter are also equipped with strong-motion recordings. This dense coverage with modern seimic stations enables not only precise epi- and hypocenter locations for most areas but allows also to derive detailed information about seismic source processes, wave propagation properties, Earth structure etc.

3. BADEN-WÜRTTEMBERG

The Land of Baden-Württemberg is the currently most active territory of the Federal Republic of Germany. It comprises both the Upper Rhinegraben and the Swabian Alb seismic provinces (cf. Figs. 5 and 9). Both areas are capable of earthquakes with intensities of ground shaking up to 7.5° to 8° (earthquake zone 4). The probably strongest shaking ever observed in the Upper Rhinegraben was related to the famous earthquake of Basel on 18 October 1356, maybe the strongest event ever in Central European history. Nowadays, very dense population and degree of industrialization of Basel has drastically increased its vulnerability to strong earthquake ground shaking since then. Estimates of current damages in Switzerland alone in case of another event of this strength range between some 13 and 47 billion Swiss Francs (Schaad 1989).

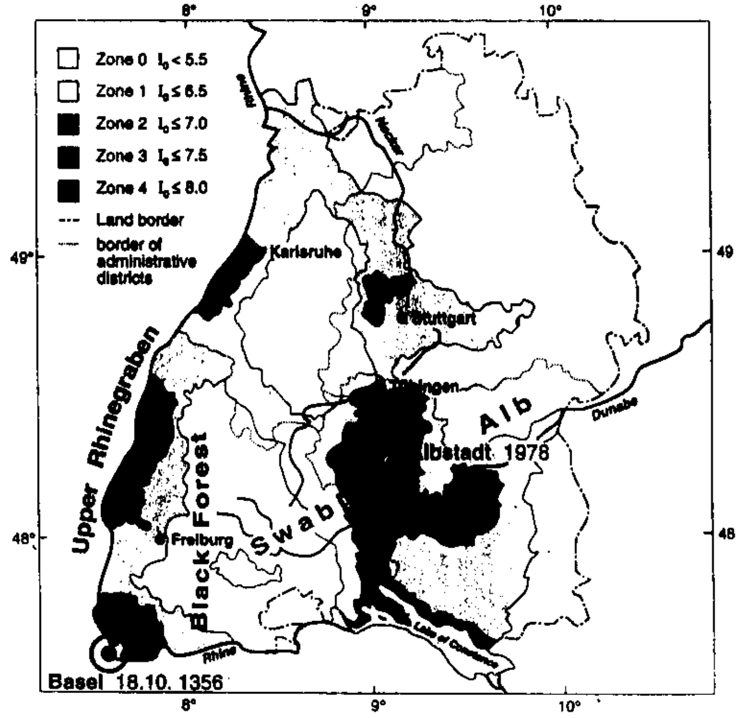


Fig. 9 Earthquake zones in the Land of Baden-Württemberg (redrawn and complemented after Schlee 1988).

Detailed accounts of the seismicity and dynamics of the Upper Rhinegraben in their relation to crustal structure and tectonics give Bonjer et al. (1984) and Faber et al. (1994). They also showed variations of focal depth across the Upper Rhinegraben (Fig. 10a). While underneath the crustal block of the Black Forest east of the graben focal depths may reach down to 20 - 24 km (see also Fuchs et al. 1987) underneath the southern graben seismic foci do not occur beyond 16 km, in some parts not even beyond 13 km depth. Also in the Vosges mountains, west of the graben, focal depths of 13 to 16 km are not exceeded. According to Edel et al. (1975) and Fuchs et al. (1987), underneath the southern Upper Rhinegraben and the Vosges Mtns., a slight updoming of the upper mantle is observed. The crust-mantle boundary there is only at 24 to 25 km depth as compared to depths up to about 30 ± 2 km in the wider surroundings. Additionally, the European heat flow map (Čermak and Hurtig 1979) shows rather high values between some 80 to 110 mWm^{-2} underneath the Upper Rhinegraben while values drop down to about 70 mWm^{-2} east of the Black Forest in the Swabian Alb before they go up again in connection with the Urach geothermal anomaly (80 to 100 mWm^{-2}) about 40 km NE of the Swabian Alb earthquake zone. In the latter also no seismic events occur beyond 18 km depth (Fig. 10b). The majority of earthquakes takes place there at depths between 3 to 6 km while the strongest shocks occur between 6 and 10 km depth (Turnovsky 1981). Also here the maximum source depth seems to be controlled by heat flow and its influence on crustal rheology (Bormann et al. 1986) although for the Black Forest with still rather high heat flow values (about 70 to 100 mWm^{-2}) this correlation is not obvious.

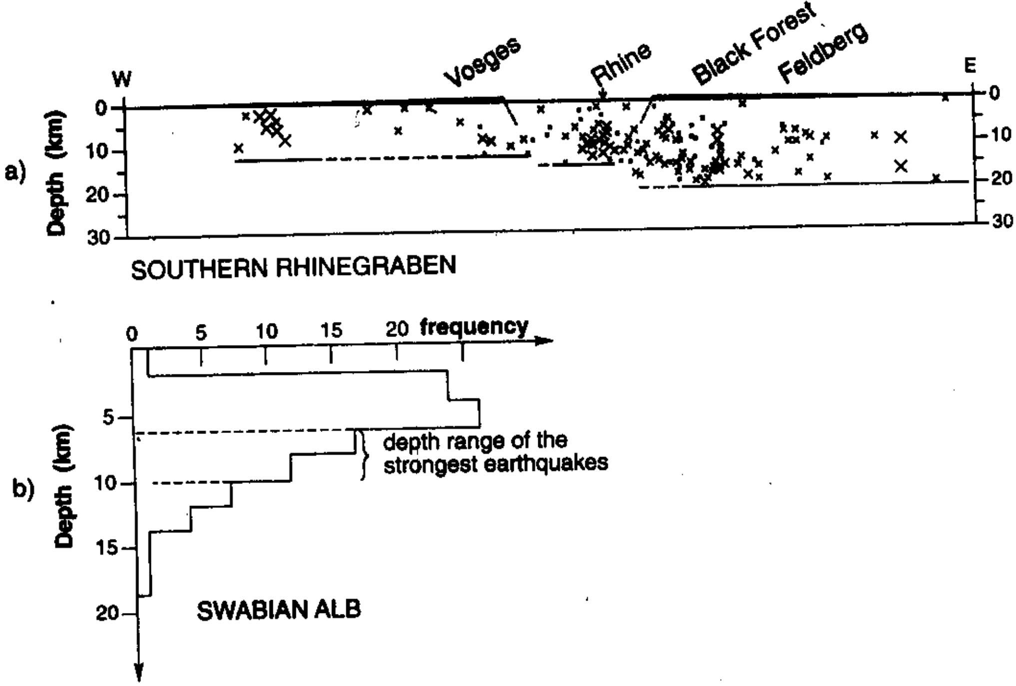


Fig. 10 Depth distribution of earthquakes a) along an E-W profile through the southern part of the Upper Rhinegraben and b) in a histogram for the Swabian Alb (redrawn and supplemented from Fuchs et al. (1987) and Turnovsky (1981), respectively).

The Swabian Alb in the eastern part of Baden-Württemberg has released within the first 60 years of our century significantly more seismic energy then the Upper Rhinegraben and even more than the whole eastern part of Germany since 1500 (cf. Fig. 7). But interestingly enough, no significant seismic activity had been observed there during historical time before the strong event of 16 November 1911 near the town of Albstadt. This was a kind of trigger event which activated the whole area to become the currently most active one in Germany. Kunze (1986) gives the following values for the event of 1911: ML = 5.6, M (Wood-Anderson) = 6.1, I_0 = 8°, $M_0 = 3.75 \times 10^{17}$ Nm, focal depth h_0 = 10 km, maximum distance of felt shaking 505 km. Other strong events with aftershock activity have occurred since then near Albstadt on 2 and 28 May 1943 (ML = 4.5 and 5.1, respectively), 26 February 1969 (ML = 3.9), 22 January 1970 (ML = 4.6) and 3 September 1978 (ML = 5.0). Fig. 11 shows a photo of damages related to the latter event (I_0 = 7° - 8°). Another strong event about 50 km SE of Albstadt near Saulgau happened on 27 June 1935 (ML = 5.4, I_0 = 7° - 8°).

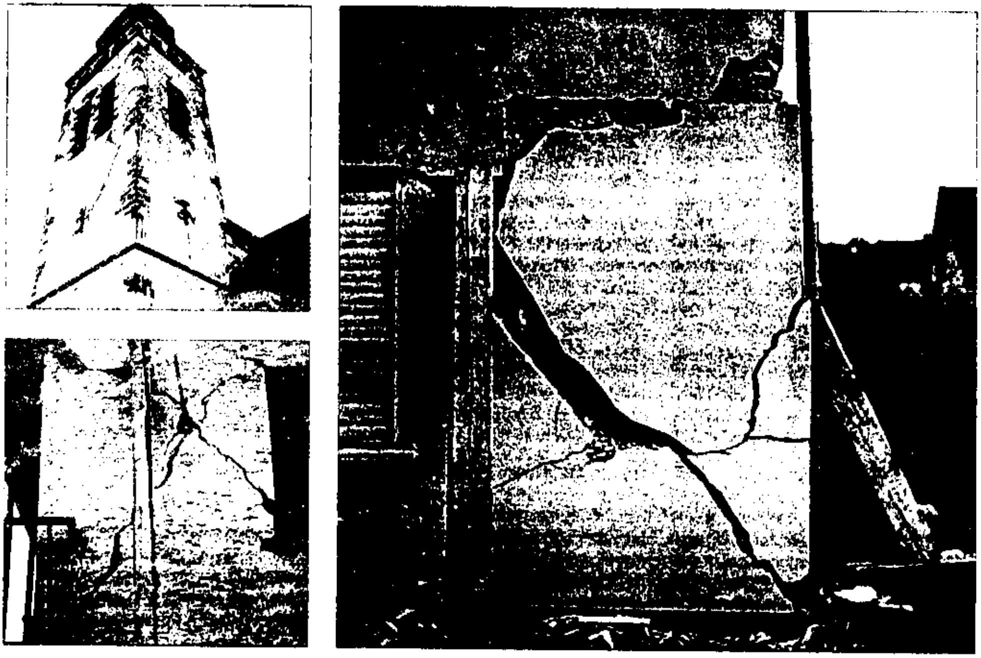


Fig. 11 Typical damages that occurred in the near epicentral area of the earthquake in the Swabian Alb on 3 September 1978 (from Schlee 1988).

For the earthquakes in the Swabian Alb, Schneider (1992) identified a tendency of SSW-NNE migration of events. It can be interpreted as being controlled by a slip-creep mechanism in connection with the current stress relaxation process in the Earth's crust there. The latter consists of a rheologically stratified system of a brittle upper crust over a visco-plastic lower crust. When the seismotectonic energy, accumulated within this system obviously over hundreds of years without any significant activity, will be discharged completely by the still on-going stress relaxation it might take another several hundreds of years of seismic quiescence before this source zone has been "recharged" again to the level it had reached when becoming active early this century. A more detailed account of the seismotectonic character of the September 3, 1978 Swabian Jura earthquake series give Tumovsky and Schneider (1982).

4. LOWER Rhinegraben

The second most active area in the western part of Germany is the Lower Rhinegraben with the Lower Rhine Embayment (Fig. 12). The strongest event ever observed and instrumentally recorded there took place on 13 April 1992 near the town of Roermond in Belgium in close proximity to the border with Germany. Damages have occurred, therefore, in both countries. According to Steinwachs (1992) about 500 houses and 80 churches had been affected. The total economic losses according to estimates of the insurance industry were in the order of 200 to 300 million DM. Due to thick cover of unconsolidated sediments in the epicentral area both soil failure and selective amplitude enhancement have been observed as well.

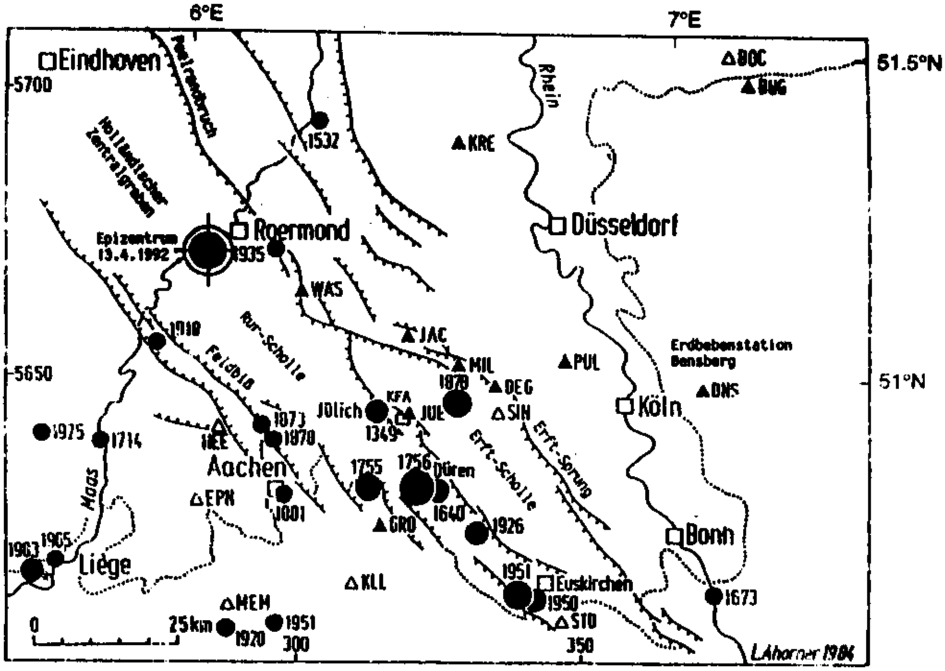


Fig. 12 Map of strong earthquakes and active tectonic features in the Lower Rhine Embayment. Seismic stations are shown as triangles (supplemented from Ahorner 1992a).

The Roermond earthquake was a normal faulting event which occurred on the northern boundary fault of the NW striking Rur Valley Graben and Central Dutch Graben (Fig. 13). Since the Quartemary, i.e. during the last 1.5 million years, along this fault cumulative vertical displacements of some 170 to 180 m have occurred. Recent average vertical motion rates of about 1 mm per year were confirmed by geodetic measurements (Ahorner, 1968). This is unusually active for Central European conditions (cf. Fig. 8). According to Ahorner (1992a and b) the following source parameters were determined for this event: ML = 6.0, $I_0 = 7°$, h = 20 - 30 km, $M_0 = 6.5 \times 10^{16}$ Nm, source radius $r_0 =$ 2230 m, source dislocation $d_0 = 13$ cm, stress drop $p_0 = 2.5$ MPa. Similar values have been determined by Grünthal and Grosser (1992) who give ranges for these values according to different model assumptions: ML = 5.3 - 6.1, $I_0 = 7 - 8°$, h = 18 - 31 km, $M_0 = 1.1 \times 10^{17}$ Nm, $r_0 = 1.9 - 3.6$ km, $d_0 = 9 - 30$ cm, $p_0 = 1 - 7$ MPa.

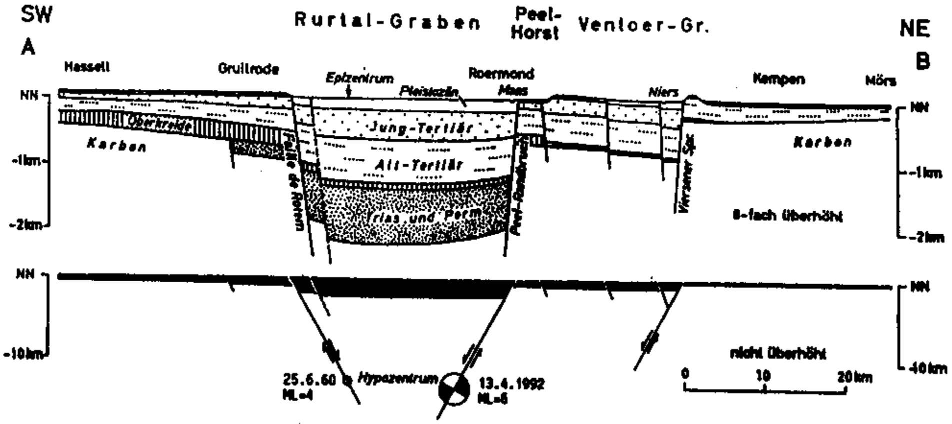


Fig. 13 Geological cross section through the northern part of the Lower Rhine Embayment (upper part, vertical scale 8 times horizontal scale) and position of the hypocenter of the Roermond earthquake (lower part, vertical and horizontal scale identical) - (from Ahorner 1992).

There have been no nearby strong-motion records of this event. The only useful records were made at a nuclear power station at 150 km epicentral distance both in the free field and in two reactor buildings. The values between various components and sites ranged between 0.14 and 0.44 ms^{-2} (Anonymous 1992). Up to now there exist no acceleration measurements from German earthquakes corresponding to a site intensity $I \geq 7$.

The Roermond earthquake was felt up to the easternmost towns in Germany such as Dresden, Cottbus and Zittau. The radius of the isoseismal intensity with I = 4° was, at least towards the east, about 370 km large. Some of the strongest earlier seismic events in the Lower Rhine Embayment could also be felt far towards the east, e.g. the earthquake at Düren on 18 February 1756, I_0 = 8° and h = 18 km, was felt up to Magdeburg, Halle, Erfurt, Gotha. But according to Grünthal and Grosser (1992) this was only the case for events with focal depth deeper than 15 km. More detailed general accounts of the historical and current seismicity, of the seismotectonic dislocation pattern and the earthquake-generating stress field in this area have been given by Ahorner (1983a, 1983b, 1985).

5. EASTERN PART OF GERMANY

The eastern part of Germany (former GDR) has seismotectonic characteristics which are rather different from those described before for the Rhinegraben and Swabian Alb, respectively. For this area exists a rather comprehensive and well documented earthquake catalogue covering the time span 823 to 1984 A.D. (Grünthal 1988). Fig. 14 depicts all events from this catalogue with $I_0 \geq 5°$.

The related Benioff graph of the cumulative seismic energy release in the Saxo-Thuringian province between 50° and 52° N (but without the swarm earthquake region) was

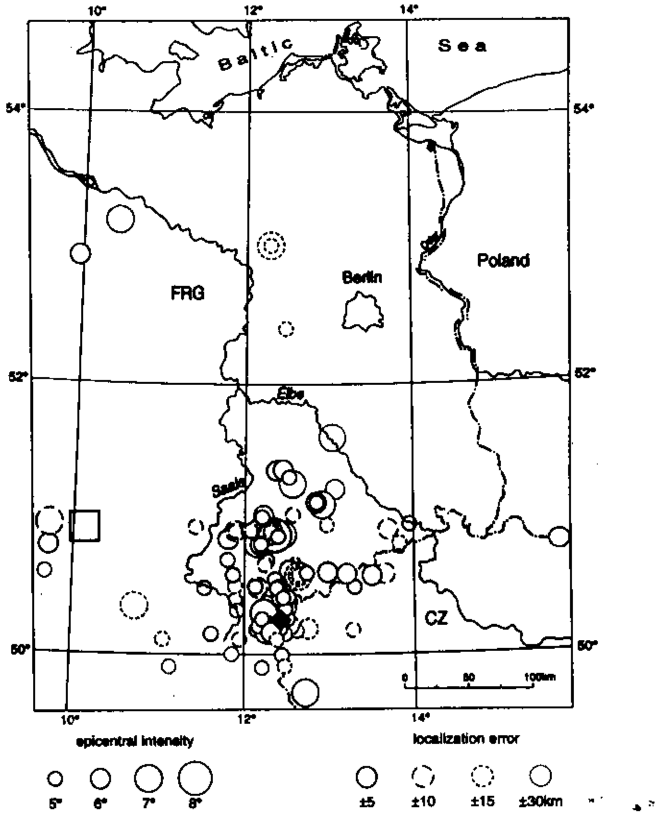


Fig. 14 Epicenter map for the eastern part of Germany and adjacent areas of all historically known statistically independent events with $I_0 \geq 5°$ and localization errors < ± 30 km (until 1984). The black diamond-shaped area gives the position of the earthquake swarm 1985/86 while the open quadrangle shows the area of strong mining induced events (supplemented from Grünthal 1989b).

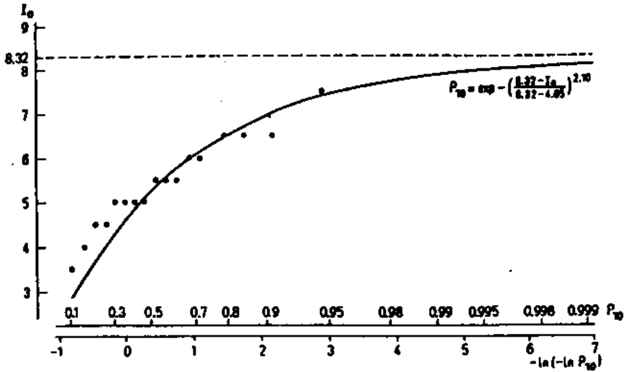


Fig. 15
Distribution of extrem values of earthquake intensity within 10 years' intervalls since 1800 in the Saxo-Thuringian province over the probability P and related average return periods T of non-exceeding the respective epicentral intensities I_0 (Gumbel III distribution). The asymptotic value of I_0 = 8.32° is an estimate of the maximum possible earthquake intensity in that region (from Grünthal 1991).

shown in Fig. 7c. Fig. 15 shows the Grumbel-III statistic of extreme values from which the maximum possible intensity of an earthquake in that area was determined to be $I_{max} = 8.3°$. Fig. 16 illustrates the relationship of seismicity in East Germany with the major seismotectonic elements. On the basis of seismotectonic and seismicity characteristics the area was subdivided into various regions for which different Gutenberg-Richter relationships were found (Fig. 17, Grünthal 1980, 1981). For region V (Vogtland swarm earthquake area; for position see Figs. 4, 14 or 16) both a and b are by far largest (b = 1.35). This gives hint to rather peculiar properties of this area. But although region V is the seismically most active one in East Germany the strongest event ever noted there occurred in region IV (eastern Thuringia) near the town of Gera on 6 March 1872 (M = 5.1, $I_{max} = 7.5 - 8°$). Fig. 18 shows an older version of the isoseismal map for this event. A more recent map and detailed data account covering also the adjacent areas gives Grünthal (1992). For comparison, the respective maximum events in earthquake swarms had values of M = 4.0 to 4.6 and $I_0 = 6.5$ to 7°.

According to Bankwitz et al. (1985) an analysis of recent crustal movements shows that the Vogtland swarm earthquakes' area is characterized by a superimposition of strong compressions with significant shear strain. Additionally, as seen from Fig. 15, the area of swarm earthquakes coincides with the intercrossing of very different directions of fault and lineation patterns. Consequently, it seems not to be capable of storing large amounts of tectonic energy and discharging it in single major events. Rather, it releases energy in some larger time intervalls dominatingly as randomly scattered smaller single events and at other times as swarm-like "bursts" with many events within a rather short time span (Fig. 19). The swarms itself are mostly connected with the Mariánské Lázně fault zone and its northern extension (Fig. 23) while the individual events occur chiefly in the wider surroundings of this zone. Most swarms are rather short in duration (< 1-2 weeks)

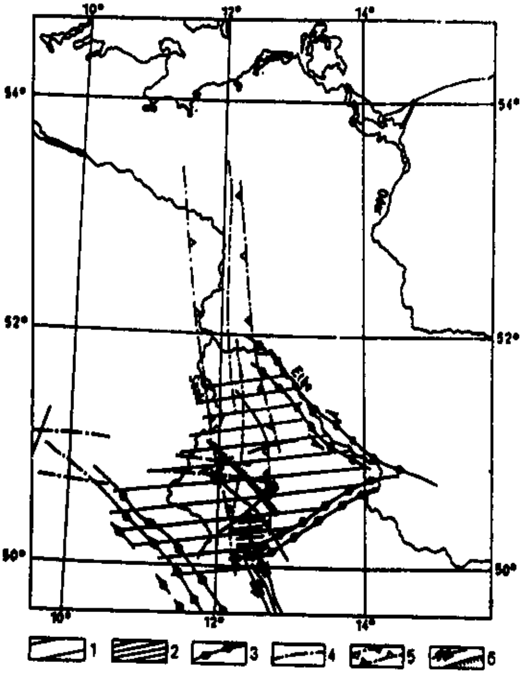


Fig. 16
Scheme of a tentative connection of seismicity and major tectonic elements. 1 - Saxo-Thuringian seismic province, 2 - focal area of earthquake swarms, 3 - faults or fault systems delineating the seismic province, 4 - photolineations derived from satellite images, 5 - delimitation of an overregional N-S up to NNW-SSE directed bundle of photolineations, 6 - post-Oligocene active faults, probably connected with seismic activity (from Grünthal 1989b).

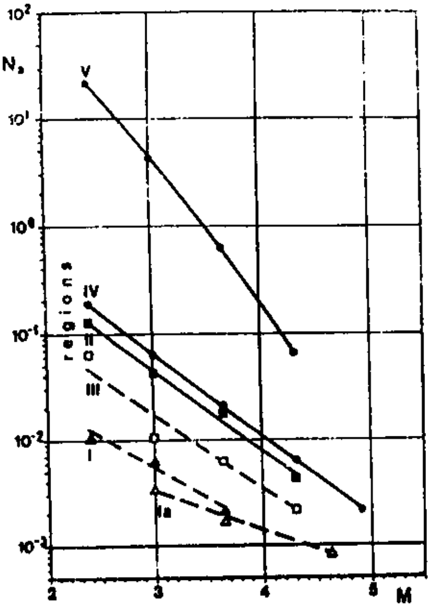


Fig. 17 Annual frequency of magnitudes in the seismic regions of eastern Germany (from Grünthal 1980).

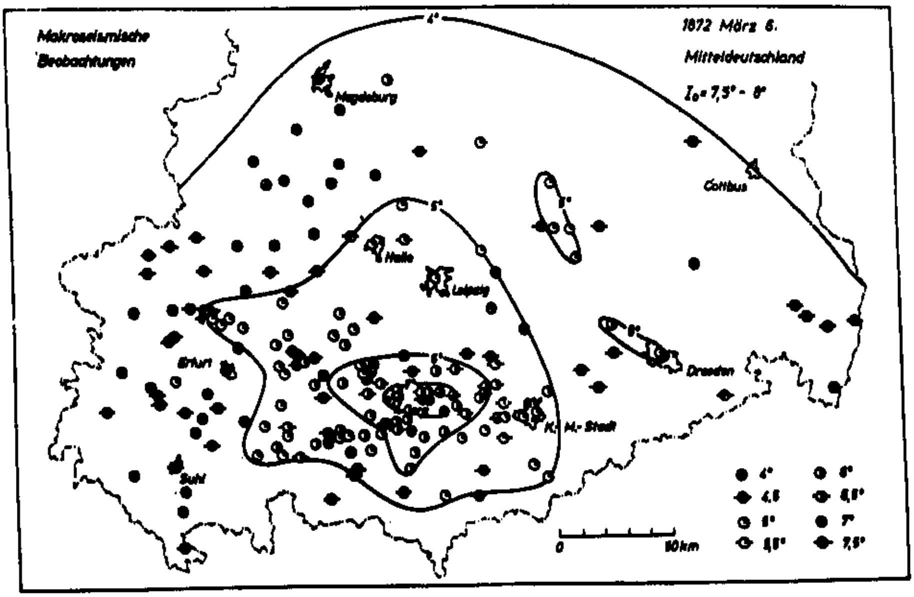


Fig. 18 Observed intensities and interpolated isoseismal lines for the Central German earthquake of 6 March 1872 (according to Sponheuer and Grünthal 1981).

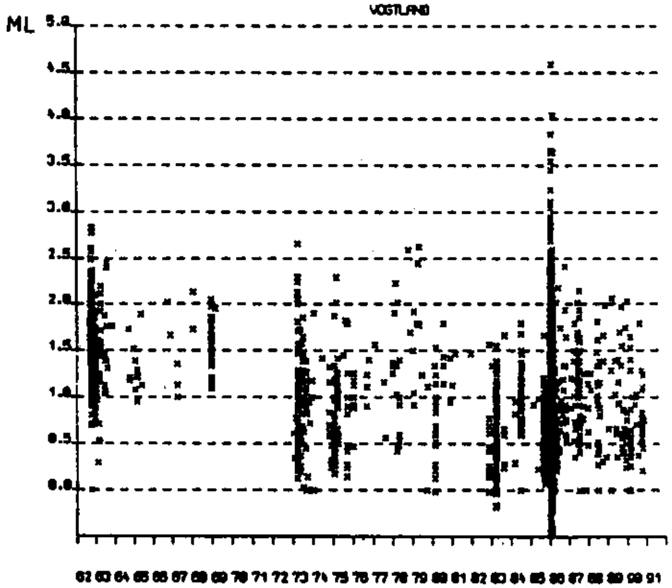


Fig. 19 Magnitude-time plot for all seismic events recorded between 1962 and 1990 in the region Vogtland/Western Bohemia (according to Neunhöfer et al. 1991).

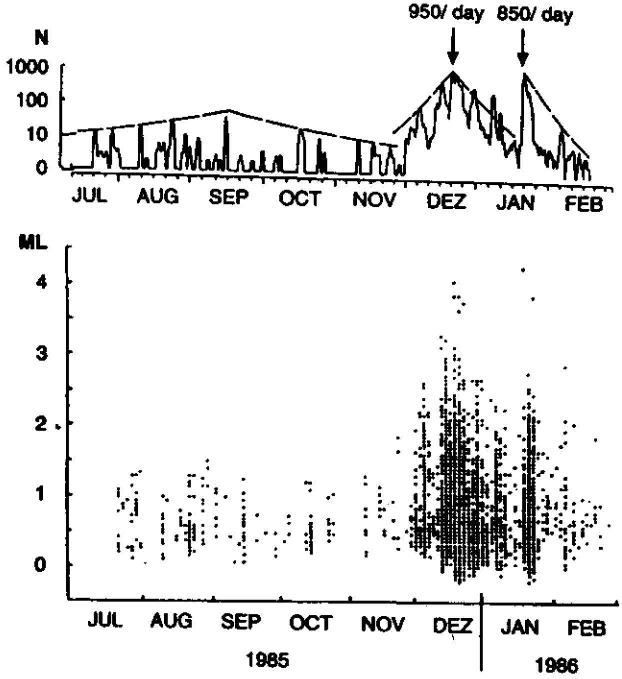


Fig. 20 Daily frequencies of seismic events during the pre- and main swarm in 1985/86 (above) and related magnitude plot (below) - (complemented from Neunhöfer and Güth 1989).

and only locally perceptible (ML < 3) but the strongest swarms may run for up to about 3 months duration. Typical for earthquake swarms is the rather symmetrical build-up towards and following decay of both frequency and magnitude of earthquakes after the main event (Fig. 20). The strongest swarms have events with peak magnitudes between ML = 4 - 4.6, epicentral intensities $I_0 = 6° - 7°$ and distances of perceptibility of shaking up to about 150 to 300 km. Since both swarm duration and area of perceptibility are related to the maximum magnitude of events within the swarm, Grünthal (1989a) was able to derive from historical reports of felt Earth shaking in Saxony and Thuringia a temporal distribution of swarm occurrence in four classes of strength (Fig. 21). It reveals that major swarms comparable with the one of 1985/86 (cf. Fig. 20) occurred since the 16th century in the area Vogtland/Western Bohemia in the average every 74 ± 10 years. On the other hand this does not exclude that occasionally several strong swarms may follow each other within a few years only, as it was the case between 1897, 1903 and 1908, with several "second class" swarms in between. Obviously, such clusters have to be considered as only one event in a long-term statistics of average return periods.

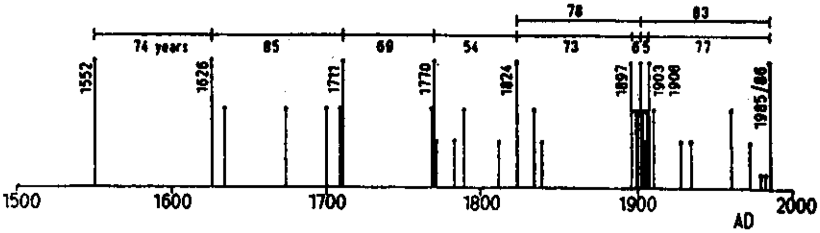


Fig. 21 Temporal distribution of earthquake swarms in the area Vogtland/Western Bohemia in various classes of strength depending on the duration of the swarm and the distance of felt shaking (from Grünthal 1989a).

During the swarm 1985/86 local seismic networks both in the Vogtland (then GDR) and in the epicentral area in Western Bohemia (then ČSSR) were in operation, partially with high resolution digital recordings. This allowed not only to derive source parameters from spectral analysis but also precision locations with about 200 m accuracy to associate the more than 8000 recorded seismic events in the magnitude range $-1 \leq ML \leq 4.6$ with a very small source volume of about 1.5 km width in E-W and 4 km length in N-S (Fig. 22). Source depths varied between about 8.5 and 10.5 km (Neunhöfer and Güth 1989, Horálek et al. 1987). This source volume could be related to the about 2 km wide NNW striking Mariánské Lázně fault zone (MLF). Even within this small volume a linear clustering of events was recognizable which hinted an association, at least of the smaller events, with secondary crossing faults. Earlier swarms, e.g. in 1962, could be related to the NNW extension of the MLF (Fig. 23). Investigations into fault plane solutions yielded, besides a few thrust type events, a domination of strike-slip to normal faulting (Fig. 24) with a tendency of increasing normal faulting components from N to S. This led Antonini (1988) to suggest that the faulting produced by the recent earthquake swarm was consistent with the general tendency of subsidence of the young Tertiary to Quarternary wedge-like Cheb basin which deepens from NW towards SE along the MLF (Fig. 25). This seems to be supported independently by the tendency of increasing focal depth from N to S (Horálek et al. 1987, Neunhöfer and Güth 1989).

Grünthal et al. (1989a and 1990) proposed a seismotectonic model which relates the 1985/86 swarm to a splay-structure connected with a right-lateral offset along a N-S fault element dissecting the MLF. They relate, at least the majority of smaller events, to dominatingly left-lateral strike slip along such ± N-S striking secondary faults within this wedge-like feature of the MLF. Contrary to this, Neunhöfer and Güth (1989) interpreted the mostly NE trending linear clustering of smaller swarm events in Fig. 22 as such secondary crossing faults. They also identified within the source volume a systematic migration of the "epicenters" of microearthquake clusters along these elements both NE- and SW-ward and from S towards N during the course of the swarm. This would be consistent with the concept of progressing, both in-strike and lateral, stress readjustment within the source volume and its surroundings (e.g. Mendoza and Hartzell, 1988) but also with Fig. 25 and its comment. Available fault plane solutions (Fig. 24) would be compatible with both proposed options of active secondary faults and also agreeable with strike-slip to normal faulting of some stronger events along NNW trending faults, subparallel to the MLF itself.

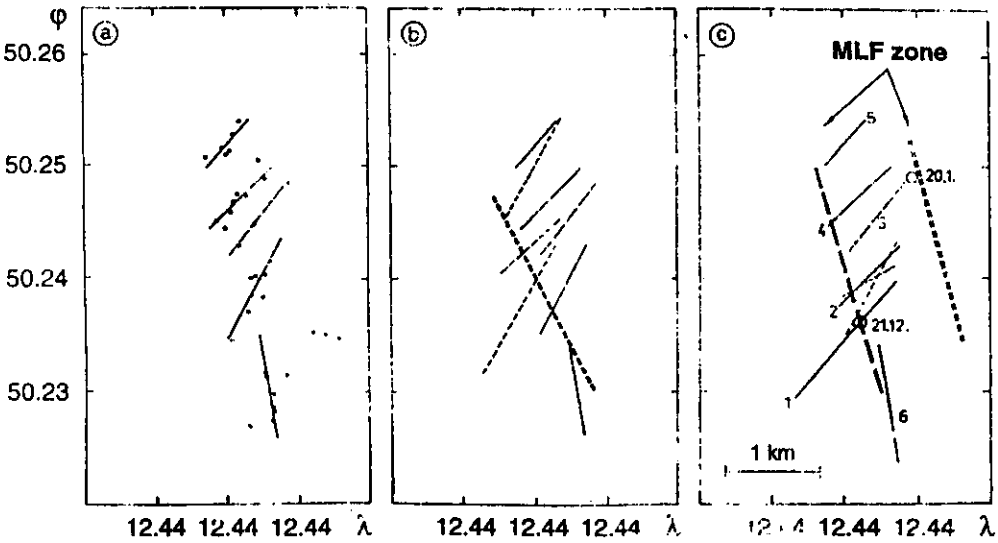


Fig. 22 Localization results by Horalek et al. (1987) (a), their generalization together with results by Neunhöfer and Güth (1987) (b), and a final joint scheme of the source region as derived from both results (c). MLF - Mariánské Lázně fault zone; 1 to 6 - secondary crossing faults as inferred from the clustering of microearthquake epicenters; open circles - location of the two main events on 21 Dec. 1985 (ML = 4.6) and on 20 Jan. 1986 (ML = 4.2); λ and Φ - geographic longitude and latitude in degrees (supplemented from Neunhöfer and Güth 1989).

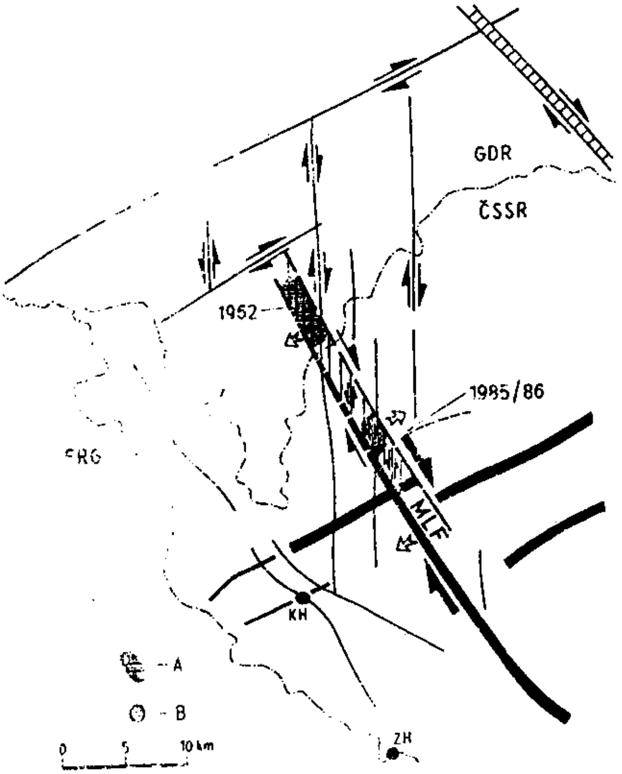


Fig. 23 Seismotectonic scheme for the focal zone of swarms in Vogtland/Western Bohemia. A - epicentral zone of swarms, B - youngest volcanoes, active 0.85 ± 0.1 Ma B.P. (KH - Komorní hurka, ZH - Zelezná hurka). The tendency of tectonic blocks for horizontal movements is given. Hatched parts depict epicentral areas of swarms within the Mariánské Lázně fault zone (MLF). Dextral creep is observed in the N-S fault elements intersecting the Marianské Lázně fault zone, whereas sinistral elastic rebound occurs during the focal process of swarms (from Grüntnal et al. 1989e).

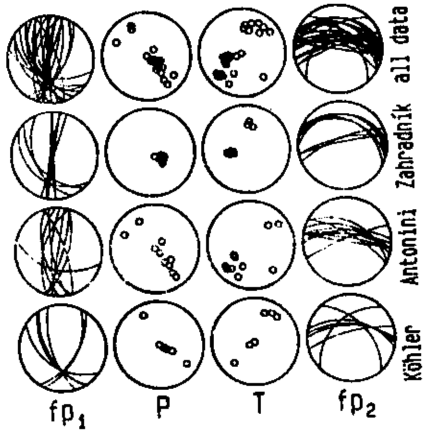


Fig. 24 Published fault planes (f_{p1}, f_{p2}, both solutions), pressura (P) and tension axes (T) of swarm events 1985/86 (from Baumbach 1989).

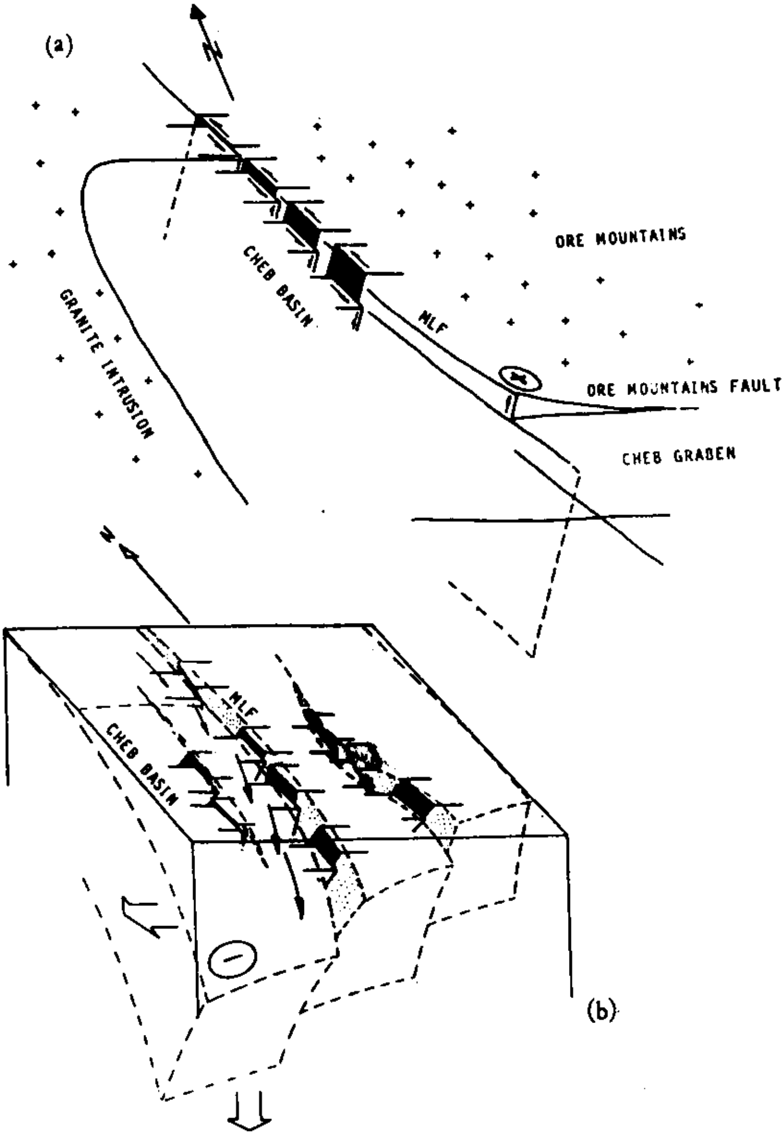


Fig. 25 a) Schematic block diagram illustrating the geometry of faulting during the 1985/86 earthquake swarm. The continuing subsidence of the eastern Cheb basin in connection with normal oblique-slip faulting is indicated. b) Enlarged sketch of faulting in the active area. The possible fault planes of the nine analysed mechanisms are shown. The observed W-E extension of the active area suggests that the Cheb basin subsides on several similarly orientated planes. This is typical for graben tectonics (from Antonini 1988).

To reconcile these various views, the author holds the view, that most of the stronger swarm events (ML > 2.5) took place along the large regional fault (MLF) while the majority of smaller events, which are mainly related to the process of stress readjustment within the fault system, might be associated with crossing or subparallel secondary faults. This assumption can be supported by additional evidences and arguments. Firstly, events with ML > 2.5 should have a rupture length L larger than the width of the MLF zone and of the observed active source volume (L > 1 km). Secondly, Neunhöfer and Güth (1989) could show that average b-values determined from events with M < 2.3 were significantly larger (b = 1.06) than those determined from stronger events (b = 0.84). They related lower b-values to higher deformational energy density (DED) required to cause rupturing and vice versa. They could also show that before the escalation of the pre-swarm between July and November 1985 with ML < 2 for all events and rather large b-values of about 1.3 into the main swarm of December 1985 with ML_{max} = 4.6 the b-values dropped down to about 0.8. At the end of the first main phase with many small aftershocks b-values were up again in mid January to about 1.2 and dropped again down to 0.9 with the second phase of strong events around 20 January. These drastic changes in b and thus DED clearly affected the discharge ("pumping" effect) of mineral springs in the area at about 18 km epicentral distance (Kämpf et al. 1989) while the associated changes in the chemical composition of the springs seems to hint at a deeper situated magmatic lower crustal-upper mantle origin for the tectonic impulses which are manifested by these swarm events. The youngest volcanic activity in the area is of Quarternary/Pleistocene age (Fig. 23; Kämpf et al. 1993, Weinlich et al. 1993).

This relationship between changes in b, DED and magnitude of events is consistent with the finding by Baumbach (1989) that, in the average, events with ML > 2.4 showed a larger stress drop than smaller events. Additionally, Baumbach found from the spectral analysis of 90 digitally recorded Vogtland events that the scatter of seismic moment ratios for P- and S-waves was much smaller (and consequently fault plane solutions for stronger events much more stable in their orientation) than for weaker events. All this would be consistent with the assumption that the larger events were mainly controlled by the more stable regional stress field and orientation of the NNW striking regional tectonic structure of the MLF while the weaker events were dominatingly controlled by more irregular local stress anomalies and secondary tectonic elements crossing the MLF. Taking the orientation of the secondary elements with respect to the NW-SE orientation of the regional stress field in the source region into account (cf. Fig. 3) it seems to be more reasonable to assume rather a NE-SW lateral migration of epicenters of smaller events than rupturing along the NE-SW elements while rupturing should have taken place preferably along ± N-S or E-W oriented secondary faults (Bormann and Grosser, 1989).

Another interesting finding provides also a clue to understand the influence of rheological properties in the swarm earthquake area. According to Grünthal (in Bankwitz et al. 1985 and Bormann et al. 1986) the macroseismically determined depth distribution of the strongest events during the last 160 years shows that the main activity occurs between 5 and 10 km depth with the maximum around 7 - 9 km. At greater depth follows a smaller maximum between 14 and 16 km. The minimum of activity in between coincides with the center of a P-wave low velocity layer (LVL) which was found by Knothe (1972) along a deep refraction seismic profile passing-by the source region at about 20 km towards NE. Low velocity layers are normally related to zones of weakness and reduced shear strength. This would explain the maximum of occurrence of earthquakes above the LVL and also make plausible the possibility of seismic fracturing again below it. Interestingly, according to Neunhöfer (1988, personal communication), focal depths above the LVZ are typical for swarm events while individual events in the wider surroundings have often larger focal depths corresponding to the second maximum of earthquake occurrence.

With regard to the rheological properties of this area one has to consider that its upper crust is of acid composition (nearby major granitic plutonic bodies). Also the heat flow is rather high (70 to 80 mWm^{-2}, Čermak and Hurtig 1979). According to heat flow inversions by Rugenstein and Stromeyer (1980, personal communication) we can expect, therefore, temperatures of about 250° C and 350° C at some 10 km and 16 km depth, respectively. Since acid rocks have the maximum tendency of brittle fracturing at depths corresponding to temperatures up to about 250° C the observed maximum of earthquake occurrence between 5 to 10 km depth becomes understandable. On the other hand, at temperatures of some 350° C the process of cataclasis with pseudoplasticity changes into mylonitization of rocks with dislocation plasticity and thus rock flow. This would explain why in the Vogtland area no seismic events beyond 16 km depth have been found. Strikingly enough, recent high resolution deep reflection seismic profiling along the Ore Mountain (Erzgebirge) range (profile MVE '90) has revealed above 8 to 10 km depth and below 14 to 15 km depth bands of high reflectivity underneath the Vogtland swarm earthquake region with a zone of low reflectivity in between (Schulze, 1993, personal communication). It is intriguing to relate these features to the two seismically active layers and the LVL zone of minimum activity, respectively.

6. MINING INDUCED SEISMIC EVENTS IN GERMANY

Although most types of subsurface mining do induce some kind of seismic activity the area of potash mining around 50.8° N and 10° E along the Werra river is particularly prone to strong mining induced events (cf. Fig. 14). According to Grünthal (1988) no natural earthquakes with $M \geq 3$ have occurred in this area during historical times. But since the beginning of mining operations in the late 19th century several non-tectonic seismic events with $3 < M < 6$ took place. The strongest were in 1953 (macroseismic magnitude $M_m = 5.2$, $I_{max} = 7.5°$), 1958 ($M_m = 4.7$, $I_0 = 7.0°$), 1961 ($M_m = 3.5$, $I_0 = 6.0°$), 1975 ($m_b = 5.4$, $I_0 = 8.0°$) and on 13 March 1989 ($ML = 5.6$, $I_0 = 9$) (Grünthal 1988, Ahorner 1989, Knoll 1990, Bormann et al. 1991). The latter was probably the strongest mining induced seismic event ever recorded world-wide. It occurred at about 850 m depth where more than 3200 carnallitite pillars crashed causing the collapse of a mining field of about 6.8 km² and a maximum subsidence at the Earth surface of about 0.8 to 1 m. This corresponds to a release of potential energy of about 1.3 x 10^{14} J. The epicentral intensity of $I_0 = 9°$ was extreme for German conditions. It caused significant damages in the village of Völkershausen just above the collapsed mine. But the area of strongly felt shaking was rather small due to the shallow source depth. The radius of the isoseismal of $I = 5°$ was $r = 15 \pm 3$ km only. As compared to this, for the Central German earthquake of 1872, despite of its smaller magnitude ($M_m = 5.1$), intensities $I = 5°$ were observed up to about 100 km epicentral distance (cf. Grünthal 1992 and Fig. 18). On the other hand weak shakings ($I = 3°$) were perceptible up to the towns of Dresden in the E (about 260 km), Magdeburg in the NE (about 200 km) and Frankfurt am Main in the SW (about 130 km) (Leydecker et al. 1994, cf. Fig. 26).

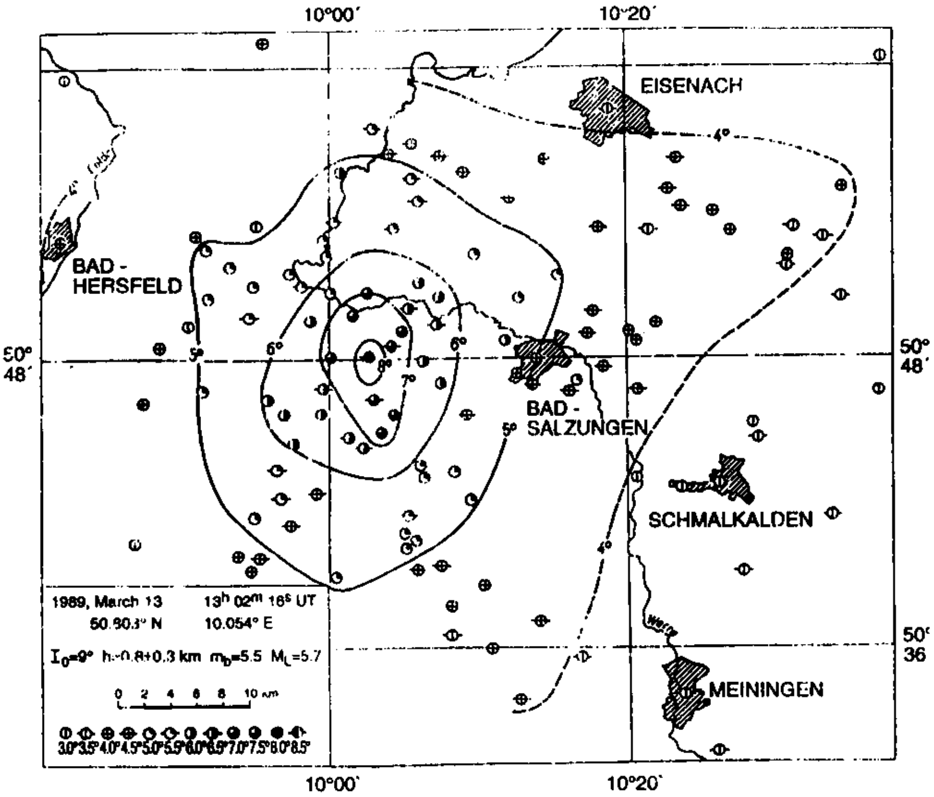


Fig. 26 Isoseismal map for the strong rock burst on 13 March 1989 (from Leydecker et al. 1994).

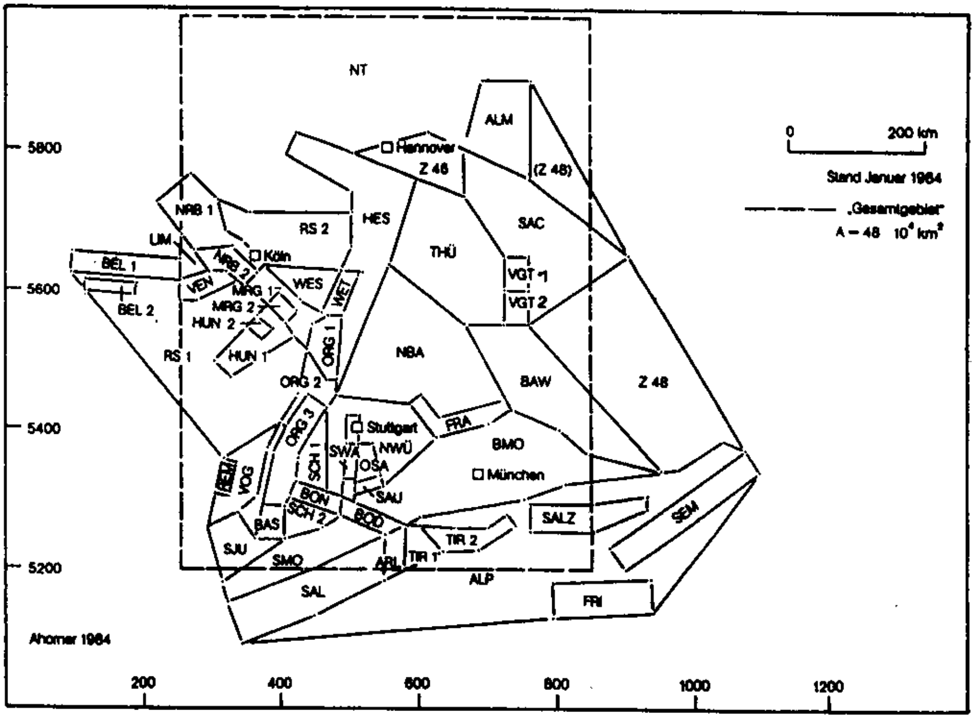
7. SEISMIC HAZARD ASSESSMENT AND REGULATIONS

On the basis of seismotectonic and seismicity characteristics, Germany has been subdivided into different earthquake zones within which a statistically uniform distribution of events in space and time was assumed (Fig. 27). For these zones the parameters of the Gutenberg-Richter relationships as well as the maximum possible earthquakes according to Gumbel-III statistics of extreme values were determined. These parameters provided the basis for probabilistic assessments of seismic hazard for the former GDR (Schenk et al 1984), for Germany as a whole (Ahorner and Rosenhauer 1986, Fig. 28) or, in more detail, for subregions, e.g. the Saxo-Thuringian province (Grünthal 1989d, Fig. 29) or the Vogtland swarm earthquake region (Schenk et al. 1989), using various procedures (e.g. McGuire 1976, Rosenhauer 1984). On the basis of these probabilistic maps, or using traditional procedures, seismic zoning maps have been developed for subregions and Germany as a whole.

The new zoning map for Baden-Württemberg (Fig. 9) resulted in a redrafted announcement by the Ministry of Interior of that country with respect to the inforcement of the German Industrial Norm "DIN 4149, part I - Buildings in German earthquake areas". The respective publication by this ministry was additionally accompanied by a well illustrated information broschure about causes and size of earthquakes, building damages due to earthquakes, legal aspects of building in earthquake areas, earthquake resistent planning and construction, a summary of general rules of earthquake resistant construction, design details for buildings with only few stories, planing examples for residential houses of different kind up to multistory buildings (Schlee 1988). The suitability of this publication for other regions as well has led to its translation, regional adaptation and publication in Spanish (Klein, Ed. 1991)

Similar zoning maps had been produced by Grünthal (1991), on the basis of repeatedly observed intensities for eastern Germany, and by Schwarz et al. (1990) for the same area on the basis of probabilistic hazard maps (e.g Fig. 29) for two hazard levels corresponding to mean return periods of 308 and 615 years respectively.

Then, to each earthquake zone free-field design spectra were allocated which were considered to be representative for the respective intensity interval of each zone and for different classes of subsoil conditions (e.g. unconsolidated sediments, weakly consolidated sediments, hard rocks) - (Schöbel 1989). Since no relevant German strong motion records were available records from other European areas made in similar environments of events with magnitudes M < 6.5, focal depths h < 15 km and intensities at the recording sites corresponding to the intensity intervals for each zone were taken into consideration.



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Abteilung Erdbebengeologie, Geologisches Institut, Universität Köln

Fig. 27 Seismic source zones in Germany and adjacent areas as used for the probabilistic hazard analysis (cf. Fig. 28) - (from Ahorner and Rosenhauer 1986).

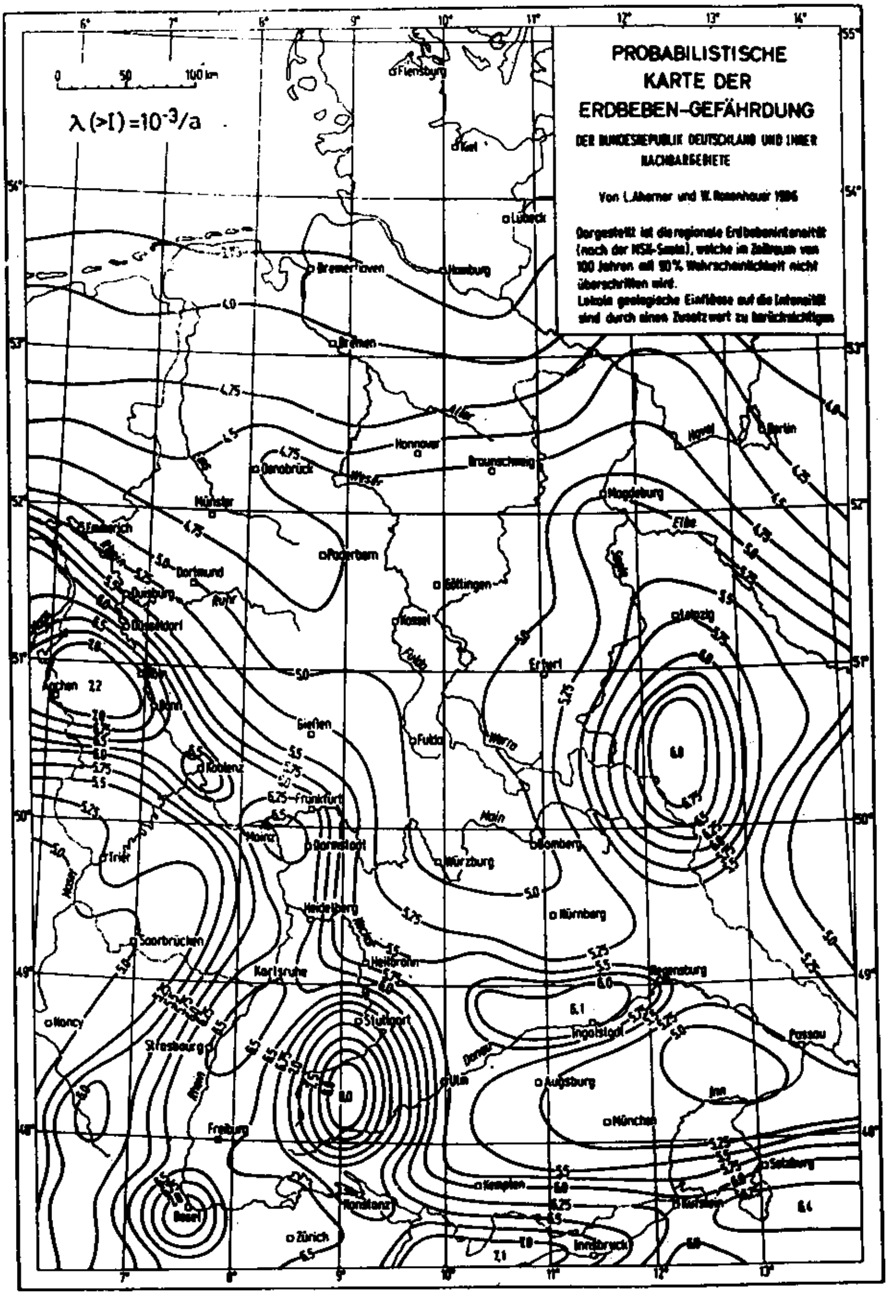

Fig. 28 Probabilistic map of seismic hazard in Germany and adjacent areas. Depicted are the isolines of regional intensity according to the MSK scale which will not be exceeded with a probability of 90 % within a time span of 100 years. In case of 10.000 years with the same probability the values shown in the areas of maximum intensities will be between 0.25 and 0.8 intensity units larger (according to Ahorner and Rosenhauer 1986, taken from Ahorner and Rosenhauer 1993).

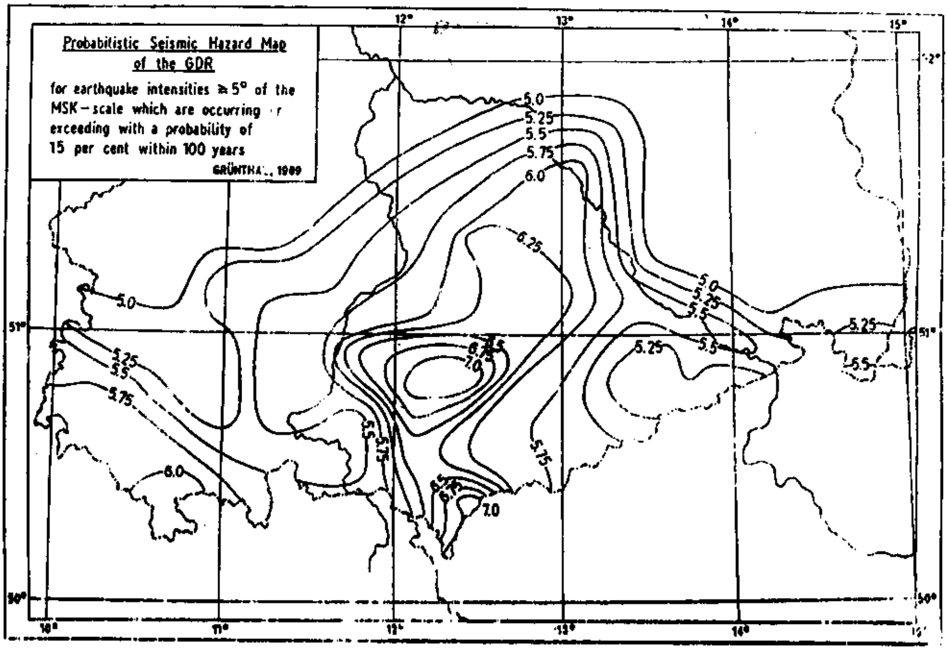

Fig. 29 Probabilistic map of seismic hazard in the Saxo-Thuringian province of East Germany according to Grünthal (1989d) based on digitized isoseismal maps (taken from Ahorner and Rosenhauer 1993).

On the basis of these earlier efforts in both parts of Germany most recently a new seismic zoning map for the whole of Germany was developed. It provides the future reference basis for the application of the relevant legal regulations according to the German Industrial Norm (DIN).

8. CONCLUSIONS

Germany is a country of modest seismic activity and hazard typical for seismic regions in active consolidated platforms. But dense population and industrialization result in a not neglectable risk. Therefore, very detailed and complex seismological investigations have been carried out by many institutions and researchers in Germany. Besides a considerably deepened insight into the peculiarities and causes of seismicity of this intracontinental environment these studies also produced reliable seismic hazard and zoning maps which provide a sound basis for governmental regulations with resprect to building codes.

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