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Seismotectonic model for the earthquake swarm of 1985–1986 in the Vogtland / West Bohemia focal area

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Abstract

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After decades of minor seismic activity an intensive earthquake swarm occurred in 1985–1986 with a maximum activity in December 1985 and January 1986, in the well-known narrow focal zone of swarm quakes in the border region of the G.D.R. and Czechoslovakia. Local seismic networks recorded more than 8000 events during this swarm, the strongest local magnitude being 4.6. Nearly all of these swarm events were located within a relatively small focal volume 3.5 km in length, 1.5 km in width, and at depths of 6–8 km.

Fault-plane solutions could be determined for 17 of the strongest events. They provided the basis for seismotectonic modelling in connection with (1) detailed tectonic data (including faults indicating conditions at the seismogenic depths, and recent active faults), (2) crustal stress data, and (3) studies on recent horizontal movements of crustal micro-blocks.

According to detailed local micro-earthquake monitoring since 1962, all epicentral areas of swarms are aligned along the N153°E striking Mariánské Lázně fault (MLf), which trends approximately in the azimuth of maximum compressive stress. The MLf is intersected by a bundle of recent active, lamellar N–S to NNE–SSW fault elements. The fault-plane solutions of 14 of the events studied show strikes in this direction. The others strike along the MLf. Tectonic evidence for the conjugate planes is lacking.

Both the MLf and the N–S fault elements show a tendency to dextral creep according to neotectonics and recent horizontal crustal movements, whereas a generally sinistral elastic rebound has been derived for the focal process of the swarm. This reflects alternating block movements which could also be deduced from repeated geodetic measurements.

Probably, the MLf system provides a suitable setting for the foci only, whereas the faulting process itself occurs mainly on secondary faults within the system. Moreover, a splay-structure along the MLf, immediately south of the 1985–1986 epicentral area and connected with a right-stepping offset along a N–S fault element, substantiates the proneness to the occurrence of swarm-like seismic activity.

1. Introduction

One of the most interesting earthquake-swarm areas, at least in Europe, is the focal region of the Saxonian–Bohemian Vogtland, as it was termed by Sieberg (1923, 1932). We use here the terms Vogtland (in the meaning of the landscape-mark-

ing Oberes Vogtland as the southern tip of the G.D.R.) and Western Bohemia (as the northern part of the Cheb district in western Czechoslovakia, ČS.S.R.). During the last 100 years, intensive swarms with maximum magnitudes of 4.6 to 4.8 occurred in 1897, 1903, 1908 and more recently, in 1985–1986. Within this interval of 100

years, swarms of medium intensity were observed in 1900, 1901, 1904, 1911, 1936 and 1962. During the swarm in 1962, a permanent local seismic network was installed (Neunhöfer, 1976) which enabled the complete recording of local shocks of $M \geq 1.3$. This detection threshold was later improved to $M \geq -0.15$. Events of $M \leq 2.5$ occurred in the focal region from 1963 up to 1984 (Neunhöfer et al., 1987). Fault plane solutions could be derived for the first time for the focal area of swarms for the strongest shocks of the 1985–1986 swarm. They served as an essential basis for the seismotectonic modelling.

2. Seismicity pattern of the 1985–1986 earthquake swarm

According to Neunhöfer and Güth (1987), the intensive swarm started with microshocks ($M > 0.8$) in July, 1985. A perceptible strength was

reached at the beginning of Dec. 1985 with several consecutive culminations of seismic energy release in that month. The intensive phase of the swarm was extensively recorded by several local and regional seismological networks. They gave partly differing earthquake magnitudes. In the present text, the magnitudes obtained by Strauch and Wylegalla (1988) are used. The activity maximum, including the largest shock with $M = 4.6$, was observed on Dec. 21, 1985. After that maximum, two additional smaller pulsations followed up to the middle of Jan. 1986. Then, after 8 days of quiescence, in which only the normal level of background seismicity occurred, a final burst of seismic activity started with the second-largest shock ($M = 4.2$), accompanied by an intensive aftershock sequence lasting 4 days. A sequence of microshocks was observed within a uniform narrow focal zone up to June, 1986. In July, 1986 the spatial seismicity pattern suddenly changed into

Fig. 1. Daily number N of events with magnitudes $M \geq 1.5$ recorded and interpreted by the seismological network of the Central Institute for Physics of the Earth, Potsdam, G.D.R., for the magnitude intervals: $1.5 \leq M \leq 1.99$ (open parts of the columns), $2.0 \leq M \leq 2.99$ (hatched parts), $M \geq 3.0$ (solid parts). Additionally, the daily magnitudes ($M \geq 2.5$) are depicted as dots.

the type of microearthquakes occurring within the whole seismically latent area of the larger focal zone of Vogtland/West Bohemia (Neunhöfer and Güth, 1987). In total, about 8000 events were observed instrumentally during that swarm.

The time pattern of seismic activity from Dec. 1, 1985, up to Feb. 6, 1986, is illustrated in Fig. 1 for events with $M \geq 1.5$. In particular, the temporal behaviour up to Jan., 13 is very typical for

that focal area. But the sub-swarm, starting on Jan. 21 with a main shock which was not preceded by any forerunner and a relatively short aftershock sequence, seems to be less typical for that pronounced swarm-quake region.

Another typical feature of the earthquake swarms is the relatively small magnitude differences between the main shock, the second largest event and the subsequent ones within a

Fig. 2. Epicentres and epicentral areas of the Vogtland-West Bohemia focal zone and fault tectonics, after Geological Map of Czechoslovakia 1 : 200,000 (1960) and Šantrůček and Kolářová (1962). Hatched areas are the focal zones of earthquake swarms since 1962 with the respective year of occurrence. Solid circles denote the foci of the single-event activity from 1973 to 1984 for $M > 0.5$ (data after Neunhöfer, 1976, and Neunhöfer and Güth, 1982, 1984, 1985). *MLf*—Mariánské Lázně fault; dotted strip—boundary of the northern part of the Cheb basin. Insert: geographical index map.

Fig. 3. Principal tectonic and geological units. *I* = focal zone of the 1985/86 swarm, *II* = Tertiary basins, *III* = Tertiary volcanites. *I* —synclinal zone of Vogtland and Central Saxony, *1a*—Vogtland synclinorium, *1b*—central Saxonian synclinorium, *2*—anticlinal zone of Fichtelgebirge and Erzgebirge, *2a*—Fichtelgebirge anticlinorium, *2b*—transverse zone of southern Vogtland and western Erzgebirge, *2c*—Erzgebirge anticlinorium, (*1a* and *2b*—Vogtlandian slate mountains), *3*—Tertiary Cheb Basin, *4*—Tachov–Domažlice Graben, *5*—Doupovské vrchy, *6*—České středohoří, *7*—Sokolov Basin, *8*—Most Basin. *a*—Central Saxonian lineament, *b*—Elbe lineament, *c*—Gera Jáchymov fault zone, *d*—Mariánské Lázně fault zone, *e*—Franconian fault zone, *f*—Litoměřice deep fault, *g*—Erzgebirge fault.

swarm sub-sequence and consequently, within the whole swarm. According to the information available for the intensive historical swarms at the beginning of this century (catalogued recently by Grünthal, 1988), the magnitude differences between the largest and the second largest can be assumed to be smaller than 0.45. In fact, for the swarm of 1985–1986 that difference is also of this order.

The precise epicentre determinations for the swarm events (Horálek et al., 1987) by a local network surrounding the epicentral region gave a surprising result. All these events occurred in a relatively small focal area oriented N10°W, with a length of about 3.5 km and a width of about 1 km. Its geographical coordinates are 50.227–50.257°N and 12.443–12.466°E. The hypocentres are within a depth interval of 2.5 km. Depending on the velocity model used for the focal area, the depth intervals have their centres between 7 and

10 km. In a W–E profile, the hypocentres are steeply inclined (dip approaching 90°), whereas in a S–N profile the events descend southward with an inclination of about 30°. These very precise localizations according to Horálek et al. (1987) have been made for the events in January, 1986 only. Their epicentre determinations are closely confirmed by Neunhöfer and Güth (1987) for the whole swarm, on the basis of a slightly more distant local network west and north of the focal region and also by later precise locations (Antonini, 1988).

The focal zone of the 1985–1986 swarm is shown on the fault-tectonic map (Fig. 2) for the whole seismically latent area of Vogtland and West Bohemia, in context with previous focal zones of swarms as well as the foci of individual events. Only those focal zones are depicted which could be localized with sufficient precision. These are the focal zones of swarms in 1962, with $M \leq 2.6$

(Neunhöfer, 1976), followed by microswarms in 1983 ($M \leq 1.2$) and in 1984 ($M \leq 1.4$), after Neunhöfer and Güth (1984, 1985). Probably, the focal zones for these three swarms were in reality smaller than as shown in Fig. 2. They could not be localized with the same high accuracy as was possible for the 1985–1986 swarm. The foci of the single-event activity ($M > 0.5$) are shown for the period 1973–1984. The largest shock of this type of event did not exceed $M = 2.5$. The single-event activity was clearly dominant from 1975 to 1982. The 1985–1986 focal zone seems to be located at the southern edge of the whole Vogtland/West Bohemia focal area.

3. General geological characteristics

Geographical position and topographical condition

The focal region of swarms in the Vogtland/West Bohemia area is situated at the transition between the Erzgebirge (Krušné hory) and the Fichtelgebirge (Smrčiny). For the geographical orientation see Fig. 3. The Erzgebirge, a NE–SW oriented mountain range, is a result of NW-tilted block uplift along the Erzgebirge fault towards the end of the Cenozoic. The resulting steep south-eastern slope to the Ohře Graben (Eger-Graben) has height differences between top and foot of 500–700 m. The post-Oligocene sedimentary fill within the Ohře Graben reaches as much as 400 m. Immediately to the west of the 1985 focal zone, the Elstergebirge forms a geomorphological contrast. South of the focal zone there is the Cheb Basin.

Block units

The focal area studied is near to the intersection of principal tectonic units of the Bohemian Massif (Fig. 3) as originally introduced by Kossat (1927): the Saxothuringicum and the Moldanubicum. The Moldanubicum can be divided in its northern part (Malkowský, 1979; Conrad et al., 1983; Stettner, 1986) into the Bohemicum (or Tepla–Barrandian) and the Block of the Böhmerwald (Český les). Relative movements of these geotectonic units are bound to the suture

zones between them. All these structures are steeply dipping which indicates late block tectonics (Stettner, 1986).

The SW–NE trending boundary between the Saxothuringicum and the Moldanubicum is formed by the Litoměřice deep fault and its southwest extension, the less pronounced Erbenzdorf line. The Mariánské Lázně (Marienbad) fault zone (MLf) separates the Bohemicum and the Block of the Böhmerwald.

The Moldanubicum is nearly aseismic. A separate zone of increased seismic activity extends into the Saxothuringicum, with the Litoměřice deep fault and the Franconian fault zone as delineating tectonic elements (Grünthal et al., 1985a, b). The highest seismic activity within this zone shows a N–S directed band extending northward from the focal zone of swarm quakes. This “Rhenotype” zone has already been pointed out by Lauterbach (1953). That part of the Saxothuringicum which will be discussed in more detail covers the geological-tectonic unit of the Fichtelgebirge–Erzgebirge anticlinal zone and the Ohře Graben (Fig. 3). A pronounced tectonic element transversely cutting this unit is the Gera–Jáchymov fault zone which separates the anticlinal zone into the Erzgebirge anticlinorium and the so-called Transverse Zone of Southern Vogtland and Western Erzgebirge.

Neoidic tectonic activity

The main faults of the study area developed mostly during Palaeozoic and pre-Palaeozoic times and were reactivated during the Alpine orogeny. The expression of Neoidic tectonic activity is the creation of Tertiary basins connected with intensive alkaline volcanism. The Tertiary basins are: the very pronounced Ohře Graben along the Litoměřice deep fault, and transversely to it the narrow Tachov–Domažlice Graben on the western flank of the MLf with relics of preserved Neoidic sediments only, at the intersection of the extensions of both grabens there is also the Cheb Basin. In some publications the term Cheb–Domažlice Graben is used which means that the Cheb Basin is understood to be a part of the Tachov–Domažlice Graben. However, the present authors

wish to emphasise the obvious autonomous character of the Cheb Basin. In contradiction to the Ohře Graben and to the Tachov–Domažlice Graben with Miocene strata, the Cheb Basin exhibits also Pliocene fill and it is apparently more active in recent times than the others. These three subsidence structures represent zones of weakness of the earth's crust.

According to Kopecký (1978), the volcanism in West Bohemia was of primary importance in the Cenozoic era, during the Oligocene phase (17–35 Ma). The younger Miocene phase (9 Ma) was substantially less intensive with only some isolated volcanic occurrences. The last volcanic phase was in the Quaternary (0.8–2.8 Ma).

Volcanic evidences near to the 1985–1986 focal zone are the present-day hills of Komorní hůrka (described as Kammerbühl in Goethe's geological studies) and Železná hůrka (cf. Fig. 9), representing the last volcanic stage in northwest-Bohemia at about 0.85 ± 0.1 Ma B.P. (Šibrava and Havlíček, 1980). Magmatic volcanic activity can be assumed to be extinct.

The focal region of the swarms also shows no locally increased heat flow (Čermák, 1986). But the recent and rather intense occurrence of juvenile carbon-dioxide waters, mineral springs, and mofettes, concentrated in the Cheb Basin, has to be considered as post-neovolcanic activity. These features occur mainly in the close vicinity of the latest and probably still active faults. It has to be stressed, however, that all the springs, enriched in gas and minerals, in the area surrounding the focal zone produce only relatively cold water.

4. Geotectonics of the focal area and its direct surroundings

Fault pattern after geological evidence and epicentre distribution

Different kinds of tectonic information were used for the seismotectonic interpretation of the swarm area. Only synoptic consideration thereof has enabled a suitable seismotectonic modelling. First, the fault pattern according to classical geological evidence is shown in Fig. 2, in keeping with the Geological Map of Czechoslovakia (1960).

More details were added to this map for the northern part of the Cheb Basin after Šantrůček and Kolářová (1962).

Additionally, Fig. 2 shows the epicentral areas of swarms since 1962 as well as epicentres of the single-event activity between 1973 and 1984 for $M > 0.5$. No regularity in the single-event activity with regard to known faults can be discerned by the authors, whereas the zones of swarm activity obviously follow the MLf or its northwestern extension, respectively. As will be shown below, most likely the MLf is not directly the causative fault but is rather a zone of weakness which facilitates the faulting process.

The fault pattern of Fig. 2 reflects faults, deduced by classical geological techniques, for which traceable vertical offsets of strata are usually the field indications for faults. In particular, fault activity manifested as alternating horizontal movements of small amplitude can be recognized as faults using the classical methods only under favourable circumstances, and even less so as being recent faults. Therefore, the fault pattern presented in Fig. 2 cannot be assumed to be a complete representation of the real fault tectonics. Especially the gap in the mapped faults in the focal area of the swarms of 1962–1984 probably reflect our lack of knowledge about fault tectonics.

The most pronounced tectonic element within the area covered by Fig. 2 is the NNW–SSE directed MLf. It creates a morphological step running within an overall length of about 100 km, while it apparently disappears immediately north of the focal zone of the 1985–1986 swarm. Its extension northward into the G.D.R. could be expected, but clear geological evidence is missing. Techniques other than those shown below confirm this assumed extension.

Blocks east of the MLf are generally uplifted in comparison with those on the west, which are characterized by subsidence. Younger, Quaternary up to Holocene tectonic activity of the MLf is confirmed by ruptured terraces of brooks which run along that fault (e.g., Liboc brook), confirming young Quaternary up to Holocene tectonic activity. A remarkable heterogeneity of the MLf occurs immediately south of the epicentral area of

Fig. 4. Heterogeneity of the Mariánské Lázně fault manifested as a splay-structure connected with a right-stepping offset along a N–S fault element. 1 = epicentral area, 2 = Cheb Basin, 3 = Cambrian–late-Algonkian mica schist, 4 = lower-Ordovician phyllite.

1985–1986. At the southern edge of this heterogeneity, the MLf splays out in a southwest direction into several fault splits (Fig. 4). The splay-like fault segments can be traced over a distance of about 1.5 km where they are truncated by a N–S fault element. Obviously, at this N–S element the MLf is right-stepping. However, we do not know if this fault heterogeneity extends down to the seismogenic depth of about 9 km. If this is the case, then it could indicate a location where epicentres tend to be clustered.

Fairly good conditions for studying young fault tectonics are obtained for the Cheb Basin. There, the fault directions of NNW–SSE to NNE–SSW are morphologically most pronounced and indicate recent crustal movements. The wedge-like basin is inclined to the southeast, i.e., towards the MLf. Along this fault, the subsidence reaches about 200–300 m. The highest rate of carbon-dioxide emanation is observed in the northern part of the Cheb Basin, immediately on the flank of the MLf in a narrow strip about 9 km in length (Myslil and Franko, 1968). This observation may

be evidence of recent active tectonics and a stress field which enables the opening of the MLf for gas emanation. In fact, such a stress direction is confirmed by fault-plane solutions for swarm quakes but also by in-situ measurements in the surroundings.

Figures 2 and 4 show two faults directed N195°E immediately south of the 1985–1986 focal zone. Actually, the swarm of 1985–1986 is probably related to the intersections of the N–S to NNE × SSW striking zone of faults with the MLf. The faulting process itself most likely occurred in N–S to NNE–SSW elements within the weakness zone represented by the MLf. Generally, the N–S direction is connected with the latest tectonics in the Cheb Basin (Šantrůček, 1986). It represents a reactivated fault system of primarily much older origin (Bankwitz et al., 1979). These faults can be traced both in the northern Cheb Basin and as a dense fault bundle southwest of the epicentral area of the 1985–1986 swarm (cf. Fig. 3). Another striking feature of that area is the bending of both NE-directed and NW-directed faults to N–S when they reach the longitude of about 12.4°E. The reason may be a dominating N–S zone but without any surficial geological evidence.

Fault pattern after geophysical data and satellite images

Some insight into the fault pattern at seismogenic depths would be of importance for a seismotectonic interpretation. Evidence of the presence of deep-seated tectonic elements can be provided by geophysical as well as remote-sensing techniques. Here, a review of previous results will be given. Conrad et al. (1983) derived a tectonic scheme (Fig. 5) based on the interpretation of steep gradients of gravity and magnetics. Probably, such fault zones can be assumed to be essential tectonic features in deeper-seated parts of the earth's crust. According to that scheme, two fault zones dominate in the focal area of swarms: the well-described MLf, with its assumed north-north-west continuation and the already postulated N–S element. Both elements are indicated both by gravimetric and geomagnetic evidence in the focal area.

Fig. 5. Scheme of faults based on steep gradient of gravity (lines) and of magnetics (asterisks), after Conrad et al., (1983). 1—Mariánské Lázně fault zone, 2—N-S fault zone crossing the focal zone of swarms.

It is noteworthy that according to these results, the NNW-striking MLf zone bends just in the focal region of the Vogtland/West Bohemia swarm earthquakes to a northwest continuation. If this proves to be true, such a bending in the fault trace may create and maintain significant local stresses on the fault zone (Segall and Pollard, 1980), which makes this area a highly earthquake-prone locality.

Lange and Steiner (1971) concluded on a regional NNW-SSE tectonic line crossing the focal area and active from young-Mesozoic up to recent times from a complex analysis of numerous geological, geophysical and geomorphological observations.

Bauer et al. (1980) found for the focal area dominating directions of deep-seated lateral inhomogeneities, on the basis of a complex correlation analysis of gravimetric, geomagnetic and geomorphological maps. According to them, four tectonic lines cross in the focal zone of the swarms. These lines are in an azimuth range of $116\text{--}178^\circ$. The N-S line ($N178^\circ\text{E}$) found became evident

mainly through very young geomorphological indications, but it is also a dominating element in the microtectonic inventory.

After Bankwitz et al. (1979) and Krull (1984), the focal zone of swarms is crossed by regional N-S to NNW-SSE photolineations on satellite images. They do not represent pronounced single lines, but a conspicuous N-S directed zone of numerous linear elements with a width of between about 10 and 20 km. The single elements of this bundle of lineations frequently intersect each other at acute angles which makes it difficult to trace any main direction.

Assuming their reality, these observational facts could be interpreted as a lamellar concentration and surface expression of a deep-seated disruption zone. The long-ranging N-S lineations have, in most cases, no (known) expression in geological or geomorphological contours. Their perceptibility by remote-sensing techniques results usually from changes in soil humidity. This indicates their generally juvenile (neotectonic to recent) character, which can indirectly be traced to the surface.

5. Focal mechanisms, stresses and stress conversion

Fault-plane solutions of single events of the 1985 swarm, computed from a sufficient number of data, have been derived by Grosser et al. (1987), Špičák (1987), Zahradník et al. (1987, 1988), Antonini (1988), and Grosser and Köhler (1988). If several solutions for one event have been calculated, the solution thought to be representative was that (see Table 1) based on the largest number of polarity readings or for which better reliability criteria can be assumed as compared with other solutions. The focal parameters (strike, dip, and rake) are given in the sense of Aki and Richards (1980). The strike directions of the assessed first nodal planes can easily be compared with observed geological faults. In the following discussion the strike angles directed to the southern quadrants will be used. Two of the calculated strikes (events 3 and 6 in Table 1) are more or less in the direction of the MLf. Except for one event (No. 1 in Table 1), all the other 14 strikes are in the range from $N170^\circ\text{E}$ to $N200^\circ\text{E}$ with a mean

TABLE 1

Compilation of focal mechanism data for the 1985–1986 swarm

No.	Date	Time	<i>M</i>	Strike (°)	Dip (°)	Rake (°)	Reference
1	1985-12-16	23:09	3.22	28	51	103	Grosser and Köhler (1988)
2	1985-12-18	14:34	2.43	197	53	−27	Antonini (1988)
3	1985-12-21	10:04	4.02	150	54	−26	Grosser and Köhler (1988)
4	1985-12-21	10:16	4.63	171	75	−30	Antonini (1988)
5	1985-12-23	04:27	4.06	18	63	25	Antonini (1988)
6	1985-12-24	00:04	3.96	161	66	−51	Grosser and Köhler (1988)
7	1985-12-25	07:16	2.49	18	78	30	Antonini (1988)
8	1985-12-30	21:49	2.89	185	73	−21	Antonini (1988)
9	1986-01-07	03:52	2.39	180	50	−15	Antonini (1988)
10	1986-01-07	17:35	1.97	190	90	−70	Zahradník et al. (1988)
11	1986-01-20	23:38	4.20	191	90	0	Antonini (1988)
12	1986-01-21	05:41	2.67	170	60	−30	Zahradník et al. (1987)
13	1986-01-21	19:04	1.82	180	90	−70	Zahradník et al. (1988)
14	1986-01-24	01:23	2.07	192	80	−62	Zahradník et al. (1988)
15	1986-01-24	02:34	2.02	180	83	−71	Zahradník et al. (1988)
16	1986-01-24	04:54	2.44	200	90	−60	Zahradník et al. (1988)
17	1986-02-06	20:24	2.44	191	85	−60	Zahradník et al. (1988)

strike of N187° E. The mean standard deviation of the strikes does not exceed 10°.

The dip values are in the range of 50° to 90° (vertical), predominantly inclined to the west. For the events in December, 1985, the dip does not exceed 75°. For the January events, vertical dips dominate. These temporally differing dips coincide with the inclination of foci on W–E profiles according to Horálek et al. (1987) and Antonini (1988).

The slip-components are generally sinistral. The azimuth of the *P*-axes is rather stable. The mean azimuth is N136° E with a mean standard deviation of 13°. This fits well into the scheme of horizontal directions of main principal stress (Grünthal and Stromeyer, 1986). They have chiefly been determined on the basis of in-situ stress measurements in the area surrounding the focal zone and range from NNW–SSE to NW–SE (for details see Fig. 6).

The same tendency of the general parameters of the single fault-plane solutions results from composite solutions. On the basis of polarity readings from up to 120 single events, Špičák (1987) concluded that the faulting mechanisms of the particular events probably did not change substantially during the swarm. All data fit with an

optimal strike of the nodal line of 180°. Schmedes (1987) concluded on a mean strike of 177°.

A decisive question in seismotectonic modelling is to which faults the foci should be related. At first glance, without considering the remote-

Fig. 6. Directions of horizontal main compressive stresses in the surroundings of the focal area. In-situ measurements: 1, 2 after Knoll et al. (1977), 3–7 after Wolter (1987); 8—azimuth range and mean value of observed *P*-axes of focal mechanisms of events of the 1985–1986 swarm; 9—directions of horizontal compression derived from repeated triangulations (Vyskočil, 1987).

sensing results, detailed local tectonics, or the faults interpreted after geophysical data, one could suppose the MLf to be the only causative fault for the swarms. After careful consideration of all geological and geophysical facts, we gave preference to a recently active N–S to NNE–SSW fault zone (cf. section 4). According to the acting horizontal component of maximum compression, the N153°E-striking MLf is probably influenced by a considerable amount of tension. The type of motion was, with a few exceptions, generally an oblique-slip, mostly normal, with varying portions of slip on the principally N–S to NNE–SSW striking fault planes. But also the possibility should be considered that in a few cases strikes nearly parallel to the MLf occurred.

From the fault-plane solutions only two rather consistent features are the essential ones for the derivation of the generalized seismotectonic model of the focal area: (1) a N–S to NNE–SSW azimuth of the majority of fault planes; (2) generally sinistral strike-slip components.

Antonini (1988) concluded from his solutions on the dominating character of combined strike-slip and dip-slip in the southern part of the focal zone, with vanishing normal faulting components to the north. He localized remarkable reverse components in the northeastern part of the focal zone. This, interestingly, can be brought into congruence with the already mentioned splay-structure along the MLf.

6. Block mosaic

There seems to be a connection between the block structure and the seismotectonics of the focal area. Figure 7 presents a conception of the block mosaic surrounding the focal area, together with the relative trend of mutual horizontal block movements as they follow from geodetic data (Thurm et al., 1977) and from a combination with neotectonics (Zeman, 1983; Grünthal et al., 1985a). This division into block units has been derived mainly from differences in the sense of movements. Not all of the block boundaries are identical with known faults or fault zones. N–S block boundaries appear in the focal area. There is no doubt that these block boundaries are identical

Fig. 7. Scheme of recent horizontal movements of the earth's surface after Thurm et al. (1977) and Grünthal et al. (1985a). 1 — central Saxonian lineament, 2 — Erzgebirge fault, 3 — České středohoří fault, 4 — Chomutov fault, 5 — Gera—Jáchimov fault, 6 — Mariánské Lázně fault, 7 — Aš—Tachov fault.

with the N–S photolineations in this area which have their analogy also in N–S fault elements according to geophysical data sources. The block movements are understood as decoupled from the upper mantle (Thurm et al., 1977). It is remarkable that the probable horizontal trends of movements change their sense at marked knots of fault zones. From this observation, a complicated pattern of relative horizontal movements results. The mostly opposite sense of movements of adjoining blocks suggests oscillating displacement processes in the upper crust. Otherwise, the relatively large amplitudes of geodetically determined horizontal movements of up to 1 cm/year (Thurm et al., 1977) cannot be explained, because they do not find their appropriate expression in neotectonics. This fact is confirmed by Vyskočil (1986), at least for the vertical movements. According to five levellings between 1946 and 1982, the oscillating character of vertical movements becomes obvious. The oscillation period could be interpreted as being of the order of one century.

The tendency of displacement or rotation of the small blocks with diameters of 10–20 km is obviously a subordinate phenomenon. Probably, it could be interpreted in such a way that the small

blocks perform enforced movements governed by the superior (i.e., more regional) block division. Such kind of superior block movements could be the cause of horizontal dextral creep both along the N–S running block boundaries crossing the focal area and along the MLf. This tendency of motion follows from geodetic interpretations (Thurm et al., 1977), but also from detailed fault mapping in the Cheb Basin after Šantrůček and Kolářová (1962). This observed horizontal dextral creep is opposite to the general sinistral slip derived from the fault-plane solutions. Actually, this controversy provides the key to the derivation of the seismotectonic model.

7. Comparison with other models of swarm activity

A fault irregularity of the MLf immediately south of the epicentral area of 1985–1986 has already been pointed out in section 4. This fault irregularity is manifested as a splay-structure connected with a right-stepping offset along a N–S fault element (Fig. 4) while, additionally, the MLf is under right-lateral shear (Zeman, 1983). Right-stepping offsets along right-lateral faults (or the conjugate with left-lateral faults and left-stepping offsets) are sites of reduced frictional resistance to slip and of increased potential of secondary fracturing (Segall and Pollard, 1980). If the observed surface offset of the MLf extends to the seismogenic depth, the right step and its immediate surroundings would be a preferable site of swarm seismicity. This would indicate the 1985/86 focal area as a locality prone for earthquake swarms.

Fault irregularities connected with swarms have frequently been observed in ocean-floor spreading zones, but also in local crustal spreading centres connected with volcanism, geothermal activity, and very young intrusions of magma into the seismogenic depth from the lower crust or upper mantle. From these observational facts, Hill (1977) and Weaver and Hill (1979) derived a model of swarm activity which can be described briefly as follows: Within the spreading centre an opening occurs in the σ_3 direction along either dikes injected by magma or by collapse along normal faults, both striking in the plane of greatest (σ_1) and inter-

mediate (σ_2) principal stress. Additionally, crack interactions ensue along oblique fault planes connecting adjacent dike edges or ends of normal fault elements. This adjustment on a system of conjugate shear failures joining the dikes occurs in swarm sequences.

From two different points of view, this model cannot be applied to the Vogtland/West Bohemia focal area: (1) The connection with recent magmatic injections and/or geothermal activity is absent. (2) The stress conditions of the model by Weaver and Hill (1979) are not applicable.

But we have to consider the intensive post-neovolcanic carbon-dioxide emanations in the immediate surroundings of the focal zone. No correlation of seismic activity with gas production could be found. So, a possible connection of both phenomena cannot be explained. On the other hand, the splay-structure along the MLf trace can really be regarded as a very local extensional zone. According to the acting stress field, the whole MLf zone seems to show a tendency of tension normal to its elongation.

Chen and Knopoff (1987) modelled the crack propagation in a rheologically relaxing medium with non-uniform stresses and/or frictions. On the basis of observational facts which prove that real earthquake faults are not plane but strongly geometrically irregular 3-D objects, they projected this complex feature, for mathematical reasons, on a plane in terms of non-uniform distribution of stresses and breaking strength in the plane. This projection is directly related to the barrier model (non-uniform strength) as well as to the asperity model (non-uniform stress drop). For different levels of geometrical irregularities (in terms of stress fluctuations) and of pre-stress and breaking strength, they found either the character of an isolated earthquake, or of an earthquake sequence (fore–main–aftershocks), of an earthquake swarm, or finally, of aseismic creep, such as a silent earthquake. The complete rupture process occurs as a series of size-comparable events alternating between instantaneous rupture and episodes of quasistatic extension for a highly inhomogeneous field, low pre-stress and/or high breaking strength. Chen and Knopoff (1987) identified such a sequence as an earthquake swarm.

The condition of strong geometrical irregularities appearing as secondary faults, echelon, parallelism, bifurcations, etc. can be assumed for the splay-structure along the MLf connected with a right-stepping offset which alone is already a place prone for swarms (Segall and Pollard, 1980).

8. Probable seismotectonic model for the Vogtland / West Bohemia focal area

A probable seismotectonic model for the swarm area can be derived, in conclusion, from all the observational facts shown and previous results.

In section 6, the controversy between a tendency to dextral creep and sinistral slip on the N–S fault elements has been pointed out. This controversy is only an apparent one. This fact is decisive for the derivation of the seismotectonic

model in connection with the stated oscillating character of block movements.

From the interpretation of the satellite images, it is known that the N–S elements cannot be understood as a sharp block boundary but rather as a bundle of N–S directed lamellar fault splits. Figure 8a illustrates schematically how they could intersect a part of the MLf, including the splay-structure, when projected down to the seismogenic depth range. The figure presents a top view on the focal volume in the stage of strain accumulation due to the superior block movements. We realize that in this stage in addition to the N–S fault splits the MLf also shows a dextral sense of creep tendency. Moreover, it is under tension.

On reaching the critical strain, the elastic stress can be released by a seismic focal process. The manifold prefractured N–S fault splits in the brit-

Fig. 8. Probable seismotectonic model for the 1985–1986 focal area. a. Illustration of the strain accumulation phase. The N153°E striking Mariánské Lázně fault zone (MLf); the splay-structure is shown schematically intersected by a bundle of lamellar N–S to NNE–SSW fault elements. Both prevailing tectonic systems in the focal area show tendency to a dextral creep during the long-lasting periods of seismic quiescence. Additionally, the MLf is under tension. b. Illustration of the focal process of the 1985–1986 swarm in the focal zone as sinistral elastic rebound, preferably on the lamellar N–S to NNE–SSW fault splits. The weakness zone of the splay-structure along the MLf provides probably the most suitable setting for swarms. Locations of the different types of faulting are given according to Antonini (1988). The large arrows give the direction of the horizontal component of main principle stress.

Fig. 9. 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 hůrka, ZH—Železná hůrka). The tendency of the tectonic blocks for horizontal movements is given. Hatched parts depict epicentral areas of swarms sited within the Mariánské Lázně fault zone. Dextral creep is observed in the N-S fault elements intersecting the Mariánské Lázně fault zone, whereas sinistral elastic rebound occurs during the focal process of swarms.

tle part of the earth's crust are most suitable as preferred fault planes. They strike within the azimuth range of probable maximum shear strain.

The process of a swarm sequence in the focal area is presented schematically in Fig. 8b. Since clear tectonic as well as geophysical fault indications are lacking in the conjugate directions, they were not considered. The splay-structure along the MLf is a site exceedingly prone to earthquake swarms due to its right-stepping offset along right-lateral shear and its strongly irregular geometry. The dominating strikes of fault planes corre-

spond with the N-S to NNE-SSW directed fault splits. After Antonini (1988), in the focal zone of the 1985-1986 swarm there occurred a combined strike-slip and dip-slip in the south of the focal zone, vanishing dip-slip to the north, and a reverse fault component only in the northeastern part. This pattern has been included schematically in Fig. 8b. It would result in a further development of that splay-structure in connection with a continued subsidence of the Cheb Basin.

As shown in Fig. 9, our model conception for the 1985-1986 swarm can be expanded over the

whole focal area of swarms in the Vogtland/West Bohemia region. For the whole area, the following features are typical:

(1) the block division of the area surrounding the focal zone and the trend of observed horizontal movements along the block boundaries;

(2) the N153°E directed MLf under tension and a tendency to dextral shear;

(3) the N–S fault elements crossing the focal zone with a tendency to dextral creep during the strain-accumulation stage;

(4) sinistral elastic rebound on these N–S elements in the form of the swarms which are localized precisely since 1962 within the weakness zone of the MLf and its probable NNW-ward extension.

Favourable circumstances for the swarm-like strain release obviously exist within the MLf due to increased geometrical irregularities and due to probably reduced pre-stress there. So, the swarms are connected with the MLf only indirectly in as much as the latter furnishes suitable conditions within that fault zone for the swarm-like faulting process. Outside the MLf, the oscillating block movements are obviously aseismic in the main, but they may be connected with individual seismic micro-events.

Additionally, Fig. 9 shows the locations of the last effusive volcanic occurrences in West Bohemia, around 0.85 Ma B.P. Their or any other connection of syn-volcanic phenomena with the earthquake swarms is unlikely. Probably, the NE–SW first-order Erzgebirge fault bounds the focal zone to the south because no significant seismic activity has been observed southward of this fault.

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