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EVOLUTION OF THE BASIN AND RANGE STRUCTURE AROUND THE ŽIAR MOUNTAIN RANGE

(22 Figs.)

Abstract: A large scale block faulting took place during the Badenian to Pannonian time in the central Slovakia, resulting in a typical basin and range structure involving vertical displacements over 2000 m. A thorough analysis of structural features, relationships of faulting to sedimentary and volcanic sequences, gradual rotation of blocks, and geomorphological features results in a conclusion that the prime cause of the basin subsidence is an extension induced by diapiric uprise in the mantle. In a lesser extent we have observed features that may be related to the left lateral displacement superimposed upon the region by evolution of the Carpathian arc.

Резюме· Крупное сбрасывание в блоки, действующие во времени от бадена до п. нона в центральной Словакии привело к впадинно-пределовому строению, имеющему вертикальное перемещение бдоков более, чем 2000 метров. Комплексный анапиз структуральных черт, взаимных связей и осадочных и вулканических отложений, а также анализ постепенного вращения блоков и геоморфологических черт позволил сделать вывод о том, что основной причиной оседания бассейнов является экстенсия индуктированная диапировым поднятием мантии.

В меньшей мере мы наблюдали черты, которые могли бы быть в отношении к левостороннему перемещению в районе возникающим под влиянием эволюции Карпатской дуги.

Introduction

The central Slovakia region at the contact of the West Carpathian orogenic arc and Pannonian basin is characterized by the basin and range structure of the Neogene age, which is shown schematically at the Fig. 1. Relevant basins are known also under the name "inner basins" (vnútorné kotliny – Buday, 1967) and their sedimentary filling as "inner mollasse" (Vass, 1981).

Models, that have been proposed to explain origin and evolution of individual basins generally vary in assumed causes of crustal extension as prime reason of subsidence. An idea of diapiric uprise in the mantle as cause of extension has been suggested by Stegena (1964) and Szádeczky-Kardoss (1968) and later elaborated in terms of New Global Tectonics by Stegena et al. (1973, 1975) and Lexa – Konečný (1974, 1979).

Contrary to ideas of active mantle diapir as cause of extension, Royden et al. (1982, 1983) stressed the role of transform faulting related to the evolution of the Carpathian arc and the role of retreating Eastern Carpathian subduction zone and orogenic arc as causes of extension within the Pannonian basin.

In the following text we will try to demonstrate on the example of the basin and range structure in surroundings of the Žiar mountain range, that the main reason for its evolution was extension caused by diapiric uprise in the mantle and that transform faulting related to the evolution of the Carpathian arc played only a subordinate role.

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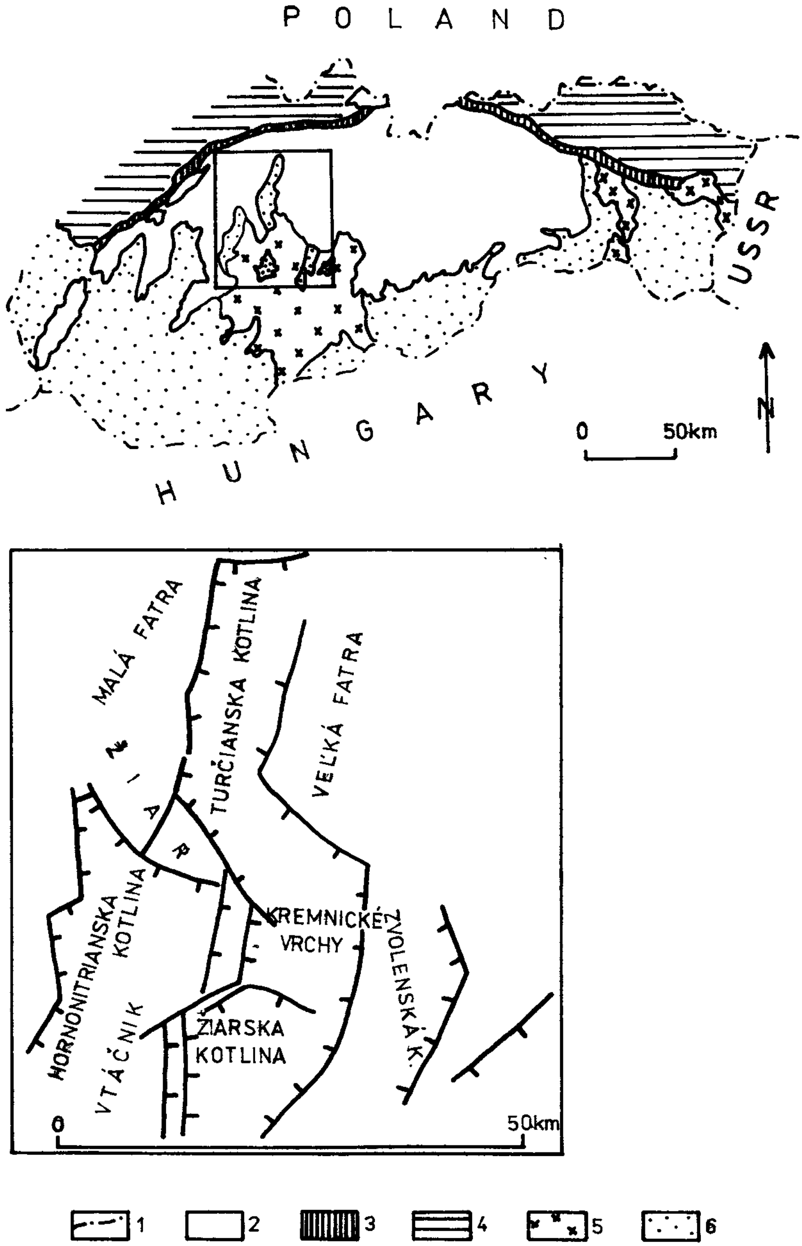


Fig. 1. Situation of investigated area in the W. Carpathians and its geographic subdivision.
1 – state boundary; 2 – inner Carpathians; 3 – Klippen Belt; 4 – flysch zone; 5 – Neogene volcanics; 6 – Neogene basins.

Main structural features

Fig. 2 through 6 show the extent of faulting and main structural features of the area under consideration. Faults with a large vertical displacement divide the area into first order blocks, that are usually tilted. At the north there is only one deep graben (Turčianska kotlina) bounded by uplifted blocks of Malá Fatra mountain range at the west and the Veľká Fatra mountain range at the east. The graben is highly assymmetrical, involving rotation of blocks around roughly north-south trending horizontal axis (Figs. 2, 3, 4) – so the graben is fault-bounded and deep at its western side, while amplitudes of faults at its eastern side are small. NE-SW trending faults subdivide the graben into partial blocks with a similar sense of movements. Geology of the western side of Veľká Fatra and Malá Fatra indicates, that these uplifted blocks underwent a similar rotation as the subsided block of the graben.

At the north the Turčianska kotlina graben ends at the ENE-WSW trending fault. At the south NW-SE trending segment offsets the axis of the graben about 10 km eastward, where it continues further southward as the Kremnica graben and Žiarska kotlina depression (graben). At this transitional zone directly south of the Turčianska kotlina graben there is almost transverse Žiar mountain range. Its NW part seems to represent the same structural block as the Malá Fatra mountain range. From the rest of the mountain range it is separated by the NNE-SSW trending Žiar fault-zone.

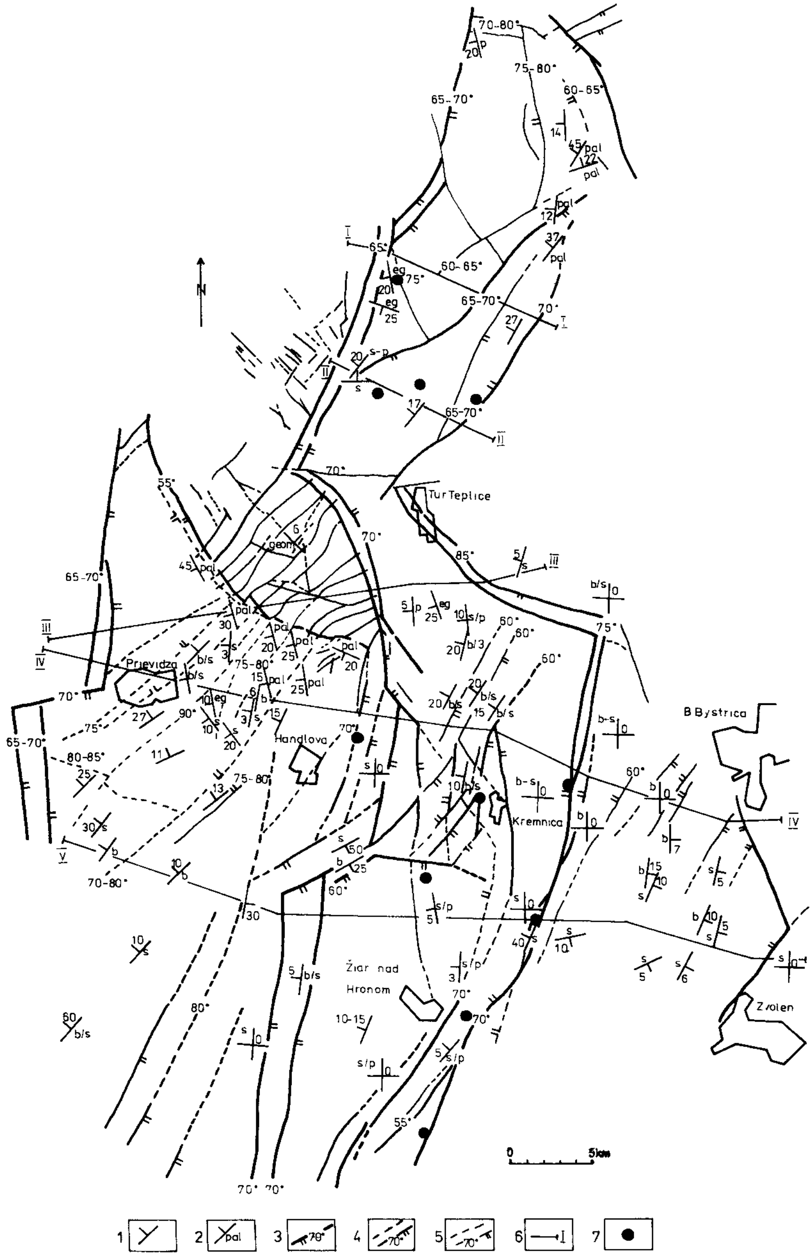
The southeastern part of Žiar is bounded by NW-SE trending faults and geomorphological analysis indicates its 6–8° tilting northeastward (Fig. 12). Characteristic of this block there are numerous NNE-SSW trending faults (parallel with the Žiar fault) that do not show larger vertical displacement.

Further south the basin and range structure involves much wider area (Figs. 2, 4, 5, 6). Starting at west we distinguish uplifted block of the Suchý and Malá Magura mountain ranges, westward tilted block of the Hornonitrianska kotlina depression including Handlová uplift at the east, the deep Kremnica graben respectively Žiarska kotlina graben at the south, eastward tilted block involving Zvolenská kotlina depression and uplift in the eastern part of the Kremnické vrchy mountain range, and finally, relatively uplifted block of the Bystrická vrchovina hills at the east. These first order blocks are further subdivided by faults with a smaller vertical displacement.

Evolution of the described basin and range structure has been facilitated by a system of normal faults. Generally, faults as well as grabens and ranges follow the N-S to NNE-SSW trend with a notable exception of the NW-SE oriented Žiar mountain range and related faults. In detail, exceptions are more frequent. Not all the faults are nice straight ones – some of them are curved, some of the faults are composed of variably offset shorter segments following older structural trends.

Major blocks usually are not bounded by single faults, but rather by systems of closely spaced parallel faults- fault-zones (Figs. 7, 8, 9). In some cases movement on closely spaced faults resulted in tilting of rocks among the faults toward the subsiding block (Fig. 9) – dips up to 45° have been observed.

Vertical displacement on faults is highly variable. Owing to rotation of blocks around horizontal axis it is systematically much higher at the western side of grabens. It is probably up to 3000 m at the fault zone bounding the Turčianska kotlina depression against the Malá Fatra mountain range, about 2500 m at the western side of the Žiarska kotlina graben, about 1500 m at the western side of the Kremnica graben and 1200 m at the western side of the Hornonitrianska kotlina depression. Contrary, faults bounding the mentioned grabens at the east show much smaller vertical displacement- an exception is large displacement on the fault-zone bounding at the east the Kremnica and Žiarska kotlina graben (1200–1500 m)



N
Tur Teplice
Prievidza
Handlova
Kremnica
B Bystrica
Žiar nad
Hronom
Zvolen
0 5km

Fig. 2.

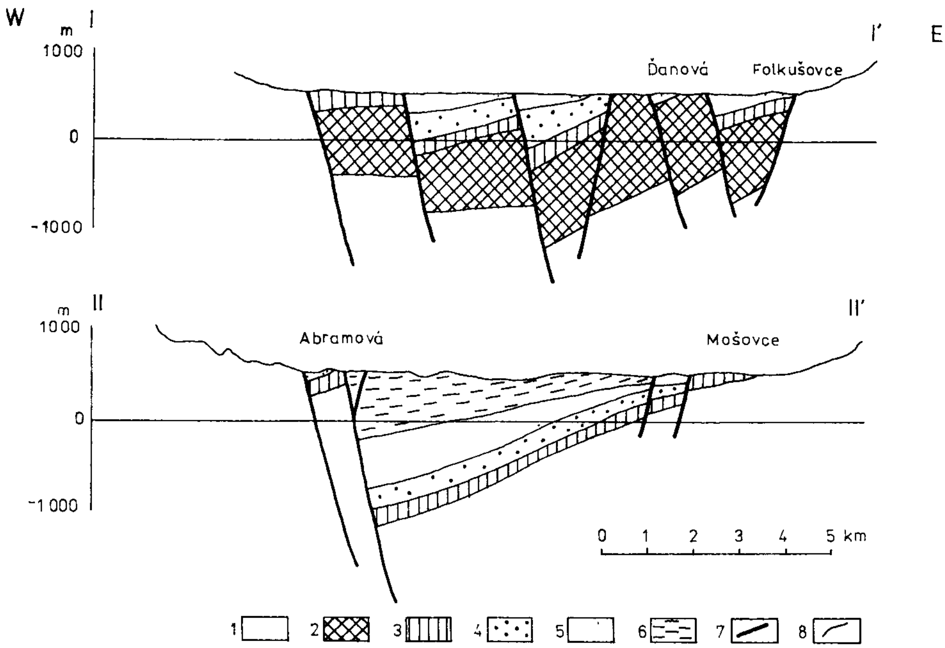


Fig. 3. Cross-sections I–I' and II–II' of the Turčianska kotlina graben. Position of sections is shown at the Fig. 2.
1 – pre-Tertiary basement; 2 – Paleogene rocks; 3 – Eggenburgian rocks; 4 – late Badenian to early Sarmatian rocks; 5 – Sarmatian rocks; 6 – Pannonian rocks; 7 – faults; 8 – geological boundaries.

and Zvolenská kotlina depression (500 m) owing to horizontal or even eastward dipping position of blocks in this area. An interesting case represents the Pravno fault bounding the Hornonitrianska kotlina depression against the Žiar mountain range. Vertical displacement along this fault increases from almost zero at the east to almost 1000 m at the west owing to rotation of the block including the depression.

Vertical displacement on individual faults is much smaller and rarely reaches over 1000 m even in fault-zones with maximal displacement.

Fig. 2. Structural scheme of the area.
1 – dips of the basement surface derived from interpretation of gravitiy measurements; 2 – dip of the surface derived from morphologic investigation (geom), dips of the Paleogene rocks (pal), Eggenburgian rocks (eg), Badenian rocks (b), late Badenian and early Sarmatian rocks (b/s), Badenian to Sarmatian rocks (b-s), Sarmatian rocks (s), late Sarmatian to early Pannonian rocks (s/p), Sarmatian to Pannonian rocks (s-p), Pannonian rocks (p); 3 – regional faults with indication of their dips; 4 – conspicuous local faults; 5 – smaller local faults; 6 – cross-sections; 7 – localities of structural measurements.

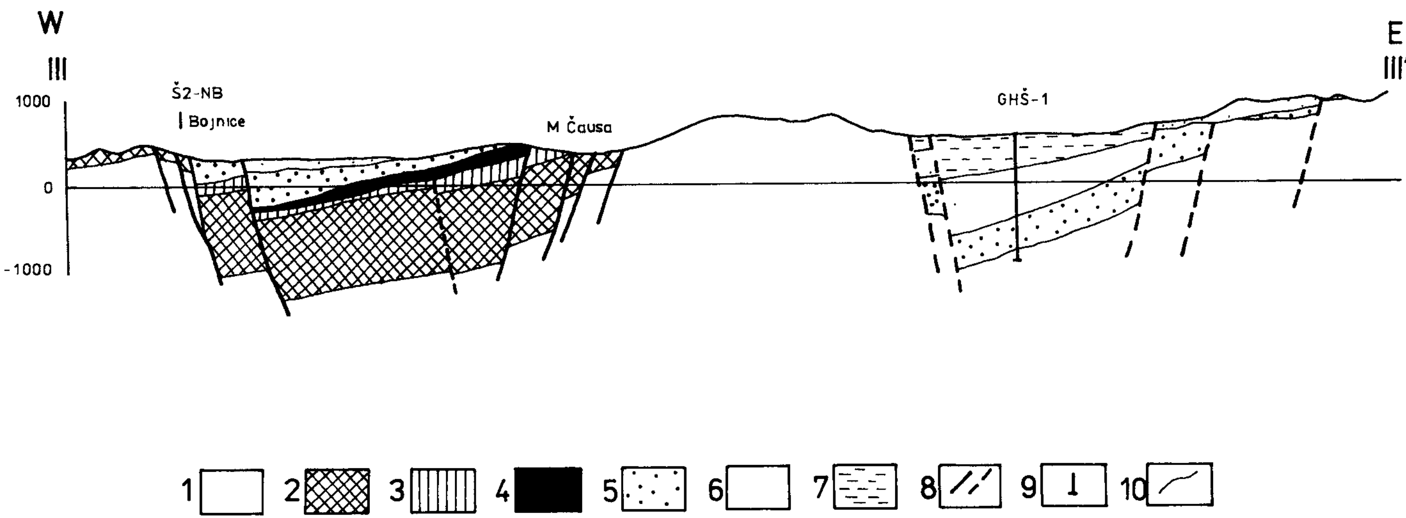


Fig. 4. Cross-sectin III–III' of the Hornonitrianska kotlina depression, Žiar mountain range and Turčianska kotlina graben. Position of the section is shown at the Fig. 2.

1 – pre-Tertiary basement; 2 – Paleogene rocks; 3 – Eggenburgian rocks; 4 – Badenian rocks; 5 – late Badenian to early Sarmatian rocks; 6 – Sarmatian rocks; 7 – Pannonian rocks; 8 – faults; 9 – boreholes; 10 – geological boundaries.

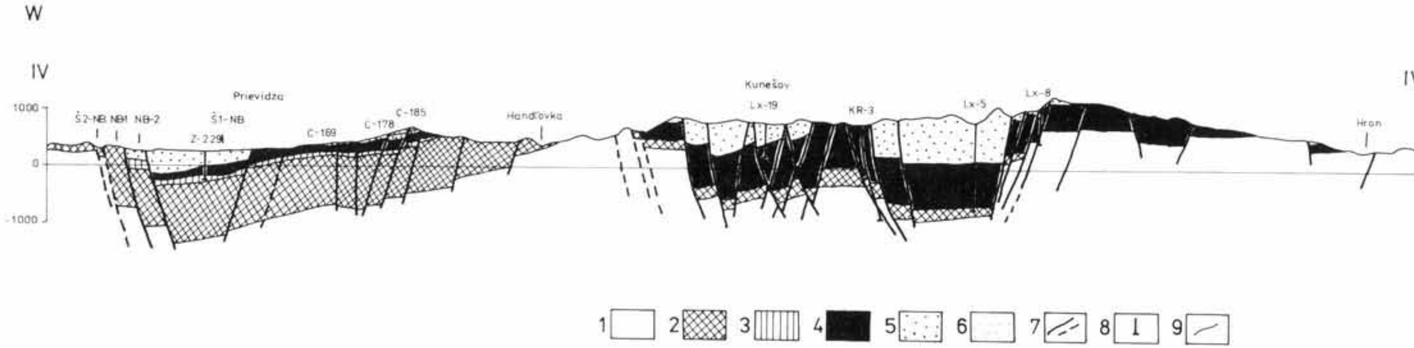


Fig. 5. Cross-section IV–IV' of the Hornonitrianska kotlina depression, Kremnické vrchy mountain range and Zvolenská kotlina depression. Position of the section is shown at the Fig. 2.

1 – pre-Tertiary basement; 2 – Paleogene rocks; 3 – Eggenburgian rocks; 4 – Badenian rocks; 5 – late Badenian to early Sarmatian rocks; 6 – Sarmatian rocks; 7 – faults; 8 – boreholes; 9 – geological boundaries.

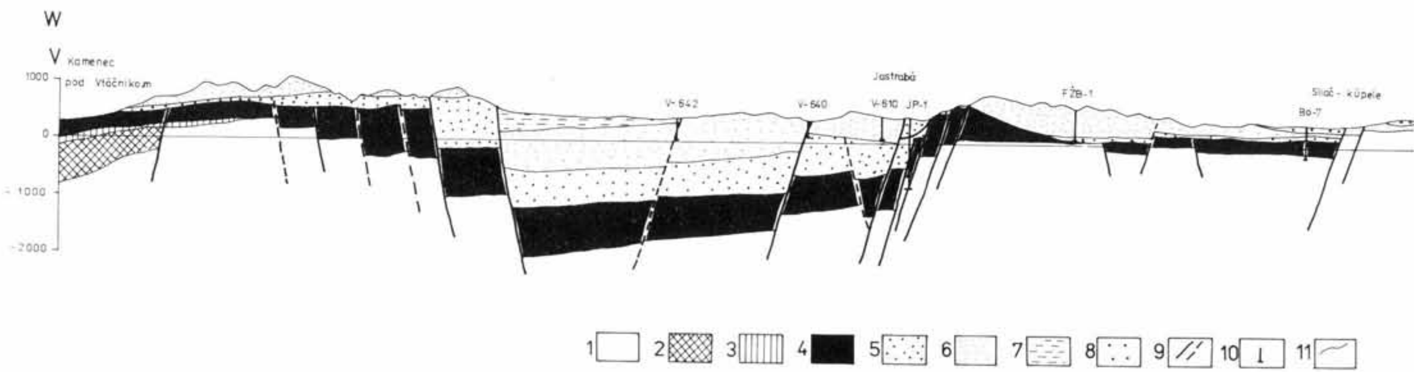


Fig. 6. Cross-section V–V' of the Hornonitrianska kotlina depression, Vtáčnik mountain range, Žiarska kotlina graben, Kremnické vrchy mountain range and Zvolenská kotlina depression. Position of the section is shown at the Fig. 2.

1 – pre-Tertiary basement; 2 – Paleogene rocks; 3 – Eggenburgian rocks; 4 – Badenian rocks; 5 – late Badenian to early Sarmatian rocks; 6 – Sarmatian rocks; 7 – Pannonian rocks; 8 – Pliocene rocks; 9 – faults; 10 – boreholes; 11 – geological bondaries.

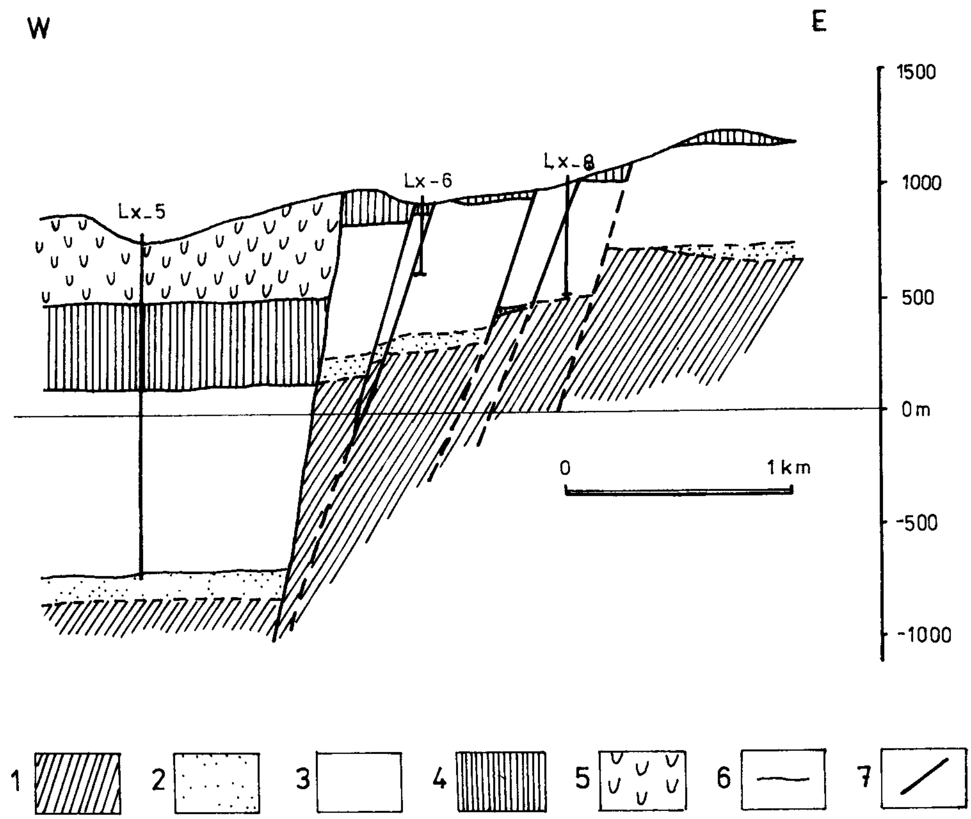


Fig. 7. Structure of the fault zone east of Kremnica.
1 – Mesozoic rocks; 2 – Kordíky formation (Lower Badenian); 3 – Zlatá studňa formation (Lower to Middle Badenian); 4 – Turček formation (late Upper Badenian to early Lower Sarmatian); 5 – Kremnický štít formation (age as 4), 6 – geological boundaries; 7 – faults.

Fig. 8. Structure of the fault zone nearby the village Sklené Teplice.
1 – basement, 2 – rocks of the first stage of the štiavnica stratovolcano (Lower to Middle Badenian), 3 – Červená studňa formation (Upper Badenian), 4 – Studenec formation (late Upper Badenian to early Lower Sarmatian), 5 – rocks of the fourth stage of the štiavnica stratovolcano (Lower Sarmatian), 6 – Middle to Upper Sarmatian sediments, 7 – Jastrabá formation (late Upper Sarmatian to early Lower Pannonian), 8 – geological boundaries, 9 – faults.

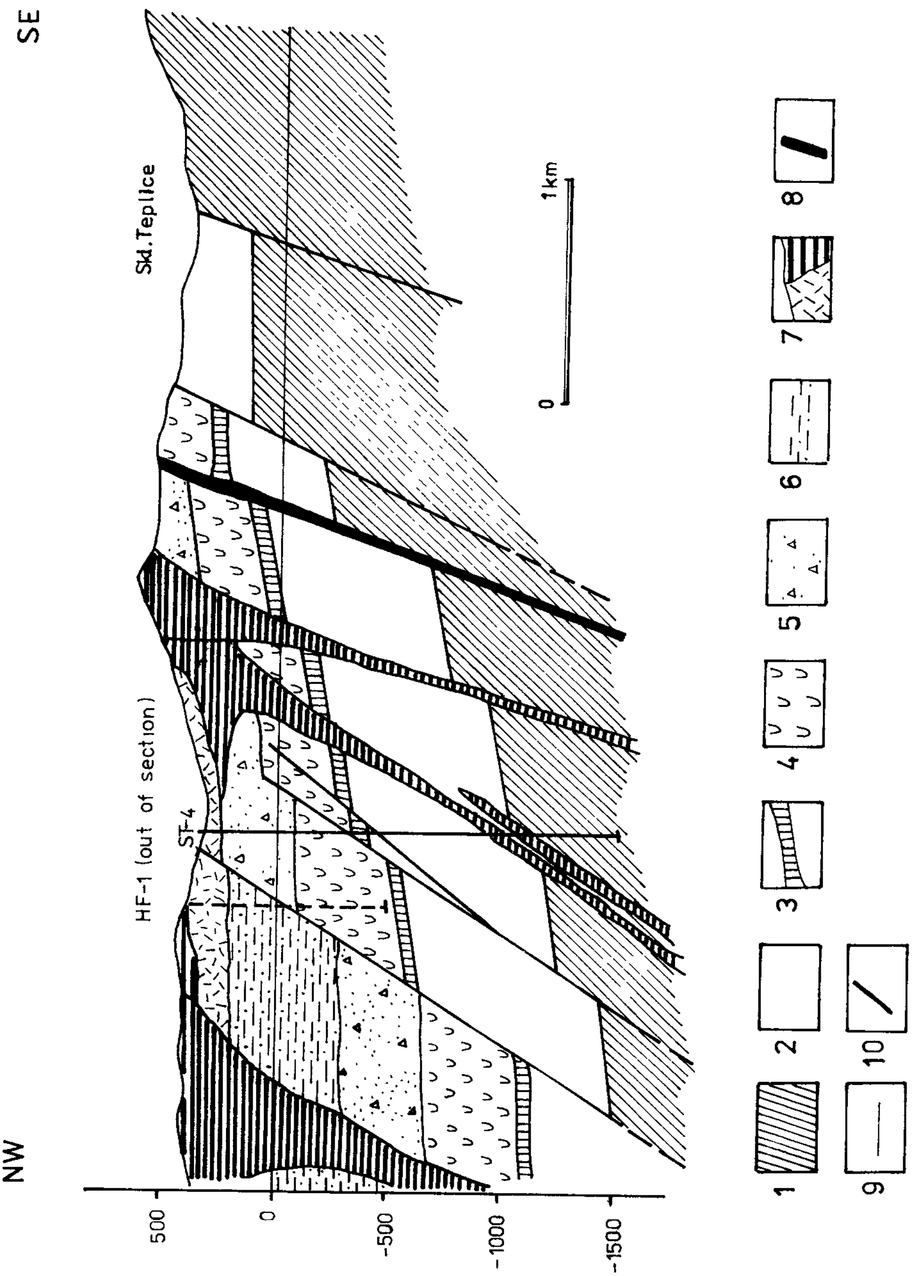

SE
NW
Skl.Teplice
HF-1 (out of section)
ST-4
0
1km
500
0
-500
-1000
-1500
1
2
3
4
5
6
7
8
9
10

Fig. 8.

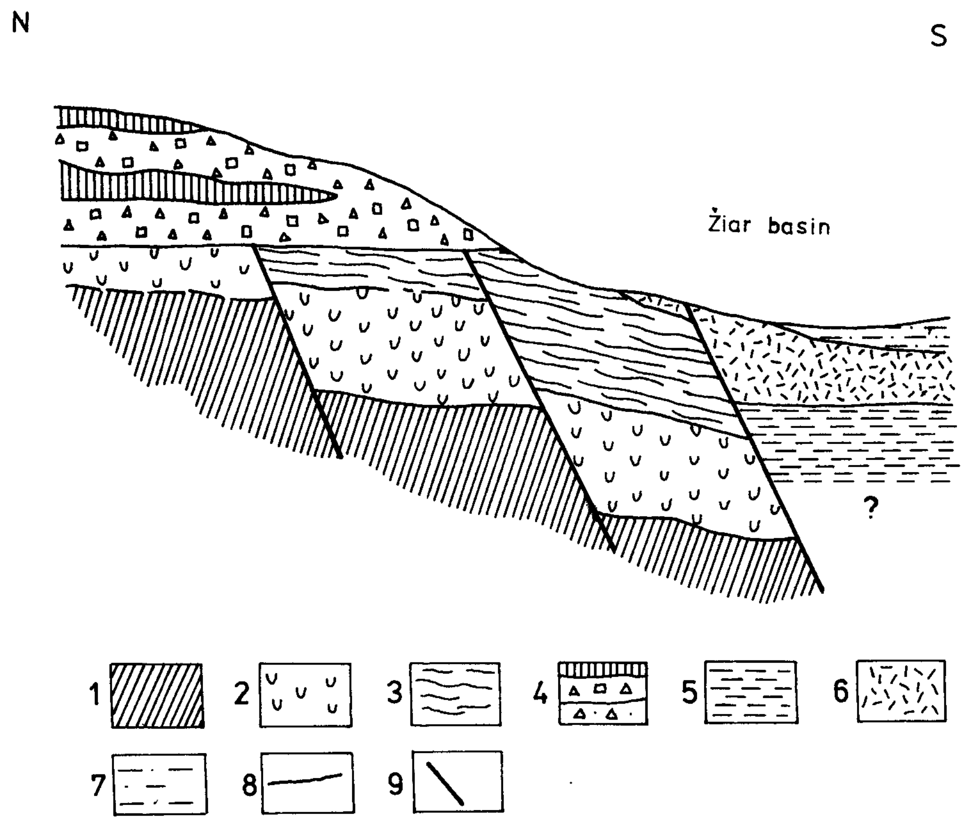


Fig. 9. Cross-section at the margin of the Žiarska kotlina graben nearby the village Janova Lehota. 1 – basement; 2 – Lower Badenian volcanic and sedimentary rocks; 3 – Turček formation (late Upper Badenian to early Lower Sarmatian); 4 – Remata formation (Lower to Middle Sarmatian); 5 – Middle to Upper Sarmatian sedimentary rocks; 6 – Jastrabá formation (late Upper Sarmatian to early Lower Pannonian); 7 – Pannonian sedimentary rocks; 8 – geological boundaries; 9 – faults.

Dips of faults are also variable and only rarely well established – estimates are given in the Fig. 2. Usual dip of normal faults varies around 60–70°, only rarely have been observed higher dips. At fault-zones external faults show often smaller dips (Fig. 7), indicating that individual faults may connect into one fault in a greater depth. Well documented section at the SE side of the Žiarska kotlina graben documents the dip of major faults in the range 50–60° (Fig. 8). Smaller dips in the range 40–60° are reported on numerous faults in the area of Nováky and Handlová coal basins (B a r t e k, 1959, 1977) – observed faults with dips in the range 25–35° are related to younger gravity tectonics (Š i m e č e k, 1980).

One may expect, that faults bounding tilted (rotated) blocks would show decreasing dip with increasing depth. Such a case has been observed in Kremnica mines (Figs. 10, 11), where the dip of the vein decreases from 60° at the surface to 50° at the depth over 700 m.

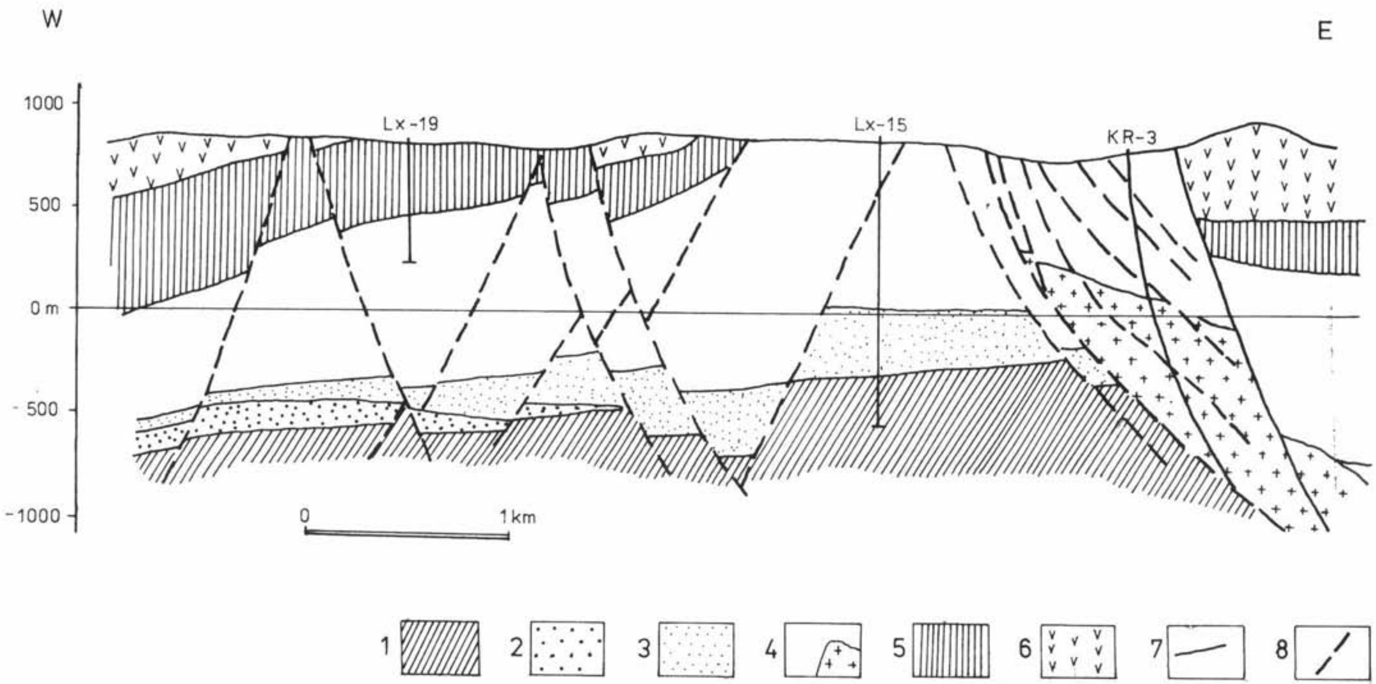


Fig. 10. Cross-section at the central part of the Kremnické vrchy mountain range.
1 – Mesozoic rocks; 2 – Paleogene rocks; 3 – Kordíky formation (Lower Badenian); 4 – Zlatá studňa formation und related diorite intrusion (Lower to Middle Badenian); 5 – Turček formation (late Upper Badenian to early Lower Sarmatian); 6 – Kremnický štít formation (age as 5); 7 – geological boundaries; 8 – faults.

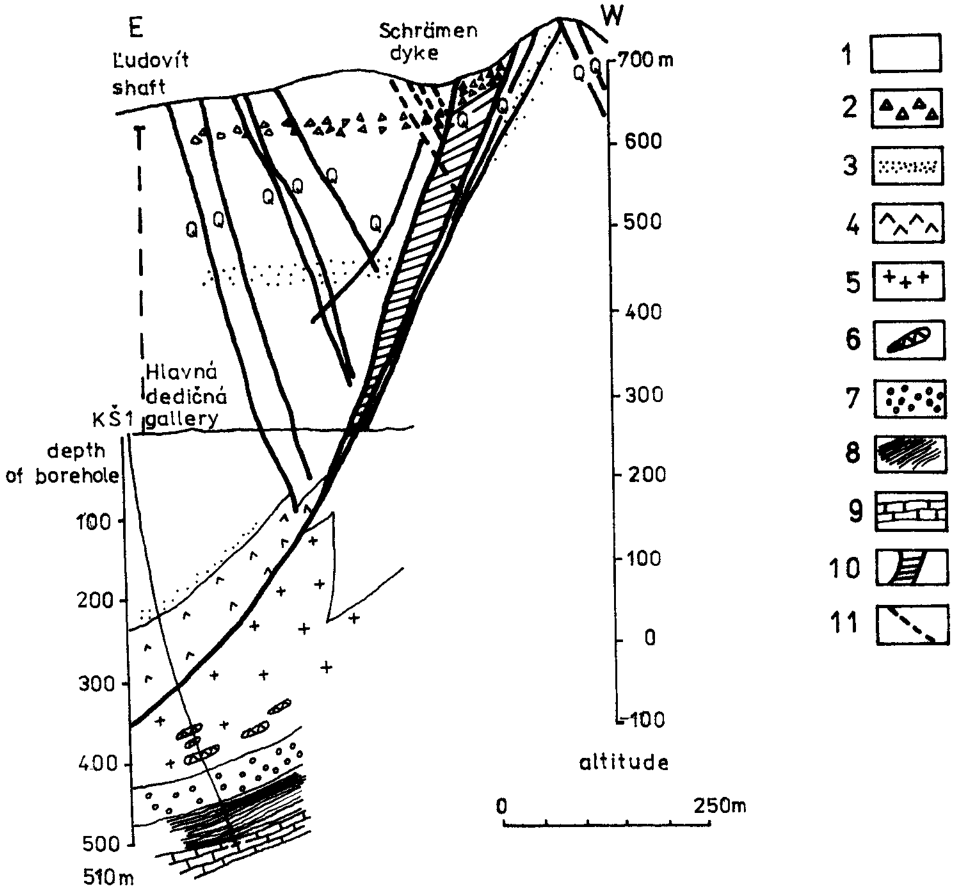


Fig. 11. Cross-section of the first vein system in the Kremnıca gold mines (according to B ö h m e r, 1977). 1 – andesite; 2 – zone of breccia; 3 – zone of hydrothermal alteration; 4 – rhyolite; 5 – diorite porphyry; 6 – metamorphosed sediments; 7 – psefitic sediment; 8 – dark shale, 9 – limestone; 10 – quartz vein; 11 – fault.

Tilting or rotation of block around horizontal axis is the next important structural feature, which is well documented by sections in the Figs. 3 to 6. Generally, we may distinguish tilting of extensive first-order blocks related probably to regional updoming preceding and accompanying subsidence, with structural axis trending NNE-SSW from the Veľká Fatra mountain range into the eastern part of the Kremnické vrchy mountain range. West of this axis we observe westward dips, east of the axis estward dips, nearby the axis the position of blocks is horizontal (Figs. 2, 4, 5, 6). Dips of this kind do not exceed 10° with an exception of Turčianska kotlina graben, where dips up to 15 to 20° have been observed (G a š p a r i k, 1980, 1985) – however, in this case a rotation involving a listric fault can not be excluded (see bellow). The mentioned dips refer to the base of the Badenian strata – the Lower Miocene and Paleogene rocks show even higher dips up to 40° that are related to mobility before the evolution of the basin and range structure. Dips observed on younger rocks are smaller. The transverse Žiar range has according to geomorphological analysis rotated 6–8° northeastward (clockwise – Fig. 12), however, geology indicates a preceding stage of counterclockwise rotation.

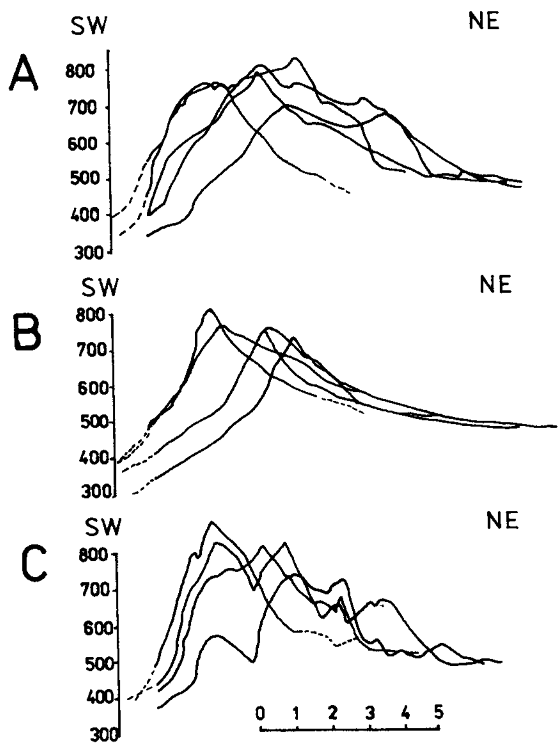


Fig. 12. Parallel morphological sections of the Žiar mountain range.
A – sections along ridges, B – sections along valleys, C – straight sections.

Another kind of rotation of blocks around the horizontal axis is represented by rather narrow blocks bounded on their western side by listric faults. Rotation of blocks at this case is given by the curvature of the listric fault. Dips up to 25° have been observed in blocks, where rotation is related to listric faulting (Fig. 10).

There are still some other observed features contributing to our understanding of faulting. Fig. 11 clearly demonstrates near-surface extention caused by movement along listric fault without sufficient rotation of the overlying block – extension is compensated by emplacement of a thick quartz vein and small scale subsidence along antithetic faults.

The Fig. 13 shows also such the features as curved faults, branching of faults into horse-tail type structures and "en echelon" fractures that indicate a sinistral horizontal displacement (component of displacement) in the area of the Nováky and Handlová coal-basin. These movements are probably related to NE-SW trending faults in the eastern part of the Žiar

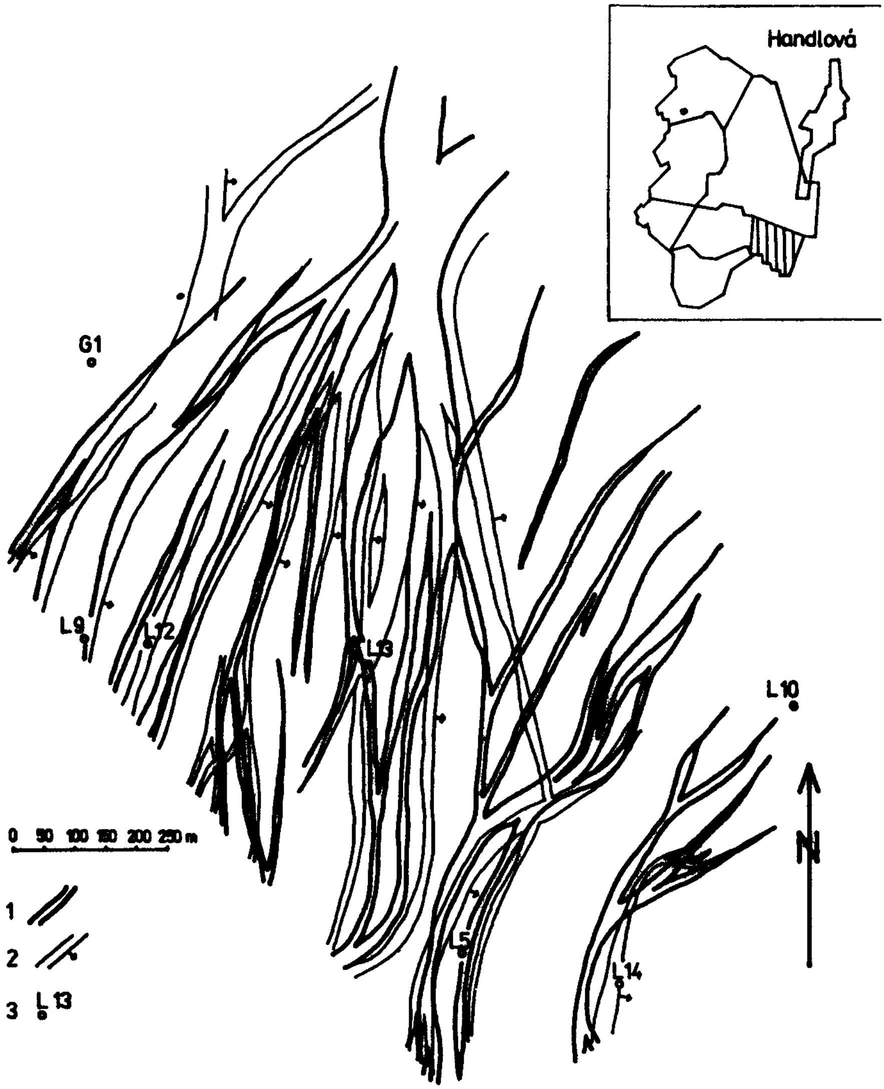


Fig. 13. Fault system in the Nová Lehota coal mine (modified according to B a r t e k et al., 1957, 1969). 1 – faults at the base of the first coal seam; 2 – faults at the base of the second coal seam with indication of dip; 3 – boreholes.

mountain range, that clearly offsest the Pravno fault line bounding the range at the south. An explanation of the offsets by normal faulting would require an oposite sense of movements as observed on faults of this trend further southward. Therefore we ascribe the offsets to sinistral horizontal displacement, that ranges from 100 to 800 m on individual faults.

Eastward dipping reverse faults with small vertical displacement have been observed rarely in the Handlová coal basin (B a r t e k, 1972). Their orientation and vector of displacement do not allow for the relationship to observed sinistral strike-slip faults. Therefore, it is probable, that the observed reverse faults are related to gravity tectonics described bellow.

Coal seams and overlying clays in the southern part of the Handlová coal basin are disturbed by low-angle listric faults involving typical rotation of overlying blocks, that have been ascribed to gravity tectonics related to gravitation instability of uplifted plastic rocks next to the subsiding Žiarska kotlina graben (Š i m e č e k, 1980). One has to distinquish this gravity tectonics from subrecent gravity sliding caused by lovering of erosional base and recently also by coal mining.

Evolution in time

The fact, that the Lower Badenian fluvial and limnic sediments have been laid down over a flat surface represented by the Mesozoic, Paleogene and Eggenburgian rocks indicates an uplift and denudation during the late Lower Miocene time.

The first signs of faulting during the Lower Badenian time are interpreted in the central and eastern parts of the Kremnické vrchy mountain range, where they coincide with commencement of intense volcanic activity. The Fig. 14 shows a small NE-SW trending graben near the village Malachov, where marginal faults cut off volcanosedimentary rocks of the Lower Badenian Kordíky formation and graben is filled and covered by rocks of the Lower to Middle Badenian Zlatá Studňa formation (ages of lithostratigraphic units are given according to K o n e č n ý – L e x a – P l a n d e r o v á, 1983).

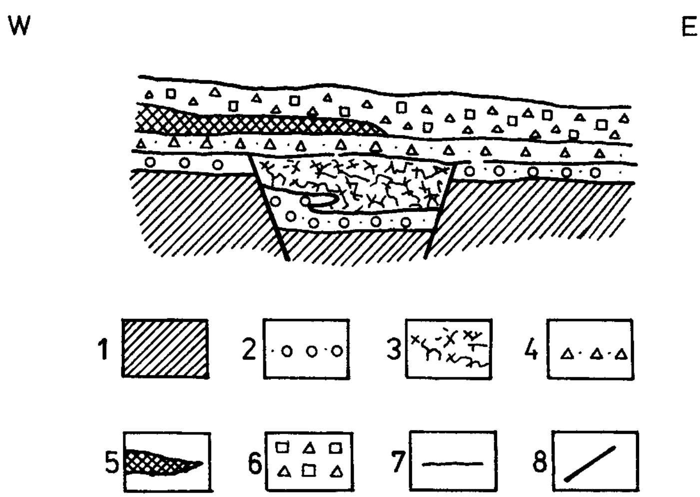


Fig. 14. Scheme of structure SW of Malachov.
1 – Mesozoic rocks; 2 – Kordíky formation (early Lower Badenian); 3–5 – Zlatá studňa formation (Lower to Middle Badenian): 3 – brecciated andesite lava flow, 4 – epiclastic volcanic breccias and sandstones, 5 – andesite lava flow, 6 – coarse epiclastic volcanic breccias; 7 – geological boundaries; 8 – faults.

There is a very strong evidence, that large scale faulting and subsidence of grabens started only during the late Badenian time. The Lower to Middle Badenian volcanic and sedimentary formations are cut off by marginal faults of the grabens, while lithology of these formations generally precludes synsedimentary (synvolcanic) faulting and subsidence.

As evolution of the grabens has not been uniform, we will treat them individually.

The presence of the 400–500 m thick complex of the Upper Badenian sedimentary, volcanosedimentary, and volcanic rocks at the base of the Turčianska kotlina graben filling puts beginning of the subsidence at the mentoined time (Konečný – Lexa – Planderová, 1983; Gašparek, 1985).

According to results of the bore-hole GHŠ-1 (Gašparik et al., 1974) intensive subsidence of the graben continued during the Sarmatian (400–500 m) and Pannonian time (400–500 m). During this stage the graben acquired its assymmetry as evidenced by decreasing dips in younger rocks and lithology which indicates a systematic position of the lowest area at the western side of the graben. A large displacement along the faults at the western side of the graben and simultaneous uplift of the Malá Fatra and Žiar mountain ranges is indicated by horizons of very coarse granitic conglomerates including boulders in the Sarmatian and Pannonian sediments (Gašparik et al., 1974; Gašparik, 1985). The presence of redeposited kaolinite clays in the late Pannonian to Pontain sediments (Kraus, 1986) implies that during the Pannonian time movements were eventually intermittent. The period of tectonic rest during the late Pannonian time is indicated also by the evolution of a peneplain whose remnants are observed at the top of the southern part of Žiar nad western part of the Kremnické vrchy mountain range (Mazúr, 1964; Činčura, 1969).

During the Pliocene and Quaternary time the absolute subsidence of the Turčianska kotlina graben ceased. Limnic sedimentation was gradually replaced by the fluvial type of sedimentation and during the Quaternary time even a slight erosion took place as evidenced by river terraces. This agrees with estimates of recent vertical movements at 0 to + 0.5 mm/year (Kvitkovič – Vanko, 1980). However, even during this time continues a relative "subsidence" of the graben in respect of the surrounding mountain ranges, whose uplift continued. Relative movements on faults at the western side of the graben during the Pliocene time are implied by evolution of narrow pediments at the base of the Žiar and Malá Fatra mountain ranges, continuing relative movements during the Quaternary time follow from the relative displacement of river terraces (up to 50 m for the Middle Riss terrace) and differences in recent vertical movements – the estimate for the Žiar mountain range is + 0.5 to + 1.5 mm/year (Kvitkovič – Vanko, 1980).

The Kremnica graben represents eastward shifted southern continuation of the Turčianska kotlina graben and its subsidence started in the same time – marginal faults cut off volcanics of the Lower to Middle Badenian Zlatá studňa formation and the graben is filled up by the late Badenian volcanics of the Turček and Kremnický štít formations in the thickness 1000 m (Lexa, 1979). As these formations do not extend in larger thickness behind margins of the graben the subsidence was synvolcanic. This conclusion is supported by details of geology along the eastern marginal fault of the graben (Lexa et al., 1982) and by the fact, that marginal faults of the graben are in the western and northern part covered by the Lower Sarmatian volcanics of the Remata and Flochová formations (Figs. 4, 15). The large amplitude of subsidence in a rather short time interval may be explained in this case by volcanotectonic character of the graben – evacuation of the underlying magma chamber is at least partially responsible for its subsidence (Kaličiak – Konečný – Lexa, in press).

Before covering by the Lower Sarmatian volcanic formations, rocks filling the graben underwent further faulting involving listric faults and rotation of blocks around horizontal axis (Figs. 5, 10). Following the Lower Sarmatian time differential movements in the area of the Kremnica graben ceased with an exception of the fault bounding volcanics of the Remata formation against Mezozoic rocks of the Žiar mountain range in the West with vertical displacement about 100–200 m. An uncertainity exists about the time of formation of the local horst in the center of the Kremnica graben, but at least partially it coincided with the above mentioned listric faulting (Fig. 10). The area of the graben and the area immediately east of the graben underwent during the Middle Sarmatian to Pannonian time updoming with a N-S axis east of the graben. Updoming is well traceable according to elevation of the base of the

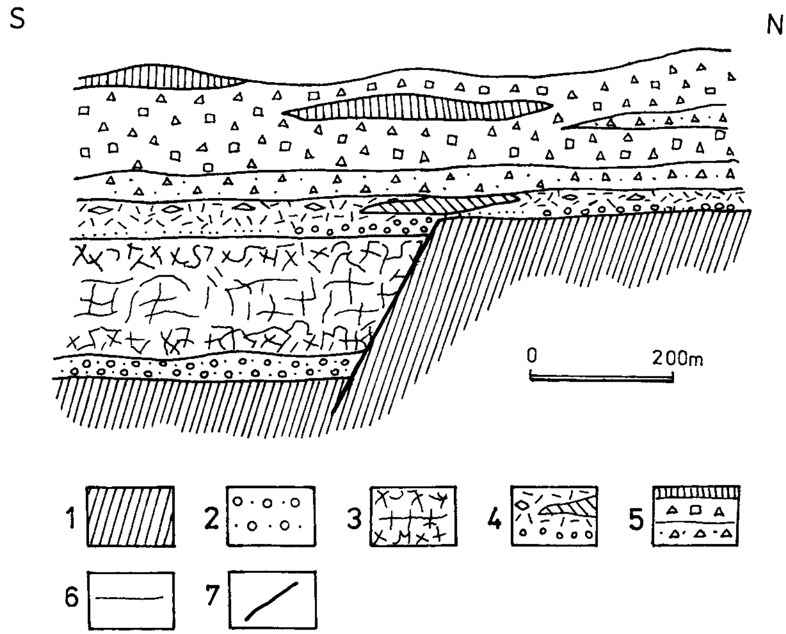


Fig. 15. Scheme of structure 2 km north of the village Kordíky.
1 – Mesozoic rocks; 2 – Kordíky formation (early Lower Badenian); 3 – Zlatá studňa formation (Lower to Middle Badenian) – brecciated andesite lava flow; 4 – Turček formation (late Upper Badenian to early Lower Sarmatian) – sandstones, conglomerates, reworked tuffs, andesite lava flow; 5 – Flochová formation (Lower Sarmatian) – andesite lava flow and epiclastic volcanic breccias; 6 – geological boundaries; 7 – fault.

Sarmatian volcanics and their dips – the age of updoming follows from the Lower to Upper Sarmatian age of rocks involved.

During the Upper Badenian and early Sarmatian time the Žiarska kotlina graben represented southern extension of the Kremnica graben and its evolution including filling of the graben by volcanics was similar – evidence is easily found in the eastern part of the Vtáčnik mountain range, which was during the mentioned time a part of the graben. Up to 1000 m thick complex of volcanics equivalent to filling of the Kremnica graben is present. Geological situation even involves the Lower Sarmatian rocks of the Vtáčnik and Remata formations covering relevant marginal faults of the graben (Fig. 9). Very fast subsidence eventually created gravitational instability in the neighbouring uplifted block, especially if plastic clays were present in its structure. Such the case is reported from the Handlová coal basin, where a large scale gravity sliding towards Žiarska kotlina during the Lower Sarmatian time has been interpreted on the basis of observed structural features (Šimeček, 1980). Contrary to the younger uplift of the Kremnica graben area and surrounding mountain ranges, the intense subsidence of the Žiarska kotlina graben continued during the Sarmatian and Pannonian time, often along more internally situated faults (Figs. 6, 8). As evidenced by drilling, thickness of the Sarmatian volcanosedimentary rocks is about 600–800 m and thickness of the Pannonian sedimentary rocks is about 200–300 m. Marginal faults of the graben from this stage variably cut of the Lower to Upper Sarmatian volcanics of surrounding mountain ranges (Figs. 6, 8). Fluvial character of the Pliocene and Quaternary rocks and evolution of river terraces indicates more or less stable position of the graben during this time, what is supported by the estimate of recent vertical movements at 0–0.5 m /year (Kvitkovič – Vanko, 1980). However, differential movements at marginal faults continued owing to uplift of surrounding area as evidenced by the much higher position of the Pliocene and early Quaternary river terraces outside the graben.

The Hornonitrianska kotlina basin (graben) is strongly assymetric, mostly owing to younger tilting and uplift of its former eastern part (the area of the Handlová coal basin and Vtáčnik mountain range). Its subsidence started probably sometimes during the accumulation of the Lower to Upper Badenian Kamenec formation represented by up to 400 m thick complex of volcanosedimentary rocks and rare interbedded clays laid down in a fluvial and limnic environment. Continuing subsidence during the Upper Badenian to early Sarmatian time without a proper supply of detritic material led at first to evolution of marshy environment with deposition of coal and later to the formation of a lake, in which several hundreds meters of clays were deposited. An older age of coal seams in the Nováky area (Upper Badenian) then in the Handlová area (early Sarmatian) (Konečný – Lexa – Planderová, 1983) indicates a gradual transgression of the marshy and limnic environments upon the inclined surface from the west towards the east owing to subsidence of the region. Inclination of the surface may be related to the original slope of underlying fluvial deposits whose source region was east of the basin, however, a westward tilting in connection with subsidence is also probable.

Following the deposition of coal seams and overlying limnic clays, still during the Lower Sarmatian time, intense tectonic movements took place resulting in drastic changes in paleogeography (Bartek et al., 1967, 1977; Brodňanová et al., 1984; Čech, 1969). Subsidence of the Žiarska kotlina graben east of the region, a general uplift of the eastern part of the block (the Handlová and Vtáčnik area) including tilting and simultaneous subsidence of the block at the west, and tectonic desintegration of the block are interpreted from the observed geological phenomena. Uplift of the Handlová coal basin and Vtáčnik area resulted in erosion of the uplifted region and eventually also gravity sliding of rock complexes including clays towards the subsiding Žiarska kotlina graben (Šimeček, 1980). Tectonic desintegration of the uplifted block (Figs. 2, 13) with displacement on individual faults up to 100 m (Brodňanová et al., 1984) is reflected in a variable depth of erosion and in redeposition of material from uplifted blocks in local depressions. The mentioned tectonic movements influenced stongly also the deposition of overlying fluvial gravels of the Lower Sarmatian Lehota formation. An uplift of the Malá Fatra, Malá Magura and Suchý mountain ranges and simultaneous subsidence of the Žiarska kotlina graben directed the transport of dominantly carbonate clastic material from the mentioned ranges towards the graben. In the subsiding western part of the Hornonitrianska kotlina basin fluvial gravels of the Lehota formation accumulated in the thickness up to 150 m and include interbedded horizons of limnic clays (eg. the borehole Š1-NB – Franko et al., 1977). In the uplifted eastern part of the former basin fluvial gravels of the Lehota formation fill up valleys cut into older rocks and eventually have been found also in open tectonic fractures and depressions created by already mentioned gravity sliding (Šimeček, 1980). At the margin of the Žiarska kotlina graben owing to synsedimentary subsidence gravels of the Lehota formation are accumulated in the thickness up to several hundreds meters and are interbedded with volcanics of the Kľakovská dolina formation filling up the graben (Konečný – Lexa, 1979).

A further uplift of the eastern part of the former basin, the so called „Handlová ridge", took place during the late Sarmatian (and early Pannonian?) time as evidenced by displacement along the marginal faults of the Žiarska kotlina graben as well as by tilting of the Lehota formation fluvial gravels and overlying Lower to Middle Sarmatian volcanics of the Vtáčnik formation (the age from Konečný – Lexa – Planderová, 1983). Secondary dips up to 10–15° have been observed (Konečný – Lexa, 1979; Bartek et al., 1969). The mentioned tilting explains also differences in magnetic declination between the Vtáčnik and Kremnické vrchy mountain ranges (Krs et al., 1986).

There is very little evidence concerning younger movements. Accumulation of Pliocene fluvial gravels in the western part of the Hornonitrianska kotlina basin indicates continuing intermittent subsidence.

Subsidence of the Zvolenská kotlina basin proceded in three stages. The first stage of the late Badenian age is implied by the fault-bounded extent of the Badenian volcanic and volcanosedimentary formations underneath the Sarmatian rocks (Lexa et al., 1983). Shape of the basin during this stage differed from the shape of the basin during younger stages of subsidence. The second stage of subsidence followed the Lower Sarmatian period of erosion and leveling and was coeval with the Middle to Upper Sarmatian Sielnica and Turová volcanic formations in the eastern part of the Kremnické vrchy mountain range

– volcanosedimentary rocks accumulated in the thickness up to 300 m, being limited by marginal faults of the basin at the east. At the west they pass gradually into mentioned terrestrial volcanics without much faulting (Lexa et al., 1983). Further subsidence of the basin and coeval uplift of the eastern part of Kremnické vrchy, including eastward tilting, during the late Sarmatian and early Pannonian time is evident from secondary eastward dips of the mentioned volcanic formations in the range 5–10°. The youngest stage of subsidence during the Pliocene and early Quaternary time is indicated by up to 100 m thick accumulation of the Pliocene fluvial gravels and by displacement of the Pliocene and early Quaternary river terraces across marginal faults of the basin in the range 50–150 m. Evolution of the late Quaternary river terraces indicates more or less stable position of the basin during this time.

Summarizing the above mentioned data we may conclude that the first signs of block faulting appeared during the Lower to Middle Badenian time. The most intense evolution of the basin and range structure took place during the Upper Badenian and Lower Sarmatian time, continuing with diminishing intensity during the Middle and Upper Sarmatian time – in the Turčianska kotlina and Žiarska kotlina grabens even during the Pannonian time. Later movements were small, intermittent and probably governed by different mechanism related to neotectonic pattern of the Western Carpathians. Subsidence of basins was accompanied by uplift of surrounding mountain ranges amounting to 1000–2000 m. So, we can envisage formation of basins as subsidence of grabens within a regional updoming with the N-S axis positioned along the eastern margin of the Kremnica graben.

Mechanism of faulting

The large scale vertical displacement, dips in the range 40–70°, frequent down-dip oriented striations and offsets in marginal faults of grabens indicate clearly the majority of faults as normal faults related to extension. An active role of extension in faulting (in contrast to normal faulting induced by loading) is implied also by the presence of listric faults, rotation of blocks around horizontal axis (tilting) and by the presence of open fractures. Some of the major faults have been used as feeders of surficial volcanic activity. Listric faults with detachment surface in the depth about 10 km have been interpreted in the area of Pannonian basin from deep reflection seismic profiling by Horváth – Tomek (1987). This allows to explain thinning and attenuation of the crust by the mechanism proposed for the Great Basin area in the U. S. A. by Hamilton (1987).

Orientation of extensional force can be estimated from the general orientation of major faults as well as from the orientation of structural axis and should be more or less perpendicular. As the general orientation of these features is N-S to NNE-SSW, orientation of extensional force during formation of the basin and range structure was roughly E-W to ESE-WNW. Only the NW-SE oriented Žiar mountain range and short segment between the Turčianska kotlina and Kremnica grabens may imply also the NE-SW oriented extension.

One may use several methods to estimate the amount of extension. The most conservative estimate is derived assuming normal faults with average dip 60° – in such the case the amount of extension is equal roughly to the half of vertical displacement on all faults, what in our case gives the result about 3 km. An assumption of listric faults involving rotation of blocks increases the estimate of extension up to 6 km. About the same result comes from the assumption of two-fold stretching of crust proposed by Royden – Sclater (1981).

Though the geometry of major faults precludes a larger horizontal component of displacement, several features have been observed in the NW part of the given area that point to involvement of sinistral strike-slip faulting or displacement component along faults of the NE-SW orientation. They may be summarized as follows: The Pravno fault bounding the Žiar mountain range against the subsided block of the Hornonitrianska kotlina depression is repeatedly offset sinistrally by a number of NE-SW trending faults (Fig. 2), that can not be interpreted as normal faults, because the required vertical displacement on these faults would be opposite to observed one further southward. Their strike-slip character with the horizontal displacement up to 800 m is supported by the observation of horizontal striations on some of the fault-planes. Faults of the same orientation in the Nováky and Handlová coal basins are accompanied by structures of the en echelon and horse-tail type (Fig. 13). Assuming the general E-W extension, geometry of the transverse Žiar mountain range and connection between the Turčianska kotlina and Kremnica grabens (Fig. 2) requires the NE-SW oriented component of motion (extension), for which we may account also by movements along NE-SW trending strike-slip faults. At the north the Turčianska kotlina graben ends at the probable strike-slip fault of this orientation.

A combination of normal and strike-slip faulting is supported by results of structural measurements carried out at localities shown in the Fig. 2. Results of measurements indicate three phases of faulting, represented by diagrams in the Figs. 16, 17, and 18. The method of Alexandrowski (1986) has been used. The probable ages are derived from observations on rock units of variable age.

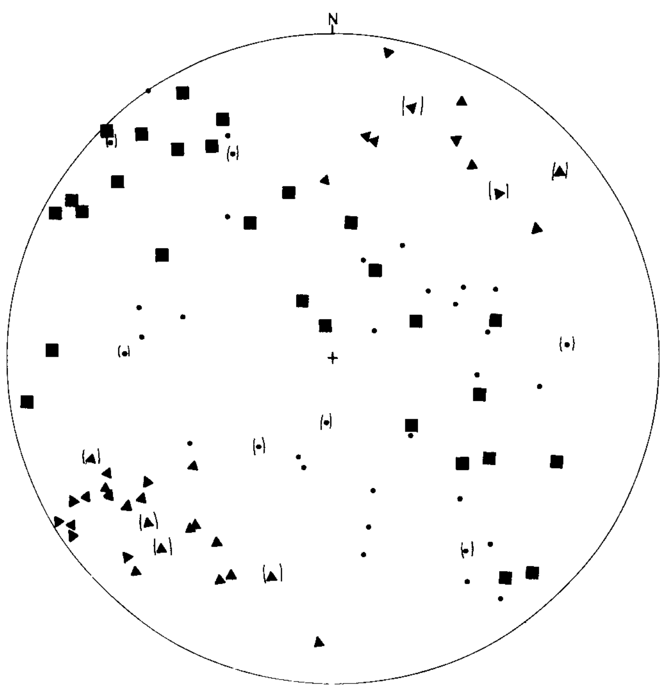


Fig. 16. Stress tensor axes for the first phase of block faulting (Middle to Upper Badenian?). σ_1 – squares, σ_2 – points, σ_3 – triangles.

The first phase of the Middle to Upper Badenian age (Fig. 16) corresponds to initial stages of block-faulting. In the sense of Philip (1987) it involved pure strike-slip as well as pure normal faulting and their combination. Mean orientation of tensor axes is σ_1/σ_2 = 315°, σ_3 = 45°. The original orientation of tensor axes was slightly different owing to possible rotation during younger movements.

The second phase of the late Badenian (to early Sarmatian?) age (Fig. 17) is not so well documented, however, it corresponds probably to the main phase of block-faulting. In the sense of Philip (1987) it involved combined normal and strike-slip faulting. Mean orientation of tensor axes is σ_1/σ_2 = 0°, σ_3 = 90°. Despite the fact, that we have not observed features corresponding to pure normal faulting (Fig. 17), orientation of the tensor axis σ_3 during this phase corresponds to the orientation of extensional force expected from trends of major faults.

The third phase of the Sarmatian to Pannonian age (Fig. 18) corresponds to final stages of block-faulting. In the sense of Philip (1987) this phase involved again strike-slip as well as normal faulting, which dominated. Mean orientation of tensor axes is σ_1/σ_2 = 40°, σ_3 = 130°.

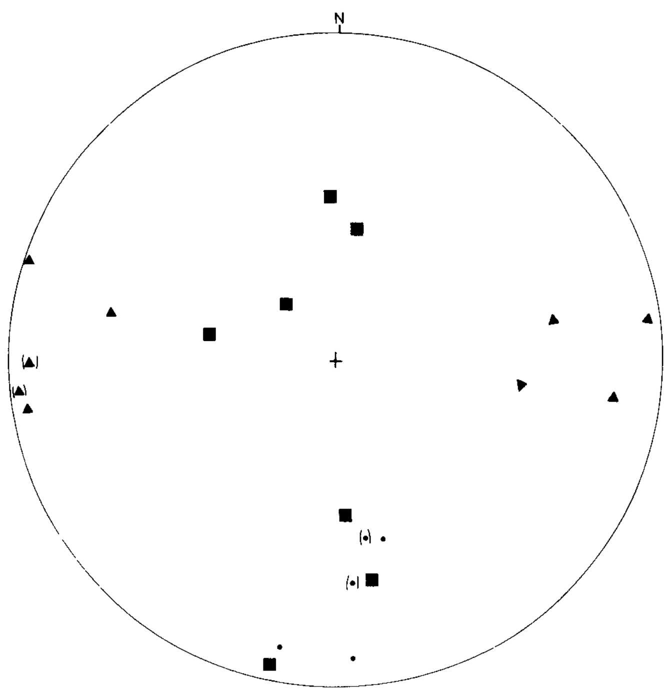


Fig. 17. Stress tensor axes for the second phase of block faulting (late Badenian to early Sarmatian?). σ_1 – squares, σ_2 – points, σ_3 – triangles.

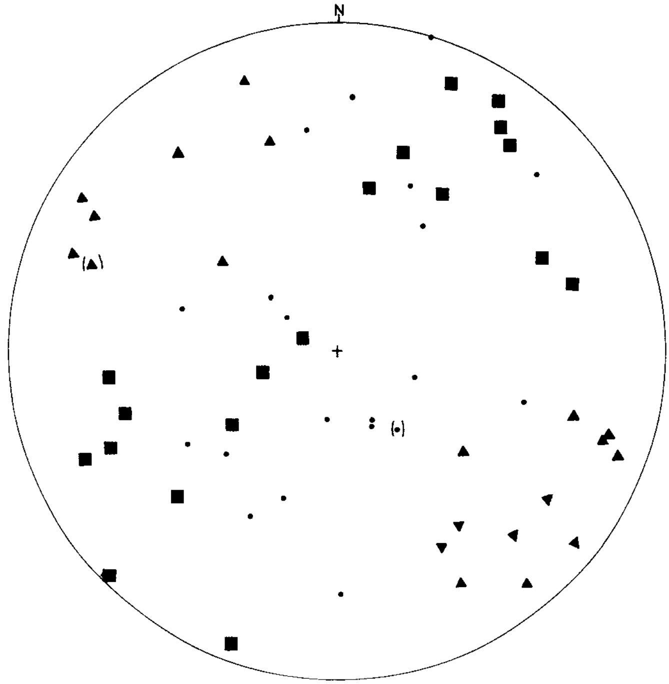


Fig. 18. Stress tensor axes for the third phase of block faulting (Sarmatian to Pannonian?). σ_1 – squares, σ_2 – points, σ_3 – triangles.

Relationship to regional geotectonic processes

Thompson (1966), Hamilton – Myers (1966), Hamilton (1969) and Stewart (1971) have related the typical basin and range structure in the Great Basin of the U.S.A. to a regional extension. The same mechanism is assumed for basins in the intra-Carpathian region by number of authors (e.g. Stegena, 1964; Lexa – Konečný, 1974; Stegena et al., 1975; Royden – Sclater, 1981; Royden et al., 1982, 1983 to name some of them). Arguments for extension as the prime reason of subsidence of basins in the given area have been summarized above. Differences among various models are in opinions concerning the cause of extension. Basically there are recognized three modes of extension: extension induced by upwelling of hot mantle material – an active mantle diapir (Stegena, 1964, 1987; Szádeczky-Kardoss, 1966; Lexa – Konečný, 1974, 1979; Stegena et al., 1973, 1975), extension induced by motion along strike-slip faults – pull-appart basins (Royden et al. 1982, 1983) and extension induced by retreating Eastern Carpathian arc and subduction zone – involving stretching of the crust and passive upwelling of mantle material (Royden – Sclater, 1981; Royden et al., 1982, 1983). It is important to note, that there is no need of a uniform mechanism for all basins in the intra-Carpathian region – all three mentioned modes of extension can easily coexist.

Royden et al. (1982, 1983) have demonstrated, that formation of the Vienna basin and possibly also of the Transcarpathian basin is best explained by the pull-appart mechanism related to sinistral respectively dextral strike-slip motion in respective parts of the arc.

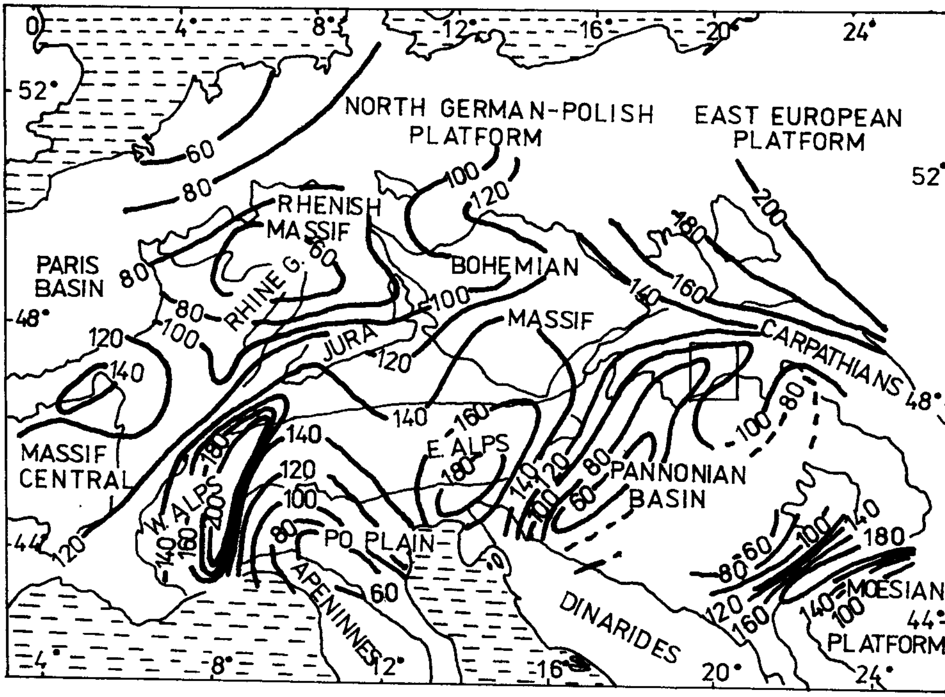


Fig. 19. Depth of lithosphere from P-wave travel time residuals (according to Babuška et al., 1986). Investigated area is indicated by black square.

Sclater et al. (1980) and Royden – Sclater (1981) demonstrated, that subsidence curves of some of the basins fit well a model of two-fold crustal stretching involving a passive upwelling of mantle material – in accordance with model calculations these basins show a distinct phase of fast subsidence related to stretching followed by the phase of slow subsidence involving a broader area related to cooling of the lithothermal system. The Danube basin may serve as an example. Royden et al. (1982, 1983) related the required stretching to eastward drift of the Eastern Carpathian arc and subduction zone involving its steepening.

Evolution of basins in the central Slovakia region does not fit these models. The most important differences are the following:

– subsidence of basins was preceded and accompanied by a regional updoming – uplift of surrounding mountains (as a part of the mentioned updoming) was at least so important as subsidence of basins;

– the phase of localized fast subsidence was not followed by a slow subsidence involving broader area – instead, we obserwe slow subsidence of basins while the broader area is still in the uplifted position; measurements of recent vertical movements indicate a general uplift with the basins in a stabile position (Kvitkovič – Vanko, 1980);

– evolution of basins was preceded and accompanied by voluminous calc-alkaline volcanics of intermediate and silicic composition.

For the mentioned features we can not account assuming only a passive upwelling of mantle material as response to crustal stretching (Neugebauer, 1987). They are explained best by

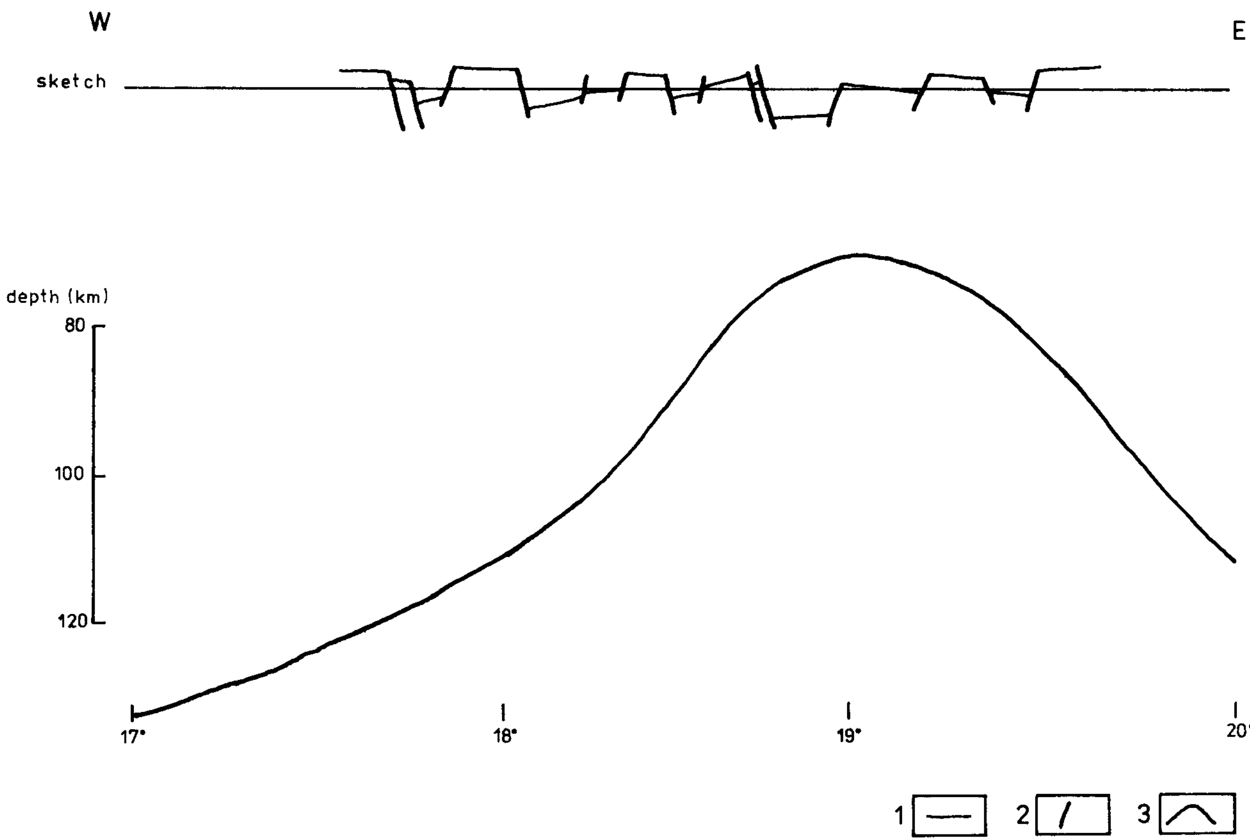


Fig. 20. Schematic cross-section of the basin and range structure in the investigated area above the section of asthenolithe according to B a b u š k a et al. (1986).

1 – geological boundaries; 2 – faults; 3 – boundary of lithosphere and asthenosphere.

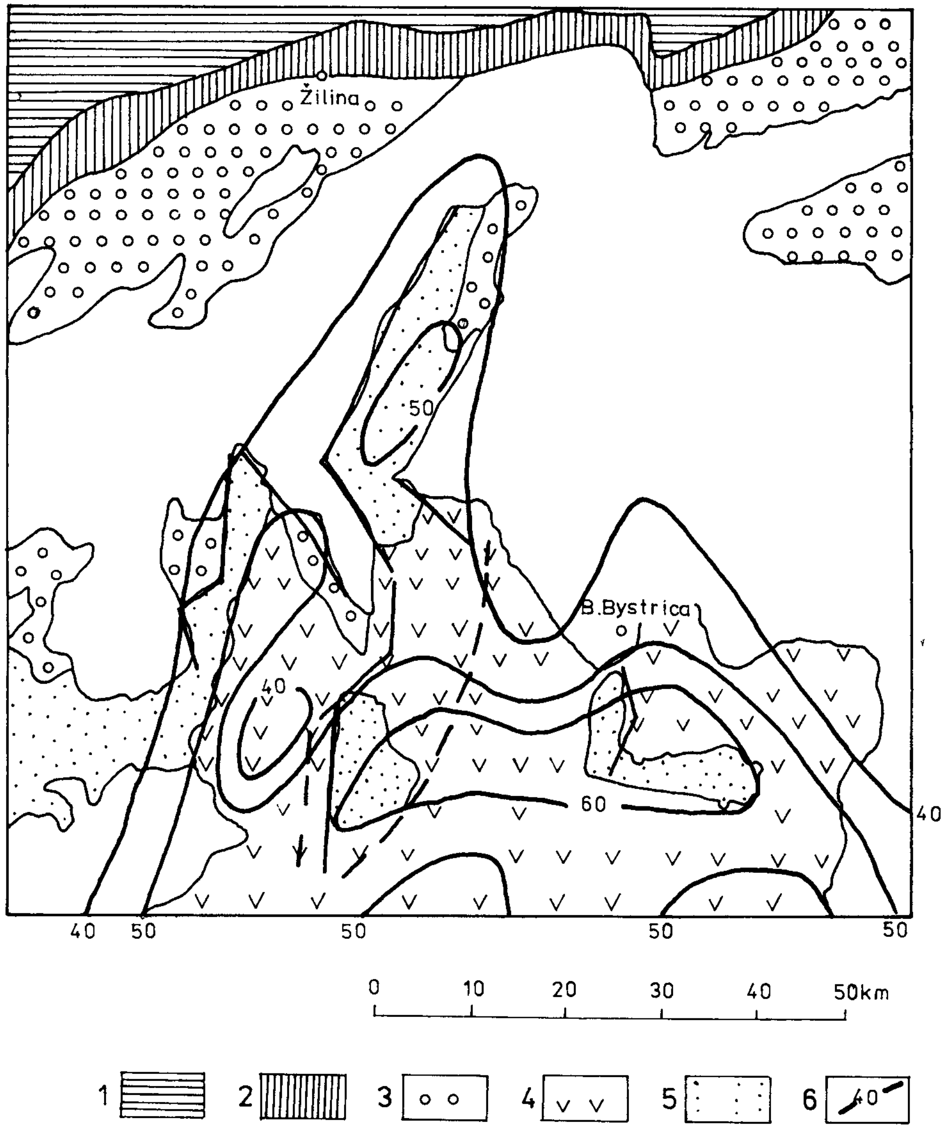


Fig. 21. Heat flow in the investigated area (according to M a r u š i a k et al., 1979).
1 – outer Carpathians; 2 – Klippen Belt; 3 – Paleogene of Central Carpathians; 4 – Neogene volcanic rocks; 5 – Neogene basins; 6 – heat flow with values given in mW . m^{-2}.

assuming an active diapiric uprise in the mantle and stretching of the crust as response to this process. Such the model, as it is well known from recent and subrecent rift zones, explains updoming preceding and accompanying subsidence, longer lasting activity and continuing high position of the area over the assumed diapir – remnants of the assumed mantle diapir in

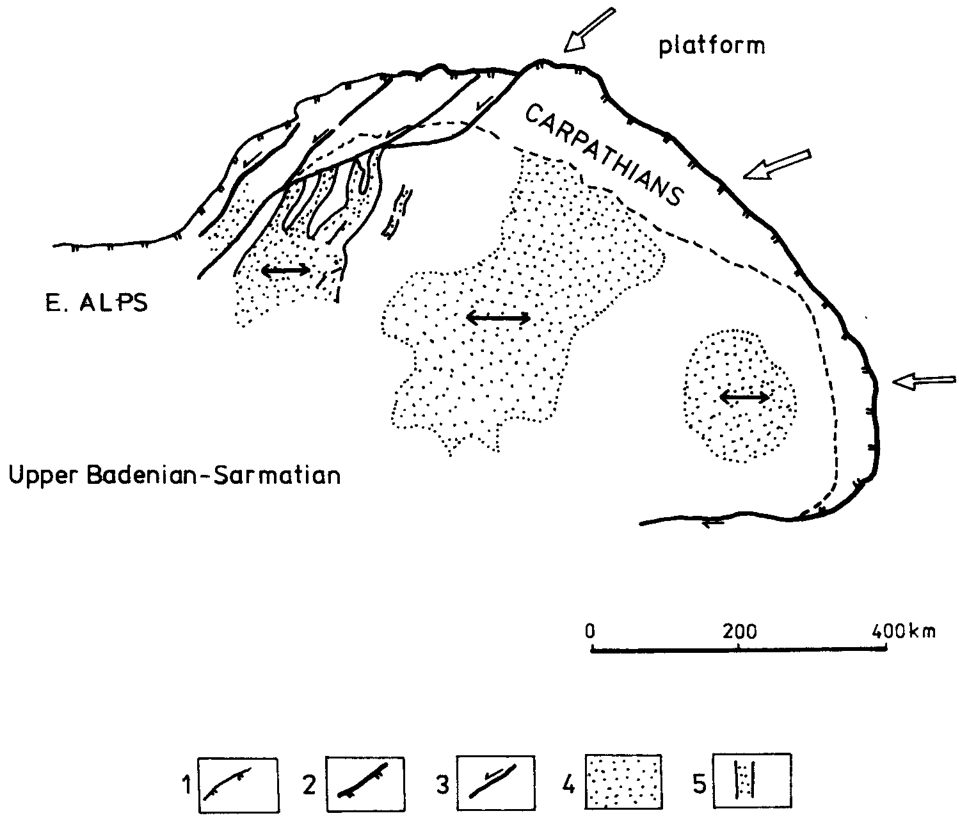


Fig. 22. Position of the basin and range system in geotectonic model of the Carpathians and Pannonian basin during the Upper Badenian and Sarmatian time (modified according to Royden et al., 1982). 1 – front of flysch nappes; 2 – active thrusting; 3 – transform faults; 4 – areas of maximum subsidence; 5 – basin and range system of the western and central Slovakia.

the intra-Carpathian region are still well visible at the surface of the asthenosphere as modeled by Babuška et al. (1986) from P-wave travel time residuals. The Figs. 19 and 20 demonstrate that the basin and range structure in the given area lies symmetrically over the top of asthenosphere upwelling including a parallel orientation. The observed orientation of asthenosphere „ridge“ agrees with assumed vector of extension about 90–110°. The Fig. 21 shows a similar relationship to heat flow. According to Čermák (1974) variations in heat flow are related mostly to the depth of asthenosphere. An active mantle diapirism is required also by associating volcanics (Lexa – Konečný, 1979). Even if we assume subduction as the prime cause of volcanism, models for generation of magmas in island arc and continental margin environment involve the process of diapiric uprise in the mantle above the subduction zone (e.g. Ringwood, 1974). A probable generation of silicic magmas by partial melting within the crust requires diapiric uprise in the mantle as a source of heat.

Similar conclusions concerning the role of active diapiric uprise in the mantle in formation of the Mediterranean backarc basins in general have been reached also by Horváth – Berckhemer (1982) and Čech – Zeman (1985).

The Fig. 22 shows the position of the given area in respect of the Carpathian arc and the rest of the intra-Carpathian region during the Badenian time as interpreted by Royden et al. (1982, 1983). The assumed E-W extension coupled with some sinistral strike-slip motion in the NW part of the area fit this picture very well. The E-W extension was compensated by continuing subduction in the Eastern Carpathians just in the same way as assumed by Royden et al. (1982, 1983) in their passive extension model. Anyway, diapiric uprise in the mantle behind the arc and subduction in front of the arc should be seen as two parts of one system and a discussion about what comes first may not have a sense. A mutual relationship of subduction and behind the arc extension follows also from the fact, that during the relevant time the subduction was not driven any more by convergence of big plates, but rather by gravity subsidence of dense lithosphere in front of the arc (compare arguments of Hamilton, 1979 for the Banda arc).

Oszczypko – Slaçzka (1985) demonstrated conclusively, that during the Badenian time overthrusting and subduction ceased gradually in the western part of the Carpathian arc, while they continued in the Eastern Carpathians, what assuming a stabile platform ought to result in the NE-SW oriented system of sinistral strike-slip faults across the NW part of the Western Carpathians as well as in changes of orientation of the principal stress axes. The observed NE-SW trending sinistral strike-slip faults in the Žiar mountain range belong to this system. In a broader sense the mentioned system of strike-slip faults limits at the north the extent of extensional basins (Fig. 22) and its existence has been proposed on the basis of sattelite immages interpretation by Pospíšil et al. (1984).

Conclusions

The presented evidence strongly supports the idea, that the basin and range structure in the central Slovakia region including voluminous calc-alkaline volcanics reflects an active diapiric uprise in the mantle during the Badenian to Sarmatian or early Pannonian time. Extension caused by the diapiric uprise of hot mantle material was compensated by continuing subduction in the Eastern Carpathians and in the NW part of the region was coupled with sinistral strike-slip motion along NE-SW trending faults induced by evolution of the Carpathian arc. Active diapiric uprise in the mantle should be considered together with transform faulting and passive crustal stretching as a possible process leading to evolution of basins in the intra-Carpathian region. Voluminous volcanics in other parts of the region as well as the excess heat in model calculations of subsidence (Royden – Sclater, 1981) indicate, that the process of active mantle diapirism may be more widespread than thought. This conclusion does not alter conclusions of Royden et al. (1982, 1983) concerning mutual relationships among extension, strike-slip faulting and subduction in the Carpathian region, however, the overall motion is not run only by retreating Carpathian subduction zone, but also by active diapiric uprise of hot mantle material in the intra-Carpathian region.

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