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FOLD-AND-THRUST SHORTENING IN THE WESTERN PART OF THE UPPER SILESIAN COAL BASIN

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A b s t r a c t . The western frame-margin of the Upper Silesian Coal Basin provides good case studies for structural evolution of the fold-and-thrust belt. This study is concerned with tectonic junctions taking place on the Late Variscan front of the Moravosilesian Fold Zone and coal basin. Clues of evolution of fold-and-thrust belt were reconstructed on the base of six cross-sections and using balancing procedure to calculate the shortening. These structural cross-sections illustrated the two principal positive and negative inversion processes of Upper Silesian Coal Basin. The fold shortening varies in range of 25 up to 30% and in low range of 4 up to 18%. The thrust shortening is contrary to fold shortening and changed range of about 10% up to 50%. In the central part of fold-and-thrust belt summarised shortening is 55%, which gradually decreases northward up to 35% and southward up to 30%.

K e y w o r d s : coal-bearing deposits, inversion tectonics, shortening, restoration, Variscan belt.

INTRODUCTION

The so called fold-and-thrust belt of the Upper Silesian Coal Basin (USCB) is situated at the Variscan front of the Moravosilesian Fold Zone and belongs to the western frame-margin of the inner-Variscan Upper Silesian depression. It is composed of lower part of the Upper Carboniferous coal-bearing strata, including paralic sediment (marginal beds of Namurian A age) up to 4000 m thick (Kotas, 1995). Here, the main structural pattern is formed by the two brachysynclines and overturned anticlines of tight profile with thrusts oriented NNE–SSW. The footwall of the marginal Orlová–Boguszowice–Gliwice thrust consists of overturned syncline and secondary folds and faults. This foreland fold zone appears as a juxtaposition between fold-and-thrust belt and fold-and-fault zone of the central USCB with structures trending W–E (Fig. 1). They are intersected by steep normal faults with regional W–E direction of activated throw up to 1000 m during the Middle and Late Alpine phases (Jura, 1992, 2001).

Numerous fold, flexure and thrust structures were investigated mainly in the underground mines. Detailed tectonic studies in mesostructural scale during the subsurface mapping of the Gliwice area (Kuzak, 1992, 1994a, b; Kuzak *et al*., 1997; Trzepierczyński, Jura, 1997), Rybnik area (Jura, Kuzak, 2000a) and Jastrzębie area (Bogacz, 1981; Bogacz, Krokowski, 1981; Jura, 1992) gave a base for the interpretation of fold-and-thrust shortening. The balancing procedure of the cross-section has been used primarily to calculate the degree of shortening and to restore palinspastic of the western USCB. This procedure was tested by Cooper, Trayner (1985); see also McClay Ed. (1992).

TECTONIC SETTING

The fold-and-thrust belt trending along the western part of the USCB is located in the eastern part of the Moravosilesian Fold Zone with N–S direction (Kotas, 1985; Grygar, 1993; Jura, 1997; Kumpera, 1997). This western frame-margin of the USCB is composed of two main fold-thrusts structures. Their overturned anticlines and flexure-like forms with east vergency are strongly disturbed by the Orlová–Boguszowice–Gliwice and Michalkovice–Rybnik thrusts. The second order distortion structures of fold-and-thrust belt is transversal segmentation dissected by the Gliwice–Concordia,

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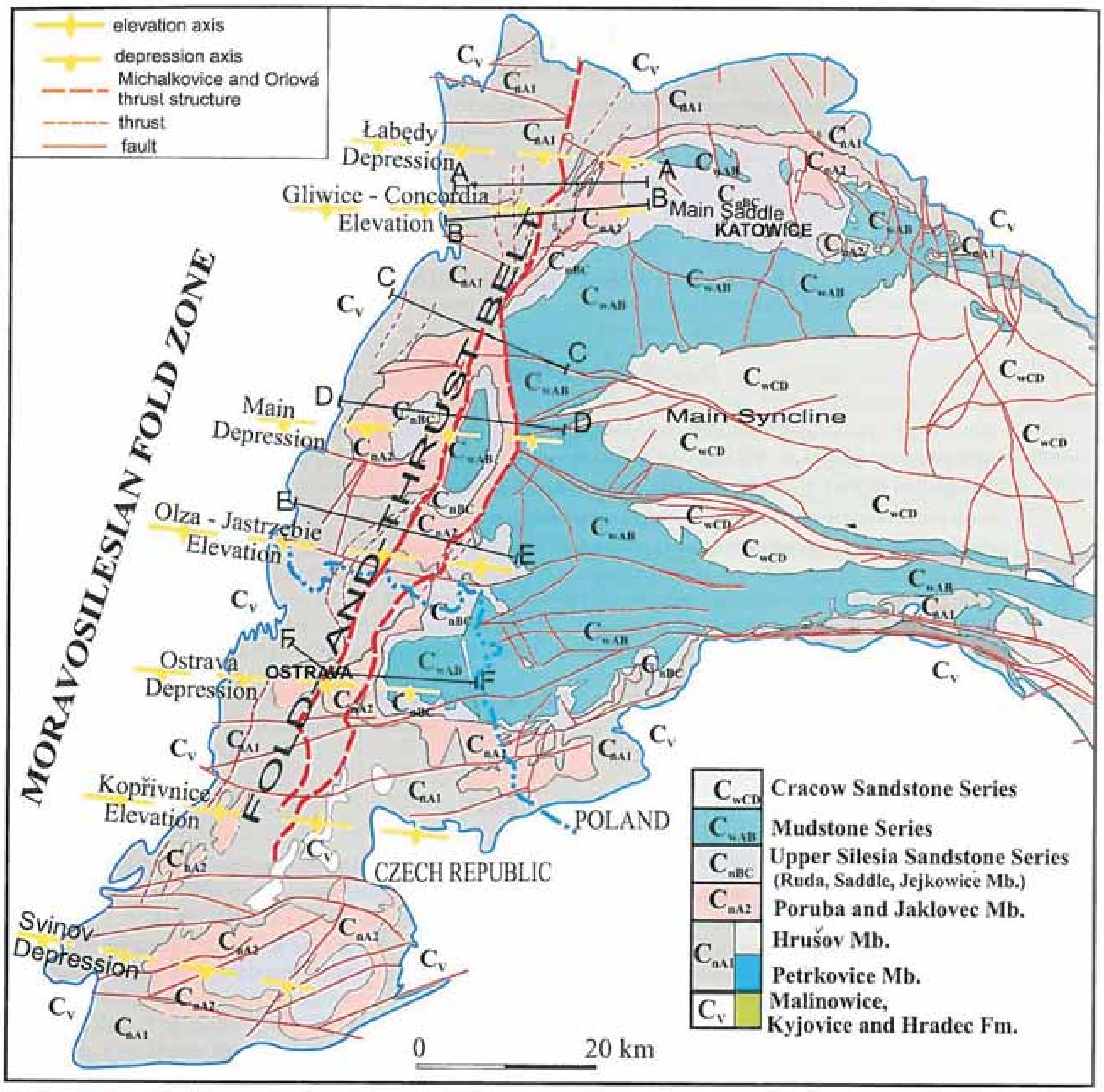

Fig. 1. Geological map of the western part of the Upper Silesian Coal Basin (Carboniferous subcrop) according to Buła *et al.*, (1994) and Jureczka *et al.*, (1995) — simplified

Olza–Jastrzębie and Kopřivnice elevations, and by the Łabędy, Main (Jejkowice–Chwałowice), Ostrava and Svinov depressions (Kotas, 1985; Jura, Trzepierczyński, 1994; Kumpera, Foldyna, 1997; Jura, Kuzak, 2000b; Fig. 1). Within the fold-and-thrust belt, there are longitudinally oriented synclinories deviated by the major thrusts. In transversal elevation zones, the synclinories are indicated by enveloping surfaces of the second-order folds (Fig. 2A–A, B–B, E–E). The major thrusts, developed from the flexural bending toward east between Moravosilesian and Upper Silesian basins, were described by Kuzak (1994b, 1997). Interdependencies of fold klinence and vergency, and the thrust amplitude in the Gliwice folds point to the conclusion that the flexures initiated the folding.

The Gliwice, Jastrzębie and Kopřivnice elevations are characterised by steep thrusts (up to 80º) and more intensely folded structures (Fig. 2A–A, B–B, E–E). Numerous tight anticlines from 500 up to 1500 m width and high altitude (about 1000 m) created box- and chevron-folds and special eastward overturned folds (Kuzak *et al.*, 1997). The footwall of the thrusts in elevation zones is also strongly disturbed, and created the tectonic junction between the thrust zone and their foreland in the western part of the USCB (Trzepierczyński, Jura, 1997).

The Jejkowice and Chwałowice broad brachysynclines mark the depression zones of the fold-and-thrust belt with 3–5 km of wide and up to 2 km of high altitude. The anticline parts of these folds remain reduced by shear and replaced by the Michalkovice–Rybnik and Orlová–Boguszowice thrusts.

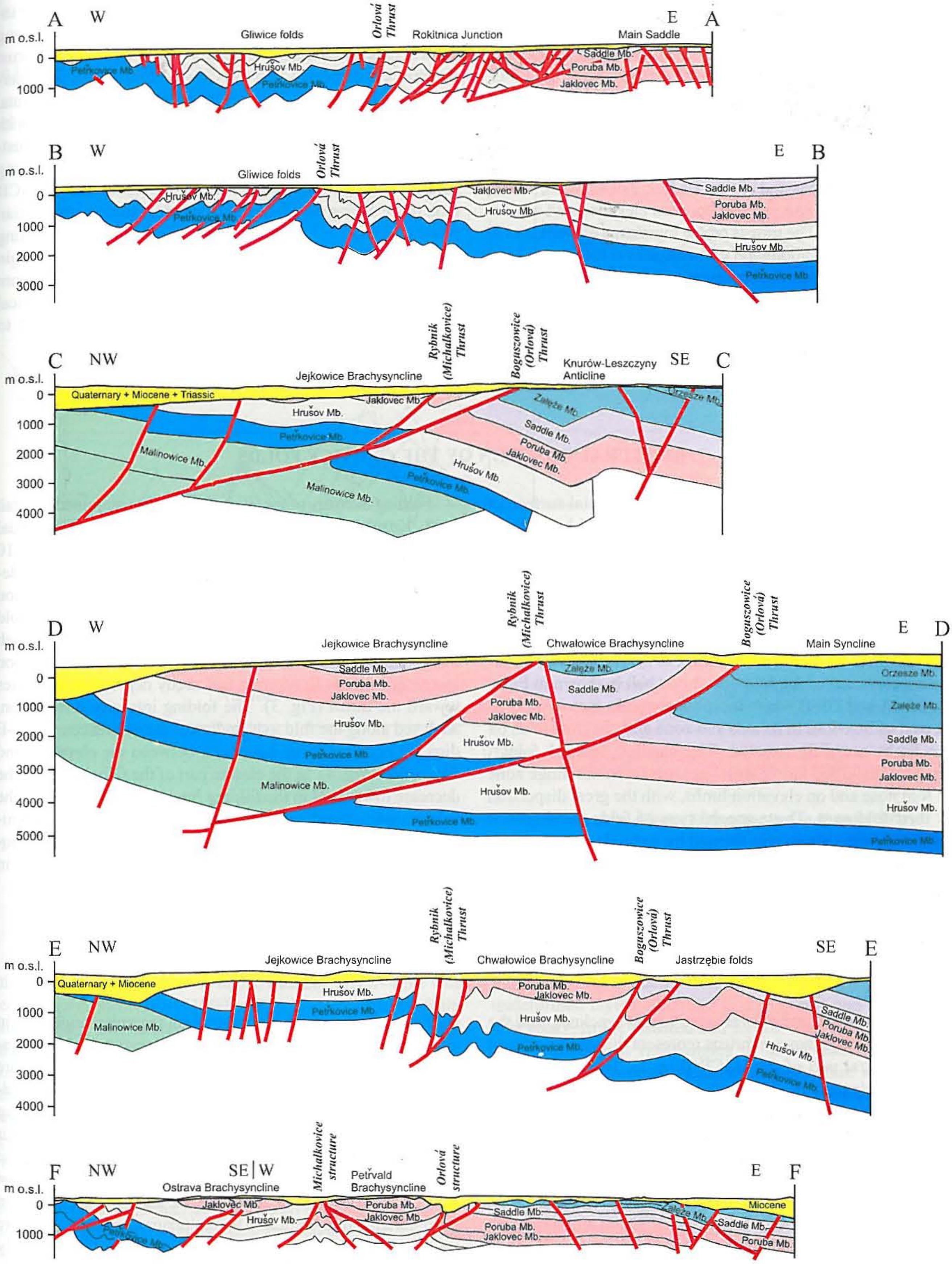

Fig. 2. Geological cross-sections of the fold-and-thrust belt in the Upper Silesian Coal Basin with the Triassic, Miocene and Quaternary cover (cross F–F according to Aust *et al.*, 1997 — simplified). For explanation see Figure 1

The transversal depressions are superimposed on the brachysynclines and pass into low angle thrust sheet (below 30°). The imbricated Boguszowice and Rybnik thrusts increase their amplitude up to 5 km along transversal depressions (Fig. 2C–C, D–D, F–F).

In the pass from depression to elevation zone, the thrust is virgated into 2–4 shear surfaces (Fig. 1). The main thrust changing into imbrication structures consists of secondary trusts and overturned anticlines and slices (Dadlez, Jaroszewski, 1994). In opposite, the thrusts connect between elevation and depression pass (Fig. 1). The thrusts create together westward arcs in the transversal elevations and eastward arcs in the depressions. The arcs are events on the basement of synclines and anticlines with meridian direction, which developed transverse elevations and depressions of the fold-and-thrust belt USCB.

The area east of the Orlová–Boguszowice thrust differs by lower degree of shortening, which is mainly caused by a single thrust, for example the Concordia thrust (Fig. 2A–A). The intensity of folding gradually decreases in the N direction along the Michalkowice–Rybnik, and Orlová–Boguszowice thrust structures is dispersed into the Gliwice folds (Jura, Trzepierczyński, 1994, 1996). The thrusts propagated through strata, especially at the floor of the siltstone Jaklovec Mb. with a smoothly curving trajectory (Fig. 2C–C, D–D). The thrusting is preceded by a ductile deformation of beds, producing folds. The stage thrusting of the western part of the USCB took place during the Stefanian (the Late Asturian and Uralian phases during 1 + 1 million years). The folding and thrusting rate of the Moravosilesian front, such as the frame-margin structure of the USCB thrusting, could be at average of 5 mm per year. However, the greatest rates of horizontal and vertical strong motions of fold-and-thrust belt vary from 100 to 50 mm per year (Jura, 2001).

STRUCTURAL POSITION OF THE GLIWICE FOLDS

Strongly deformed both the folds and its axial surface of the eastern part of the Gliwice folds are defined by tectonic junction of Rokitnica where younger fold-and-thrust belt refolds or overprints an older transverse anticline called the Main Saddle (Fig. 1). In the Rokitnica junction of folds, producing a zigzag interference pattern is refolding the W–E running Main Saddle, with the N–S trending Moravosilesian Fold Zone, (Trzepierczyński, Jura, 1997). The Gliwice–Concordia elevation of the fold-and-thrust belt is shown in Figures 2A–A and 2B–B where morphogeometric factors of folds as well as box-fold in its axis sub zone and chevron-folds on the limbs are differentiated. The smaller "special folds", strongly disturbed larger anticlines, occur on the hinge zone or fold nose and on elevation limbs, with the great dispersion of their fold axes. These special type of folds development with increasing strain was formed by a simple shear mechanism and represents an alternative shortening to continues folding and thrusting (Drozdzewski *et al.*, 1985).

Folding intensity of the Gliwice folds was examined in detail by R. Kuzak (1992, 1994a, 1997). The folds height and axial plane separation (H/R) dependencies were analysed on 10 anticlines in separate cross-sections localised in Łabędy depression (B, C, D, E, F) and Gliwice–Concordia elevation (A, G, K, L, M; Figs. 3 and 4). All the cross-sections cut the fold structures horizontally and are located 0.5–1 km from each other. The intensity within the Gliwice–Concordia elevation increases towards E, whereas in Łabędy depression decreases toward the thrust (Fig. 3). The folding intensity distribution, analysed along the fold axis, indicates the existence of a W–E directed bedding in the basement, between the elevation and depression (Fig. 4). In the eastern part of the Gliwice folds, the decrease towards N in the folding intensity is observed. In the western part, the decrease is graduate (a ramp is not manifested), and the existence of hinge fault is accepted. Distribution of folding intensity is symmetrical and changeable in relation to elevation axis.

RYBNIK AND BOGUSZOWICE THRUSTS

The Jejkowice and Chwałowice brachysynclines, and the Rybnik and Boguszowice thrusts represent the fold-and-thrust belt in central part of the USCB (Fig. 1). The most eastern structural element of the Moravosilesian thrust front is the Boguszowice thrust with folds at its footwall called the Knurów–Leszczyny fold and western (also WE) limb of the Main Syncline (Fig. 2C–C, B–B). The Boguszowice thrust dipping about 30–40° to the W, shows a 2–4 km amplitude. The thrust plane is developed in form of a 200 m wide breccia shear zone. In the footwall of thrust, a broad fold of 300 m amplitude and about 1300 m radius of the Knurów–Leszczyny anticline is developed (Fig. 2C–C). This anticline with axis running NNE–SSW is asymmetric: its western limb dips 32°, whereas the eastern — 10–15°. The eastern limb becomes further to the E a monocline with extensive fault tectonics originated in an extensional stress field. Dominant are two normal fault systems: NNE–SSW and W–E (Fig. 1). The meridional faults are concordant with the compressional structures of the fold-and-thrust belt in the western part of the USCB, suggesting their common origin (Kuzak, 1997, Kuzak *et al.*, 1997). Their tectogenesis is connected with sudden gravitational load of the thrust downthrown side originated from the weight of thrust walls. The result is local change of the main stress orientation from horizontal to vertical. The faults running NNE–SSW are short, up to 1 km and shows small throws, up to 10 m. Usually they reveal features of ductile faults, with intensively lustrous fault planes, narrow (up to 10 cm) fault fissures filled with fault gouge, and fault drag of strata (Jura, Kuzak, 2000a).

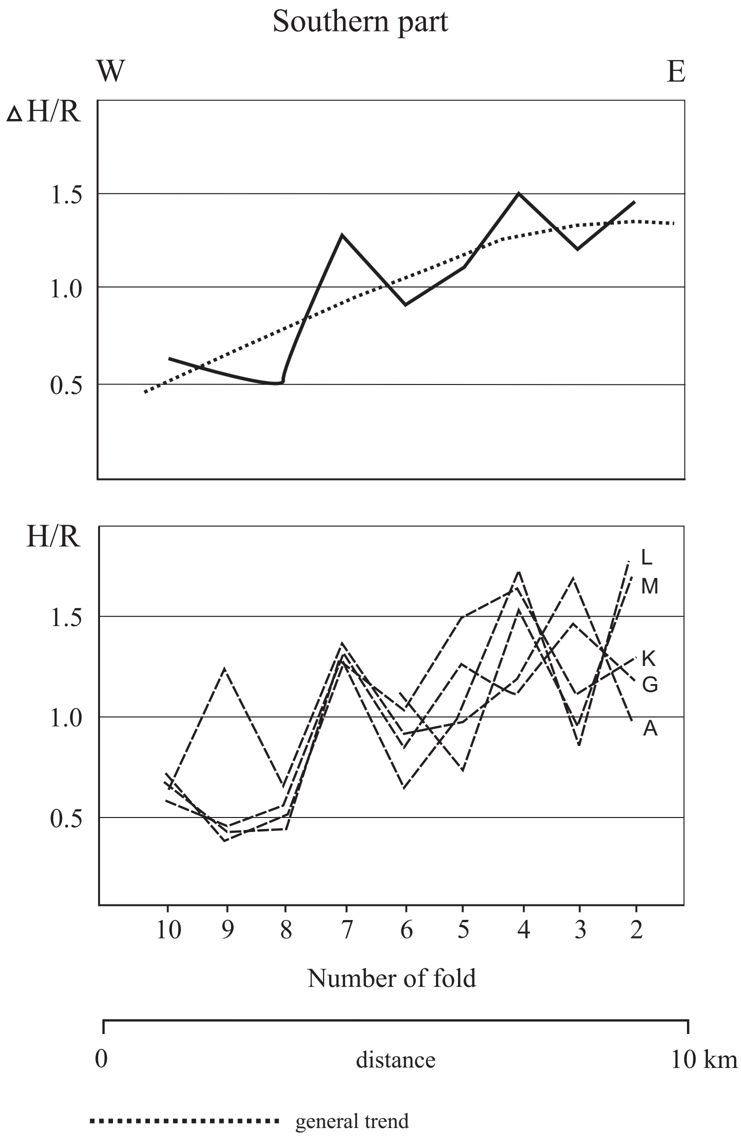

Fig. 3. Meridional changing of folding intensity along sections from M to H across the Gliwice folds according to Kuzak (1992)

2–10 anticlines, H/R coefficient, ΔH/R — medium coefficient

The main features of block tectonic of the footwall of the thrust are created by normal faults, running WNW–ESE with considerable throws up to 1000 m (Fig. 1). In general, the faults from a steep fault structure displace the Carboniferous strata to the south, with local grabens and horsts. The latitudinal faults, oriented low-angle to the thrust, display features typical of brittle deformation conditions. They have wide fault zones (throw up to 200 m) filled with products of coarse catalysis. Several parallel fault planes with a uniform throw direction can be seen within the fault zones. The faults are steeply dipping up to 75–80º, generally to the south, and genetically they are related to the thrust as an effect of rise of gravity charge during the thrusting process, causing a local reorientation of the main stress from horizontal in the hanging wall of thrust, to vertical in the footwall of thrust. The pattern of the latitudinal faults constitutes a horsetail type structure linked with ceasing of these dislocations towards west.

Frequently fold-and-fault structures are accompanying the shear zone of ductile deformation enclosed between the undeformed layers, cleavage in coal seams and fractures in host rocks. In the thrusted and folded coal-bearing deposits, joints trending at right-angles to thrust structures are restricted to the footwall rocks, whereas fracture set, trending parallel to thrust, occurs both above and within hanging-wall (Drozdzewski, 1993). The shear fractures in the coal, usually many centimetres in length, are characterised by an oblique sigmoidal cleavage striking NNE–SSW and dipping 15–30º. The cleavage microlithons thickness range is 0.5–1 cm. Both the lower and the upper surfaces of the shear zones are intensively lustrous with numerous tectonic stresses, oriented WNW–ESE (Jura, Kuzak, 2000a, b). The location of sigmoidal cleavage proves a dextral sense of a simple shear (facing N). Based on the Riedel's pattern of the orientation and relationships between principal stress directions of joints, the greatest

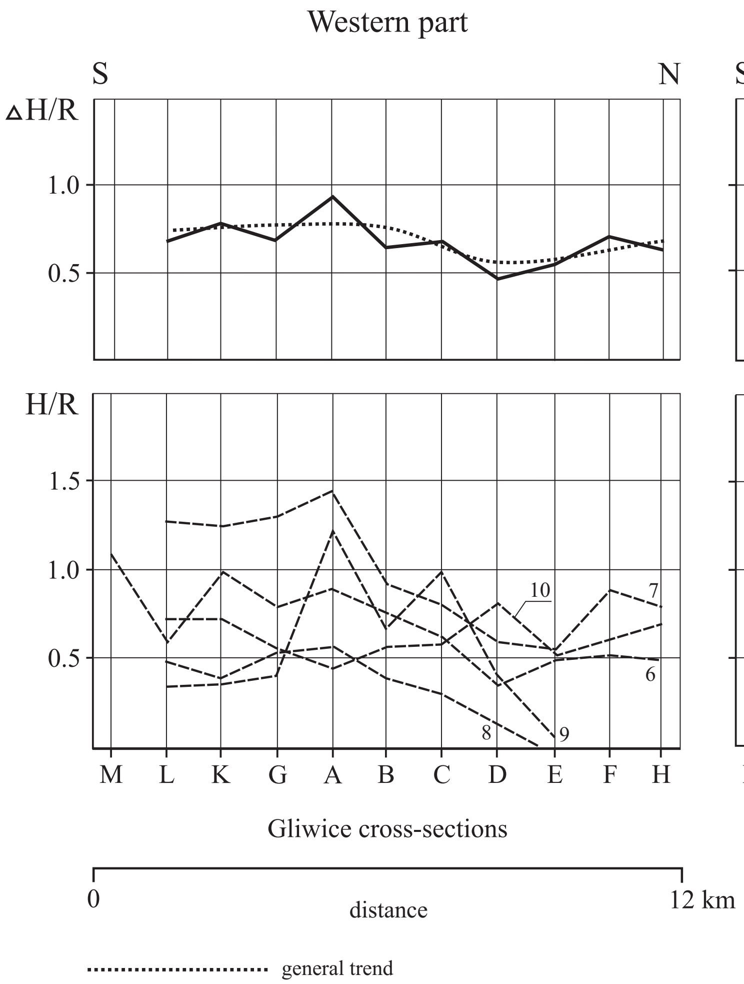

Fig. 4. Longitudinal changing observed along axes of anticlines in the Gliwice folds. For explanation see Figure 3

stress has been determined, which dips towards ESE at an angle of about 60º. This stress orientation is characteristic of the fold-and-thrust belt of the western part of the USCB, showing a NNE–SSW strike of structures (Kuzak *et al*., 1997). This consistence of tension directions proves that the shear zone in the seams (interstate) produced by a lateral displacement is tectogenetically linked with the Boguszowice thrust (Figs. 1 and 2). The steep inclination of main stress is caused by two factors: rise of share of gravity in footwall side of the thrust and also by a general ceasing of the compression towards east (gradual replacement of the smallest — σ_3 by the greatest — σ_1).

A structural feature of coal is the vertical cleavage of 0.5–1 cm density, developed in two groups: meridional (W–E, also NW–SE) and longitudinal (NNE–SSW). Cleavage directions in the coal are in general agreement with orientation of joints in the host rocks (Jura, Kuzak, 2000a, b). The surfaces of cleavage are smooth, lustrous, with anthracite reflection. The cleavage makes the coal easier to break into 1–2 cm large pieces. In the coal seam there are irregular fractures (4 cm thick).

JASTRZĘBIE FOLDS

The Olza–Jastrzębie transversal elevation of the fold-and--thrust belt displays two broad synclines and tight anticlines. This elevation in the Ostrava–Karviná coal district (Fig. 1), so called the Vrbice anticlinorium, by an expressive monocline of regional extent, is oriented WNW–ESE (Kumpera, Foldyna, 1997). In the footwall of the longitudinal Rybnik and Boguszowice thrusts parallel brachyfolds and second-order numerous reverse faults with amplitude from 1 up to 7 m are running (Bogacz, 1981). The Jastrzębie folds consist of many special folds and 2–4 thrusts (Fig. 1). The Boguszowice thrust has a NNE–SSW strike and their dip varies between 60–75º into WNW (Fig. 2E–E). In front of the Rybnik thrust, there are two upright folds of amplitude up to 500 m and 2 km wide. These folds are passing into a wide syncline cut by the Boguszowice thrust. In the footwall of the latter one, there is an inversed syncline and a few folds of diversified vergency. A contact zone of synclines of the hanging wall and the footwall, along the main thrust, points to the existence of sheared zone along the hange of flexure (Figs. 1 and 2E–E). Horizontal compression causing shear stresses produced folds in a buckling process, and deflected layers of coal-bearing deposits. The formation of buckle folds, subsequently — anticline-and-thrust, is combination of translation and rotation connected with flexure slip mechanism. According to Bogacz, Krokowski (1981), this foreland folds show en echelon pattern with dextral strike-slip movement in layer during buckling, and distortion axial surface of fold by thrust.

The folds, especially in the overturned limb of synclines in the footwall of the thrust, are cut by two sets of cleavage and joints, which strike shows a NNE–SSW direction and slight dip to WNW, and second one oriented 280/75. This cleavage is interpreted also as dislocation shears from a high-angle system of Riedel's pattern shears, in relation to the Boguszowice thrust (Bogacz, 1981).

OSTRAVA DEPRESSION

South of the Olza–Jastrzębie elevation, the Ostrava and Petřvald brachysynclines are separated by a disharmonically folded anticline which in both limbs is disturbed by several thrusts of the Michalkovice structure (Kumpera, Foldyna 1997), (Fig. 2F–F). The transverse elevation is connected with the Vrbice anticlinorium by an expressive monocline, striking ENE–WSW (Aust *et al*., 1997), (Fig. 1). The main folds are connected by a broad synclinorium and tight anticlines that are disturbed by longitudinal thrust faults. The Ostrava and Petřvald brachysynclines are flat structure with an oval outline, and have north closure more disturbed by thrust (Fig. 2F–F).

The Orlová structure in the Ostrava–Karviná coalfield has the nature of flexure-like fold overturned to east (Fig. 2F–F) with an amplitude decreasing toward the deeper levels (Kumpera, Foldyna, 1997). These anticline and thrust fault have the southern continuation into the Kozlovice saddle (Aust *et al*., 1997). The zone of broad fold and normal fault, located south of the Orlová structure, reflected the footwall that is characterised by a regular set of transversal normal faults (McClay, Ed., 1992). Fault sets at right-angles and parallel to the thrust are also symmetrically arranged around the folds beneath the thrust, especially concentrated across transversal elevation axis (Figs. 1 and 2).

FOLD AND THRUST SHORTENING

Balanced cross work is seen the best in the thrust belt where the Carboniferous deposits are commonly well outcropped in coal mine, and therefore accessible for detailed subsurface mapping in the western part of the USCB coalfields (Figs. 1 and 2). The structure map and series of cross-sections in scale 1:25,000 were the base of application of the balancing technique (De Paor, 1988) to the restoration of the fold-and-thrust belt. In the 15 km wide belt of the western part of the USCB, a fold-thrust shortening has been evaluated on the background of six geological cross-sections (Fig. 2). The fold shortening is given as coefficient: Ek = 100% – (l cosα × 100%)/L [%] (Möbus, 1989) or Sh = 15 km × Ek/100% [km] (Fig. 5). The thrust shortening is a sum of the slips of thrust larger than 50 m. The shortening of synclines and anticlines as well as the total length of slips were estimated for each cross-sections separately. The average values of the fold shortening are from 4% to 30%, or from 0.5 km to 4.4 km (Fig. 6).

In the transversal elevation zones, the fold shortening varies in high range of 3.8–4.4 km (25 up to 29.5%), however, in the depression zones it varies in low range of 0.6–2.7 km (4.2 up to 17.8%). The thrust shortening is opposite: in the elevation zones — low range of 1.6–2.4 km, and in the depression zones — high range of 2.5–7.2 km (Jura, Kuzak, 2000b). The fold-shortening curve is a "mirror image" of the thrust shortening, with the values inversely proportional. The sum of the fold-thrust shortenings is similar in every cross-section. In the central part of the fold-thrust zone, a shortening is the highest (7.8 km) and gradually decreases northward (5.2 km) and southward (4.7 km). A total shortening was averaged for the fold-and-thrust in the area 15 km wide; it was estimated at about 40% (Fig. 6). According to Kotas (1985), the shortening varies in range of 0.6–0.9 in the western part of the USCB, and in the Moravosilesian Fold Zone it is evaluated to 0.2–0.4 (Kumpera, 1980).

Fold-thrust shortening partially determines intensity of folding. This coefficient excluded folding compaction, slips, cleavages and small shears, and not observed thrusts. The shortening

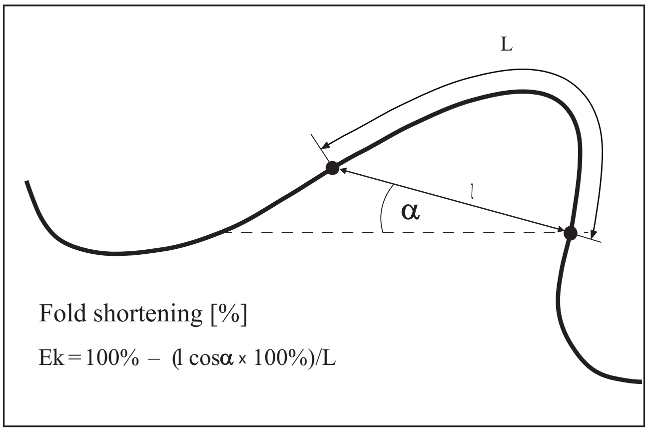

Fig. 5. Fold shortening coefficient (Ek) according to G. Möbus (1989)

l — 1/2 of wavelength between inflection points, L — wavelength along surface of beds

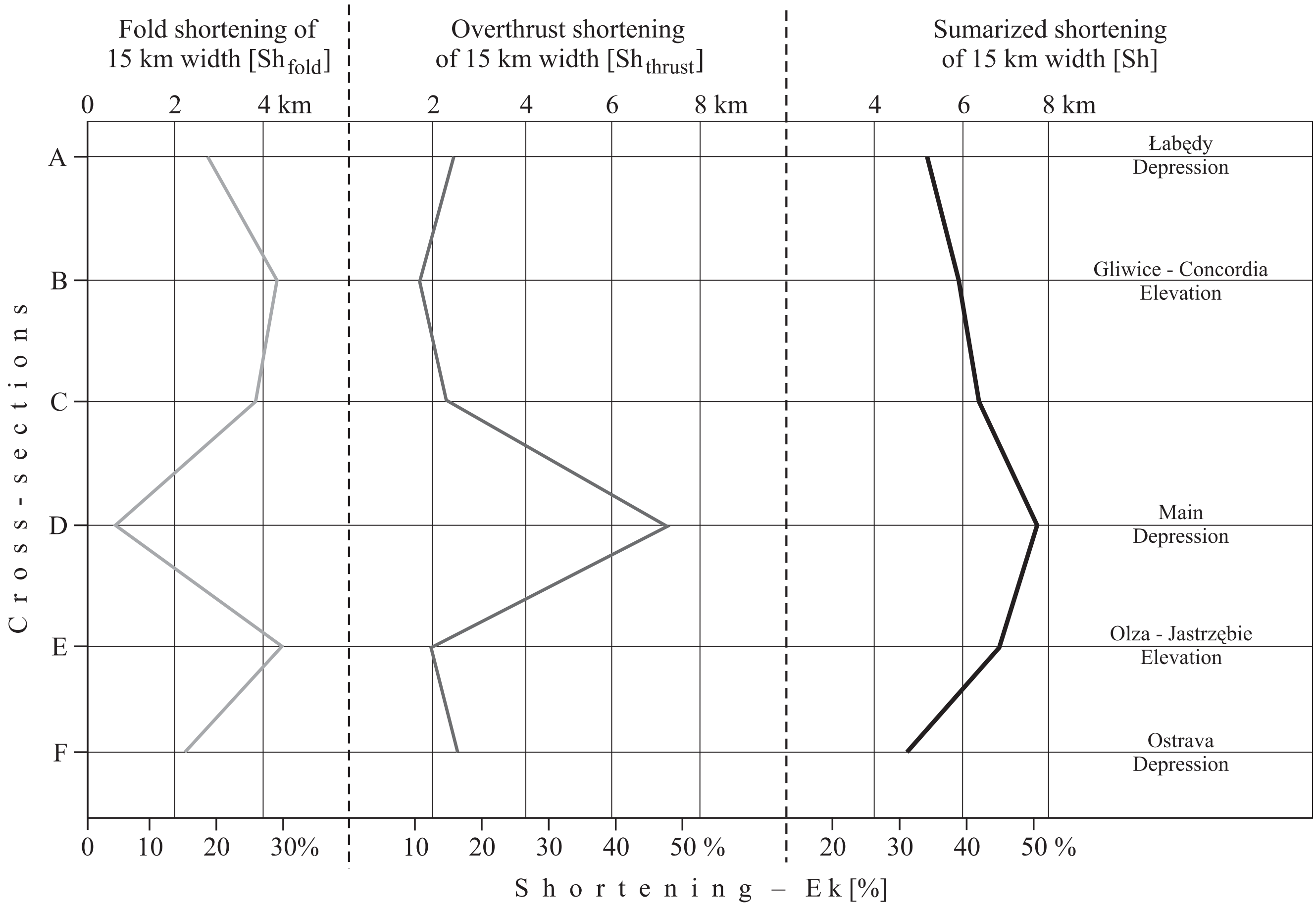

Fig. 6. Plots of the layer parallel shortening in the fold-and-thrust belt of the western part of the USCB in the area 15 km wide

accommodated by the folding and thrusting (up to 53 per cent) does not record small-scale deformation structures such as thrust rocks, shear zones, slip of layers (interstate) and stylolites etc. which are accommodating as much as 25 per cent of the total shortening along the line of a cross-section (McClay, Ed., 1992). Average shortening is about 40% (plus 25%) and increases westward in the Moravosilesian Zone. The Kyjovice beds are strongly folding and thrusting in Stará Ves village on extension between the Ostrava depression and Kopřivnice elevation (Aust *et al*., 1997) where the fold shortening is about 55% (plus 25%).

CONCLUSIONS

In general, the basic pattern of the rock motion of the USCB was the shortening by Carboniferous coal-bearing molasse displaced horizontally in two directions: first from the north and dominant second from the west. Most probable, the structural shortening is above 5–8 km in the fold-and-thrust belt of the USCB, and between the USCB and the Šternberg Zone — above 50 km, base on the medium shortening of 60% in the Moravosilesian Fold Zone.

The intensity of folding effects gradually decreases in the east direction in the fold-and-thrust belt of the USCB, and disappears in a short distance east of the Orlová–Boguszowice–Gliwice thrust. This belt evolved from flexural bending during complex inversion tectonics (Fig. 7). Structural cross-sections of the fault-and-thrust belt illustrated the two principal inversion processes at the margins of collisional type where strike slip fault system subsequently was incorporated in the thrust front, and developed along the Šternberg flower structure (Grygar, Vavro, 1995) with repeated episodes of transpresion and transtension (Fig. 7B). First positive inversion tectonics, thicker Devonian and Early Carboniferous flysch rocks of the Moravosilesian geosyncline or syn-rift basin occured on the upthrown side of positively inverted flexures, such as anticline-like uplift formed by pre-orogenic inversion of thick hanging-wall Culm series (Fig. 7B). Second negative inversion tectonics, the initially slow increase in flexure or inversion faults displacement toward centre of subsiding cauldron-like coal basin that growing strata deposited during extensional negative inversion (geoanticline stage of basin developing) or syn-orogenic Asturian stage (Jura, 2001). During folding, compression was applied parallel to

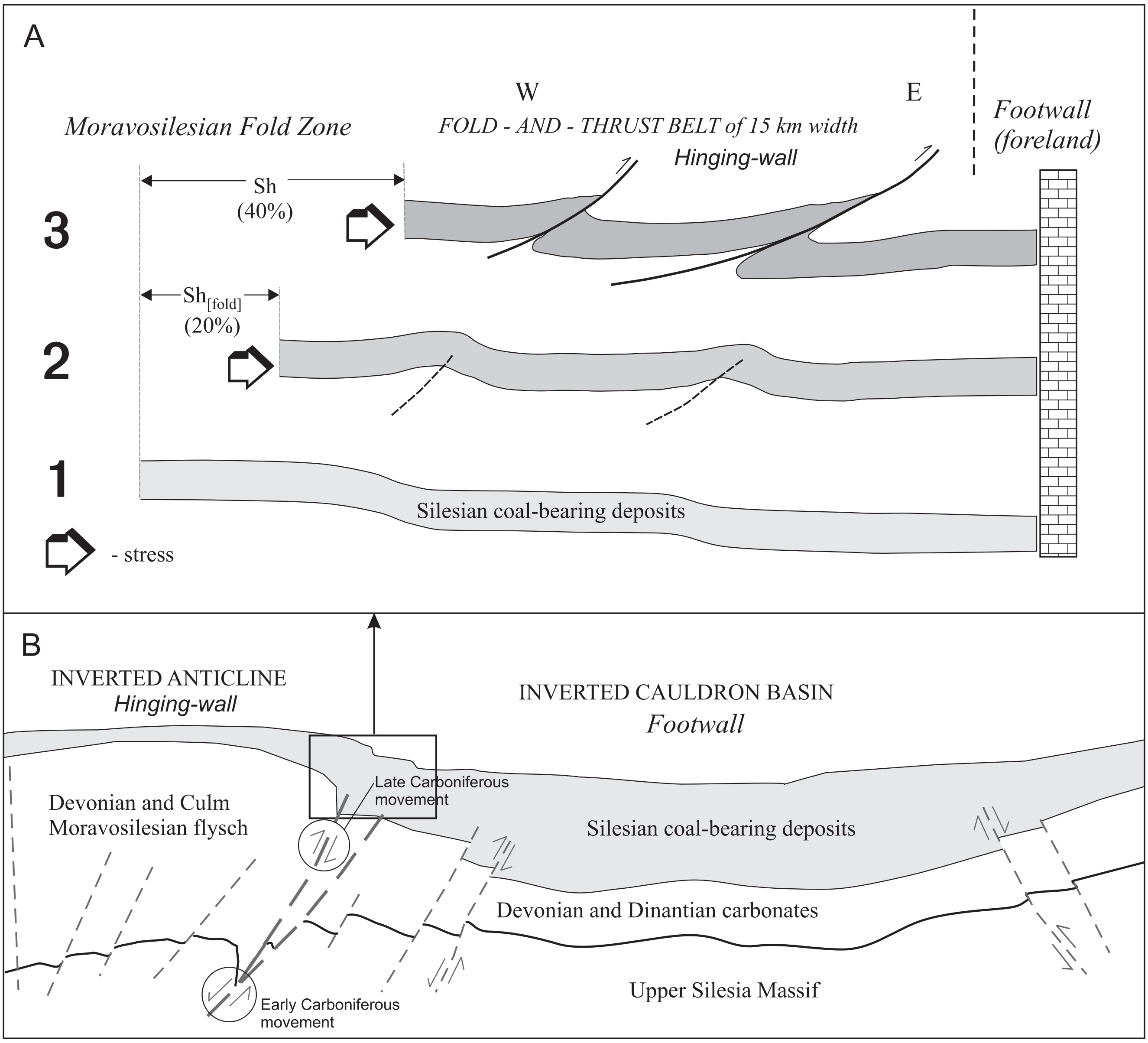

Fig. 7. A: Stages of evolution the fold-and-thrust belt in the western part of the USCB

1 — first deformation of subhorizontal bending in coal basin, *2* — folding and about 20% layer parallel shortening, *3* — folding and thrusting and about 40% shortening. For other explanations see Figure 6

B: Generalized palinspastic cross trough the Moravian–Upper Silesian–Cracow Variscides shows unfolded stage, with restored displacements during coal-bearing molasse deposited in the footwalls (downthrown side) of growth faults which subsequently were inverted

the coal-bearing layers that were of differing strengths. In the fold limbs, the move parallel to layering was restricted by flexural slip and subsequently by thrust along axial plane of anticlines (Fig. 7A).

At the margins of the Upper Silesian Cola Basin, normal faults positively inverted into the Permian Grabens showed the greatest reverse displacement during taphrogenic stage where the initial throw of normal faults or flexures was smaller (Fig. 7). This growing faulting was an important inversion movement in active hanging-wall uplift of fold-and-thrust belt in which thicker coal-bearing deposit were predicted in the footwall of normal growth faults.

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