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Structures associated with inversion of the Donbas Foldbelt (Ukraine and Russia)

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Abstract

The Donbas Foldbelt is part of the Prypiat–Dnieper–Donets intracratonic rift basin (Belarus–Ukraine–southern Russia) that developed in Late Devonian times and was reactivated in Early Carboniferous. To the southeast, the Donbas Foldbelt joins the contiguous, deformed Karpinsky Swell. Basin "inversions" led first to the uplift of the Palaeozoic series (mainly Carboniferous but also syn-rift Devonian strata in the southwesternmost part of the Donbas Foldbelt, which are deeply buried in the other parts of the rift system), and later to the formation of the fold-and-thrust belt. The general structural trend of the Donbas Foldbelt, formed mainly during rifting, is WNW–ESE. This is the strike of the main rift-related fault zones and also of the close to tight "Main Anticline" of the Donbas Foldbelt that developed along the previous rift axis. The Main Anticline is structurally unique in the Donbas Foldbelt and its formation was initiated in Permian times, during a period of (trans) tensional reactivation, during which active salt movements occurred. A relief inversion of the basin also took place at this time with a pronounced uplift of the southern margin of the basin and the adjacent Ukrainian Shield. Subsequently, Cimmerian and Alpine phases of tectonic inversion of the Donbas Foldbelt led to the development of flat and shallow thrusts commonly associated with folds into the basin. A fan-shaped deformation pattern is recognised in the field, with south-to southeast-vergent compressive structures, south of the Main Anticline, and north- to northwest-vergent ones, north of it. These compressive structures are clearly superimposed onto the WNW–ESE structural grain of the initial rift basin. Shortening structures that characterise the tectonic inversion of the basin are (regionally) orientated NW–SE and N–S. Because of the obliquity of the compressive trends relative to the WNW–ESE strike of inherited structures (major preexisting normal faults and the Main Anticline), in addition to reverse displacements, right lateral movements occurred along the main boundary fault zones and along the faulted hinge of the Main Anticline. The existence of preexisting structures is also thought to be responsible for local deviations in contractional trends (that are E–W in the southwesternmost part of the basin).

Keywords: Tectonics; Basin inversion; Donbas foldbelt; Compression

1. Introduction

The Donbas Foldbelt (DF) area belongs to a large intracratonic paleorift system that included the Dniepr–Donets Basin (DDB) that developed in Devo-

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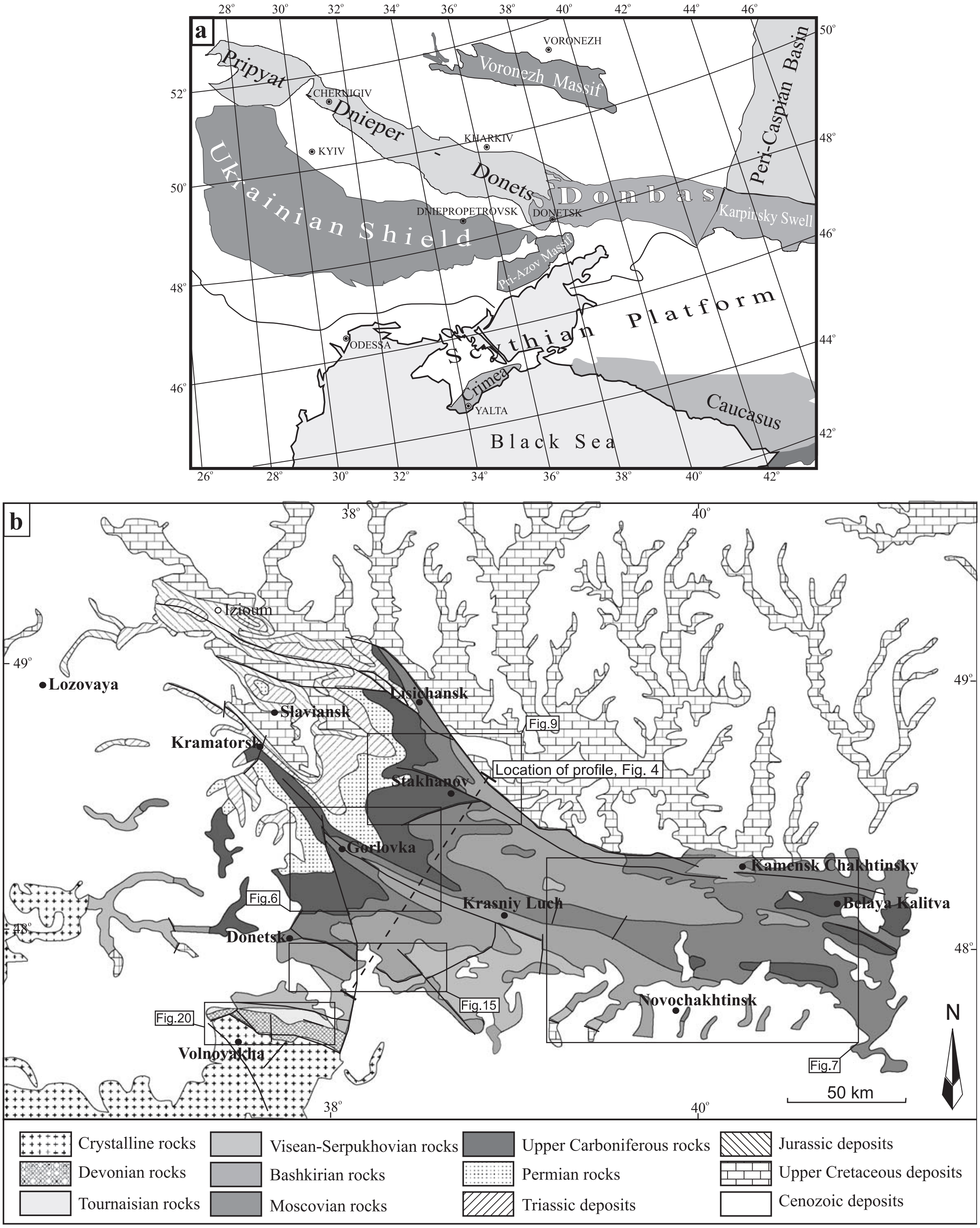

Fig. 1. (a) Location of the Donbas in the regional East European structural framework (in Stovba and Stephenson, 1999). (b) Geological map of the Donbas from the Geological Map of the USSR and Adjoining Water-Covered Areas (1983).

nian times, cross-cutting the East European Craton (EEC; Fig. 1a). Unlike other parts of the basin system, the DF suffered phases of severe inversion: relief inversion, i.e., uplift-topographic inversion, and also tectonic inversion, i.e., reverse displacements along prior normal-rift faults and fold-and-thrust belt development under compression/shortening. The DF is a typical inverted basin as described by Cooper and Williams (1989), i.e., an intracratonic extensional basin that later was compressionally deformed. Consequently, Palaeozoic strata crop out in the Donbas (Fig. 1b). In Permian times, the southern Donbas region and the Pri–Azov–Ukrainian Shield was strongly uplifted (compared to the adjacent regions, Stovba et al., 1996; Stovba and Stephenson, 1999) and a major Permian unconformity developed with increasing erosion toward the DF and its southern margin (with several kilometres of mainly Carboniferous strata eroded). Recent geophysical and geological data (Stovba and Stephenson, 1999; Saintot et al., 2000) revealed that the Early Permian uplift occurred in a (trans) tensional tectonic stress regime. Salt movements and active diapirism were widespread in the DDB during this (trans) tensional event (Stovba and Stephenson, 2002). It is likely that this has also occurred in the DF part of the basin system, including the growth of salt pillows and associated anticlinal structures (DOBREflection-2000 and DOBREfraction’99 Working Groups, 2002). These new data contradict the classical concept which stipulates that the Permian basin ‘‘inversion’’ of the DF was an effect of an Hercynian/Uralian orogenic belt ringing the margins of the EEC (Chekunov et al., 1992). Phases of compressive deformation, with the development of thrusts and folds, occurred later, during Cimmerian tectonogenesis (at Triassic–Jurassic times) with inversion of the northern marginal primary normal fault zones of the DF (Konashov, 1980; Popov, 1963; Sobornov, 1995; Stovba and Stephenson, 1999) and at the K/T boundary (Stovba and Stephenson, 1999; ‘‘orogenic’’ phase according to Popov, 1936, 1939; Stepanov, 1937). In this paper, based on field data, we will describe the structures at the micro- and mesoscale (outcrop scale) that developed during inversion phases in the postrift evolution of the DF.

2. Geological setting

From west to east, the intracratonic rift system of which the DF is a part can be subdivided into several

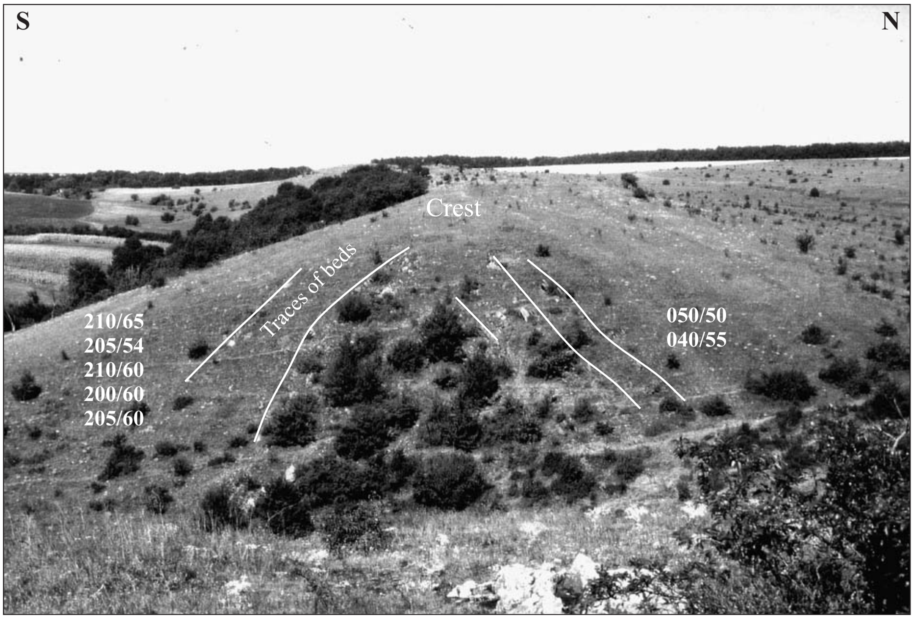

Fig. 2. View to the west of the hinge of the Main Anticline with N115-directed axis (Andreevka, located in Fig. 6a). The hinge forms a singular topographic high in the Donbas. On picture: dip directions and dips of beds (Middle Carboniferous strata).

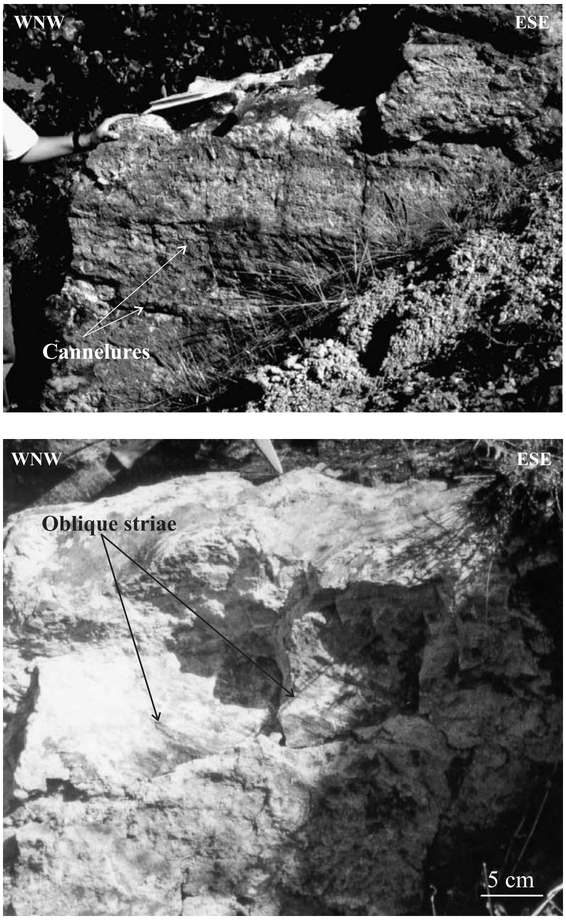

Fig. 3. N110 vertical strike-slip fault plane (undetermined sense) located exactly at the hinge of the N110 Main Anticline (at Andreevka, located in Fig. 6a).

segments: the DDB, the DF, Karpinsky Swell and Pri–Caspian Basin (Fig. 1a). The DF is one of the deepest rifts in Europe, filled with 20 km of sedi-

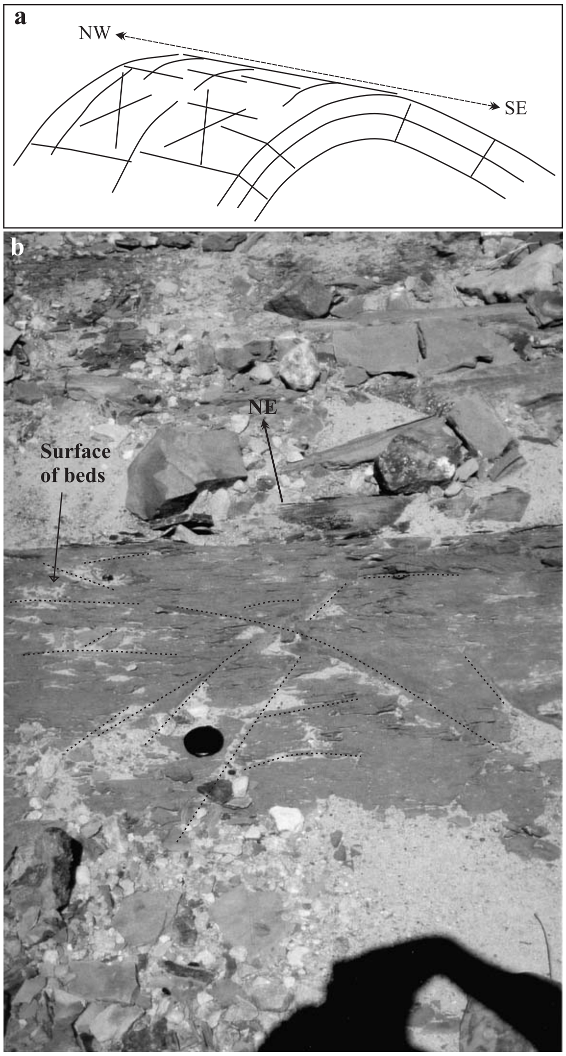

Fig. 5. (a) Scheme of system of joints which developed on the limbs of the Main Anticline. (b) Conjugate system of shear joints developed on the northeastern limb of the NW–SE-directed anticline (Nikitovka ore field, located in Fig. 6a).

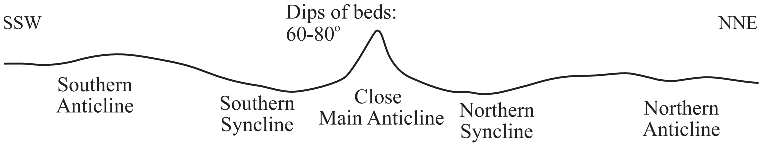

Fig. 4. Schematic cross-section across the DF perpendicular to the MA axis, following the Bashkirian stratigraphic beds (located in Fig. 1b, after John and Versloot, 2001).

ments, comprising mainly Carboniferous strata (Chirvinskaya and Sollogub, 1980). It is bounded to the south by the Pri–Azov Massif–Ukrainian Shield and to the north by the Voronezh Massif.

Previous studies at the scale of the DF and adjacent DDB, based on seismic line analyses (Stovba and Stephenson, 1999), have confirmed that rifting was characterised by several phases of stretching: in Late Devonian times (Frasnian–Famennian, Kusznir et al., 1996a,b; Alekseev et al., 1996), in Visean times (Chekunov et al., 1993; Stephenson et al., 1993), in Serpukhovian times and in Early Permian times. Deep WNW–ESE-trending faults form the southern and northern Devonian rift-marginal fault zones of the DF (Sollogub et al., 1977). Devonian continental rifting was accompanied by intense volcanic activity possibly associated with a series of mantle plumes (Wilson and Lyashkevich, 1996; Wilson et al., 1999). Extensively studied Middle/Upper Devonian to Lower Carboniferous rocks crop out on the southern margin of the DF where they overlie crystalline basement rocks of the Pri-Azov Massif (Fig. 1). The Middle/Upper Devonian stratigraphic succession is characterised by syn-rift extrusive rocks, continental clastics (fluvial, lacustrine) with intercalated volcanoclastic units deposited in E–W-trending grabens and half-grabens. Early syn-rift activity was accompanied by the extrusion of basalts in mainly fissural eruptions (600 m thick). The thickness of exposed Middle/Upper Devonian deposits can reach 1800 m, depending on local variations in the quantity of volcanic rocks. The Devonian syn-rift sediments within the

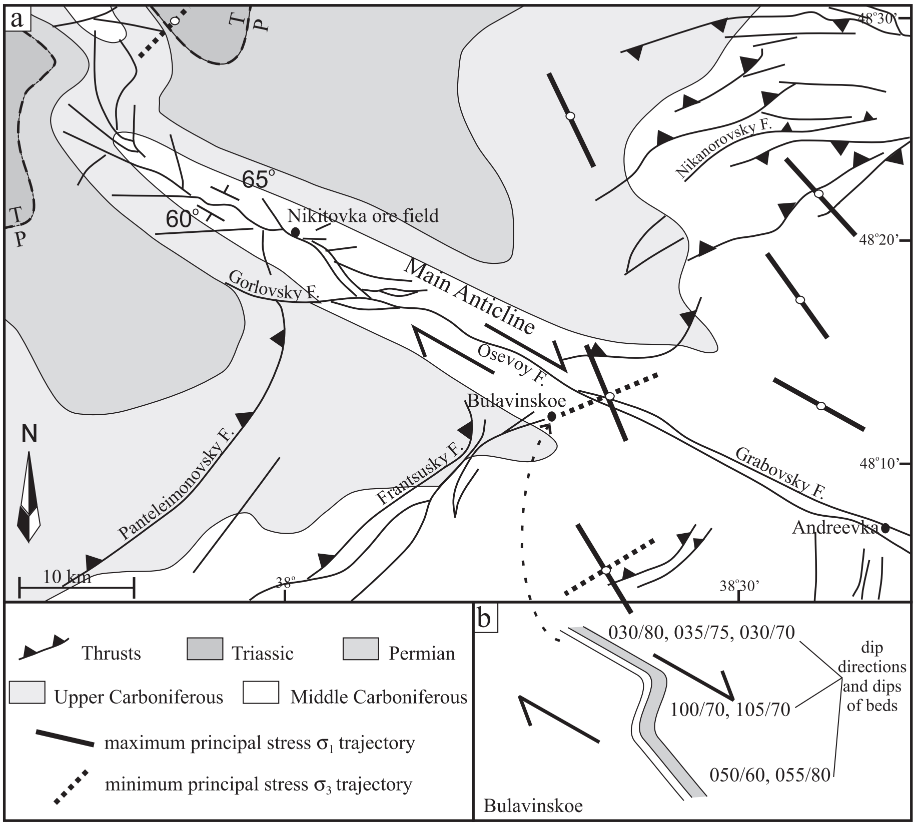

Fig. 6. (a) Paleostress field corresponding to the latest tectonic event recorded along the Main Anticline zone: a NW–SE compression along the Main Anticline (after Saintot et al., in press). (b) Scheme (vertical view) of a Z-shaped fold, with vertical axes, in the area of Bulavinskoe, probably developed with dextral movement along the faulted hinge of the MA. As background: extract of the Geological and Structural Map of the Donbas 1/500,000 (1985).

axial zone of the DF could reach 5-km thickness (Stovba and Stephenson, 1999). The overlying upper Famennian to lower Visean thick, shallow water carbonate platform sequence (1000 m) records an epoch of tectonic quiescence. Evidence of the early Visean rift reactivation is amply manifested near the southern margin of the DF as volcanism (trachytic), renewed normal faulting and subsequent tilting of blocks, rapid development of local topographic variations and syn-sedimentary normal faults in the upper part of the lower Visean strata (cf. McCann et al., 2003). The thickness and lithology of Lower Carboniferous strata at the axis of the DF is not constrained.

The rest of the Carboniferous corresponds to the phase of postrift subsidence in the DF and in the DDB, interrupted by a mild extensional reactivation in middle Serpukhovian times (cf. Stovba et al., 1996; Van Wees et al., 1996). Carboniferous sedimentation reflects frequent sea-level variations, with alternating shallow-marine (offshore, littoral) and continental facies (coal beds and sandy clay), including erosional hiatuses (e.g., Dvorjanin et al., 1996; Izart et al., 1996). These middle and Upper Carboniferous rocks are well exposed in the DF (Fig. 1b). The total thickness of the middle Carboniferous (Moscovian and Bashkirian sequences) is 2200–7000 m, of the Upper Carboniferous, 2500 m.

Permian strata are absent within the DF. Lower Permian sediments exist along its northwestern margin (in its transition to the DDB). Coastal–continental and some shallow-marine facies are typical of the Permian sand–shales and sparse intercalated limestones and coals. Five to seven rock-salt layers, interstratified with clastic-carbonate rocks and beds of gypsum, anhydrite and dolomite compose the Asselian succession. A thick layer of salt is also present in the Sakmarian succession. The DF was uplifted in the Early Permian, especially its southern margin. Recent studies have shown that fault deformation of Permian age is normal in style and that the uplift occurred under a transtensional–extensional stress regime accompanying a postrift tectonic reacti-

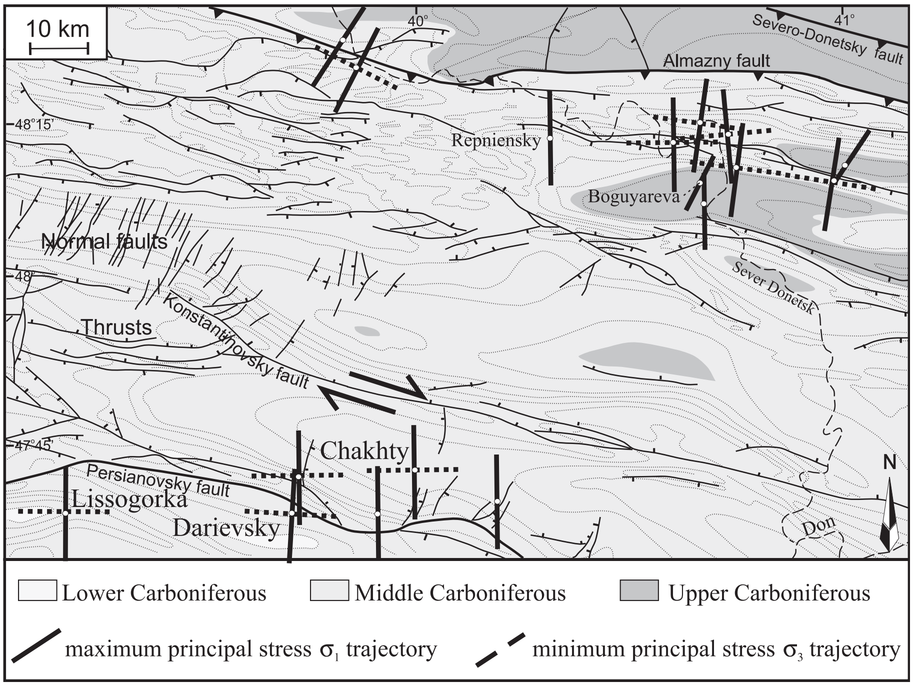

Fig. 7. Compressional paleostress field with N–S to NE–SW trending σ_1 axis recorded in the eastern ending of the Donbas (Russia) in Carboniferous and Upper Cretaceous strata (after Saintot et al., in press). As background: extract of the Geological and Structural Map of the Donbas 1/500,000 (1985).

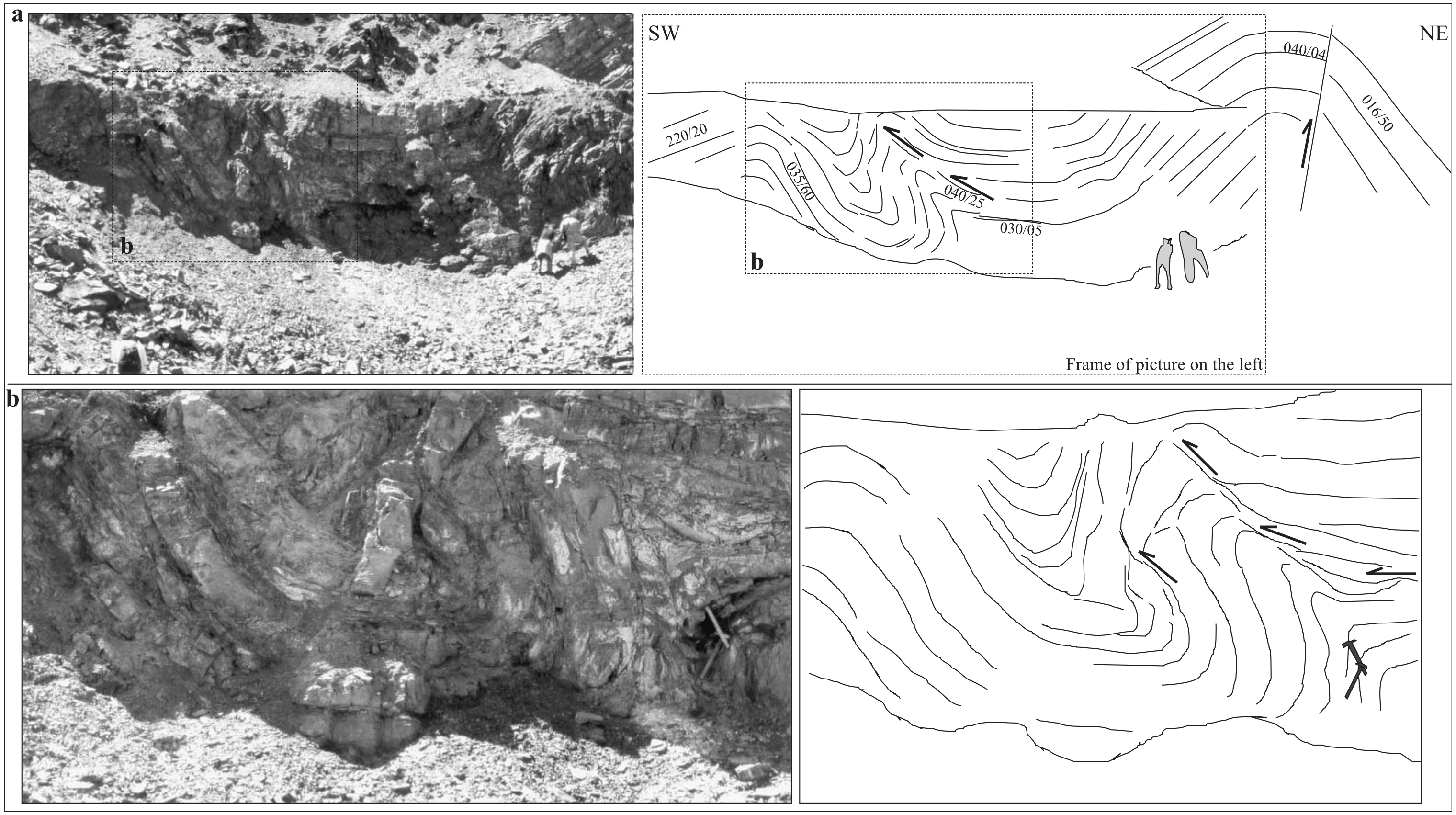

Fig. 8. (a) Picture and corresponding scheme of compressional structures (thrust and folds) at the hinge of the Main Anticline (Nikitovka Ore Field, located in Fig. 6a), with a SW predominant vergence (dip directions and dips of beds are on the scheme). (b) Detailed picture and corresponding scheme of the highly deformed hinge of the MA.

vation (Stovba and Stephenson, 1999). Gavrish (1985) and Chekunov (1994) argued that the Permian uplift could have been due to renewed activity of a mantle diapir.

Little Mesozoic sediment is preserved within the DF. Nearby, in the DDB, marine and continental sediments "close to" platform type (Chirvinskaya and Sollogub, 1980) compose the Mesozoic strata. In the northwestern margin of the DF, Triassic sediments up to 150–200 m thick are present in a narrow strip, and are commonly found close to Palaeozoic outcrops (Belov, 1970). Jurassic sediments are absent in the same zone. Marly chalks and chalks make up most of the Upper Cretaceous succession, as in the surrounding platforms. Upper Cretaceous sediments are up to 500 m thick on the southern margin of the DF, where they unconformably overlie Palaeozoic rocks and crystalline basement. On the northwestern margin of the DF, angular unconformities have been reported at the Triassic/Jurassic and Jurassic/Cretaceous boundaries (Konashov, 1980; Eisenverg, 1988). The occurrence of Cimmerian tectonic inversion is observed where Mesozoic sediments are preserved (Popov, 1963; Konashov, 1980); as recorded through the offsets of Triassic beds along the inverted major fault zones of the northern margin (Sobornov, 1995; Stovba and Stephenson, 1999). Cimmerian compression is intensively recorded in the Karpinsky Swell (Sobornov, 1995). Tectonic inversion also occurred at the end of Cretaceous times (probably at the K/T boundary), with development of localised folds commonly associated with thrusting (Stovba and Stephenson, 1999). This deformation stage was recognised in earlier studies as an "orogenic" phase but involving relatively minor reactivation of compressive structures thought to be related to the main foldbelt development in the late Palaeozoic (Popov, 1936, 1939; Stepanov, 1937).

Upper Cretaceous and older rocks are unconformably overlain by Palaeogene (sands, clays, marls) and Neogene (sands with clayey interbeds) units. The Cenozoic succession can be up to 400 m thick in local depressions developed over salt diapirs in the northwestern part of the DF (Eisenverg, 1988). Note that Popov (1936, 1939, 1963), Stepanov (1937) and Milanovsky (1987) report the existence of a Paleocene orogenic phase.

3. Structures associated with postrift tectonic activity of the DF

Two main structural trends exist in the DF. The first one is WNW–ESE and corresponds (1) to the

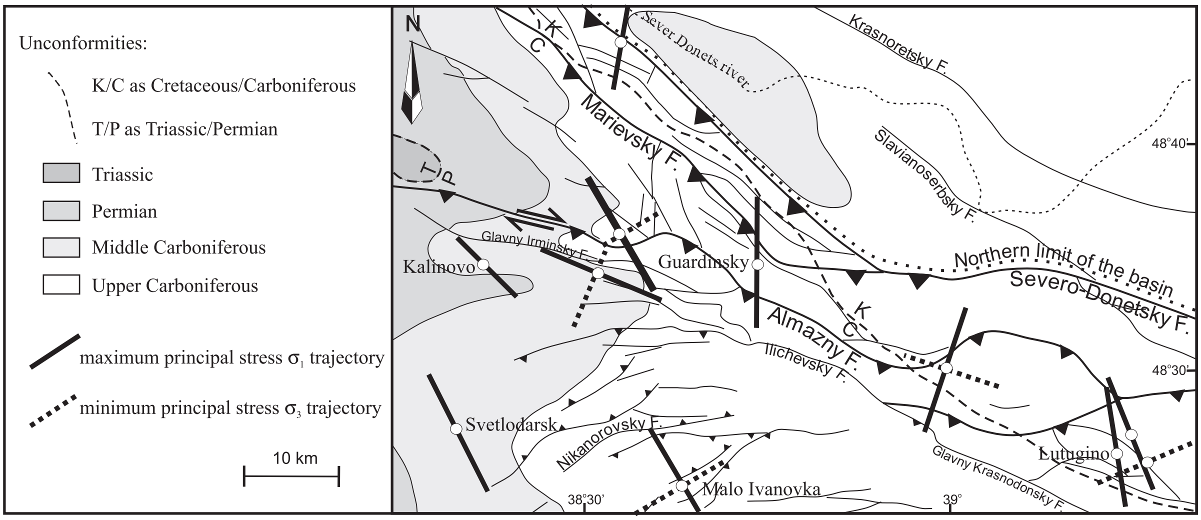

Fig. 9. Compressive paleostress trends in the northern zone of the Donbas: the record of a N–S to NW–SE compression as the last tectonic event (after Saintot et al., in press). As background: extract of the Geological and Structural Map of the Donbas 1/500,000 (1985).

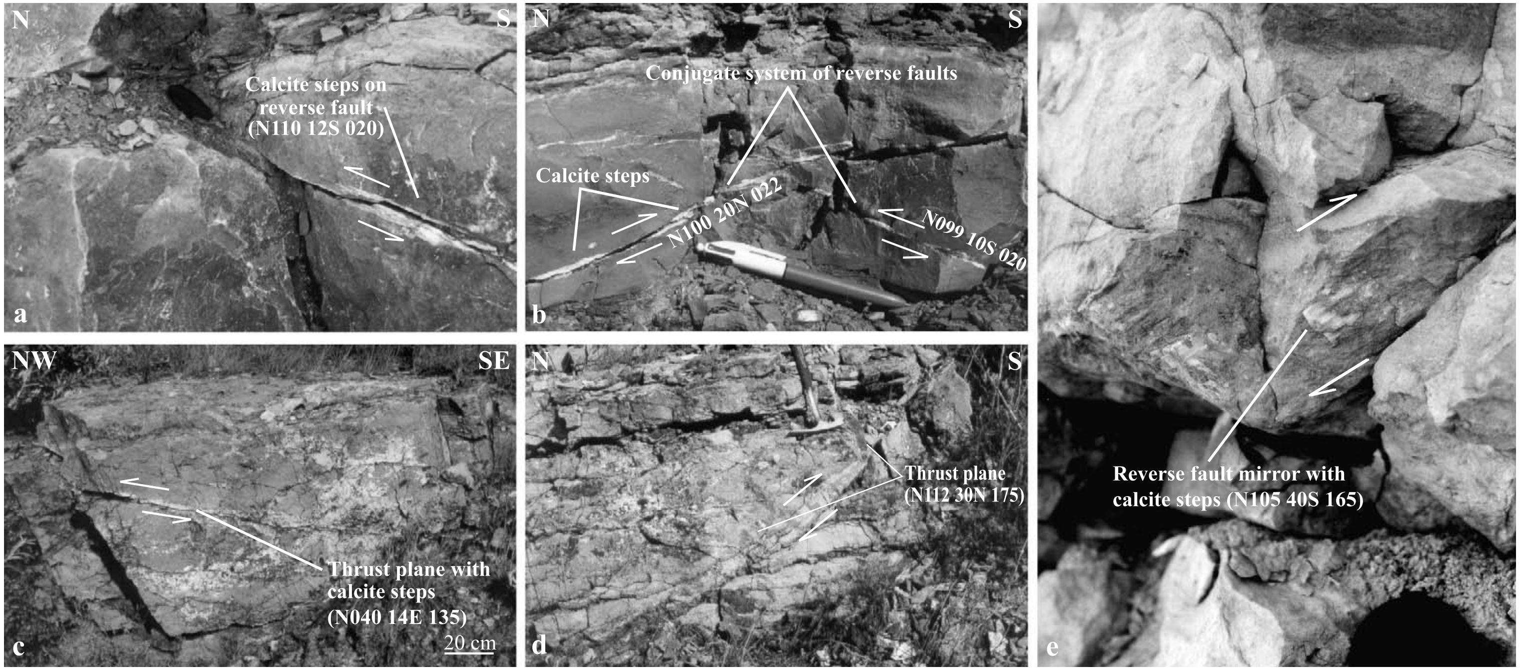

Fig. 10. (a and b) Reverse microfaults in Ghezlian limestones (Bogurayeva quarry, located in Fig. 7) with calcite steps on mirrors, consistent with a NNE–SSW pressure axis. (c and d) Reverse faults developed in Upper Carboniferous limestones (south of Kalinovo, located in Fig. 9) consistent with a NNW–SSE to NW–SE pressure axis. (e) Oblique reverse fault developed under NNW–SSE compression in Ghezlian limestones (Svetlodarsk, located in Fig. 9). Keys for fault measurements: first number as the strike azimuth, second number as dip of the fault plane with dip direction (N, E, S, W), third number as strike of the striae (if flat fault plane).

axis of the rift and associated major normal faults and (2) to the singular Main Anticline (MA, and described below) and gentle fold trends, north and south of the MA. The second one varies from NE–SW to N–S and corresponds to the latest folds and thrusts. In the next sections, we will describe the structures associated with the inversion of the DF. We choose to present them approximately according to three different structural zones of the DF, as defined by Popov (1963). The first zone is the MA zone; the second is the northern zone, north of the MA; and the third one is south of it.

We will also briefly report paleostress trends related to compressional stress regimes, i.e., inversion of the DF, which have been reconstructed through a large paleostress study described in detail elsewhere (Saintot et al., in press) as is the method used to compute paleostress tensors (Angelier, 1990, 1994). For information, the detailed paleostress analyses of the DF was based on the inversion of 3500 small-scale brittle tectonic data (i.e., fault slip data sets to compute stress tensor but also tension gashes and stylolitic peaks to determine the strike of one of the principal stress axes) collected at 135 sites, in Proterozoic, Devonian, Carboniferous, Permian and Mesozoic rocks.

3.1. Main Anticline and gentle WNW–ESE fold development

The WNW–ESE Main Anticline (MA) is the largest and most pervasive close to tight fold of the DF (its hinge forms a crest in the DF, Fig. 2). It is an almost symmetric structure with steeply dipping limbs (60–80°), complicated by faults as thrusts (or oblique thrusts) and as oblique normal and strike-slip faults developed at its hinge (Lutuguin, 1956, Fig. 3). The MA is bordered by two gentle synclines and anticlines of the same trend (Fig. 1b). Schematic cross-sections across the DF and perpendicular to the MA show the uniqueness of the DF with this single, close to tight anticline, located close to or directly above of the previous rift axis (Fig. 4). In the easternmost Russian part of the DF, the MA structure attenuates somewhat, with limbs dipping 45–60°. The MA is believed to continue eastward, beneath up to 1500 m of Mesozoic platform cover sediments in the area of the Karpinsky Swell (e.g., Popov, 1963; Belov, 1970; Garetsky, 1972). During our field studies, we have observed sets of joints on its limbs that are directly related to the growth of the MA (Fig. 5). The orientations of all these brittle structures are consistent with the geom-

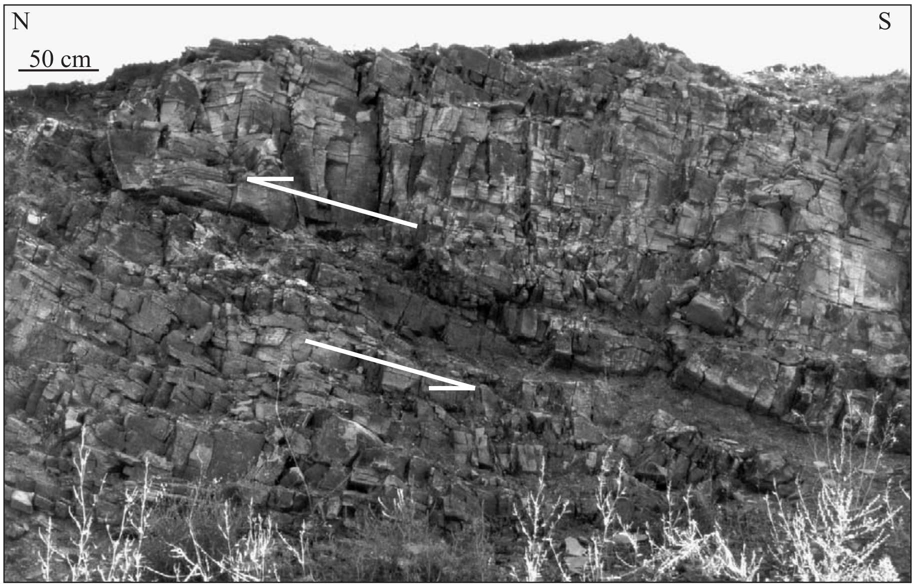

Fig. 11. Thrust plane developed in Lower Moscovian sandstones (Repniensky Quarry, located in Fig. 7), under a NNW–SSE- to NW–SE-directed compression (measurements on the thrust plane: N075 42S 135, N072 44S 158). Keys for fault measurements in caption of Fig. 10.

etry of the fold, and with the orientations of 'internal' stresses that exist during fold development in general, and herein, during the formation of the MA (Fig. 5a). For example: (1) joints are systematically perpendicular to the bedding planes, (2) joints developed parallel and perpendicular to the fold axis, (3) conjugate shear joints trend 60° from the fold axis (Fig. 5a and b). No deviation of the orientations of brittle structures seems to exist relative to the geometry of the fold and, therefore, it can be argued that no regionally acting stresses (which might have developed oblique structures relative to the fold geometry) occurred during the formation of the MA.

Secondary structures developed after initial MA growth during the latest phase of compressive tectonism. They have a well-defined signature and are clearly superimposed on the primary MA fold. Dextral movement has been recognised along the fault zone at the hinge of the MA (Maidanovich and Radzivill, 1984; Belichenko et al., 1999; Privalov et al., 2000). Reconstructed paleostress trends (Figs. 6 and 7) are also consistent with dextral displacement along the fault at the hinge of the MA (Saintot et al., in press) with a NW–SE (Fig. 6a) to N–S (Fig. 7) trend of σ_1 in a compressional regime. The Konstantinovsky Fault zone lies along the MA hinge (in the Russian DF, Fig. 7) and it is a right lateral strike-slip fault according to associated fault patterns at its western termination (NNE–SSW striking normal fault pattern north of its trace and E–W[?] striking reverse fault

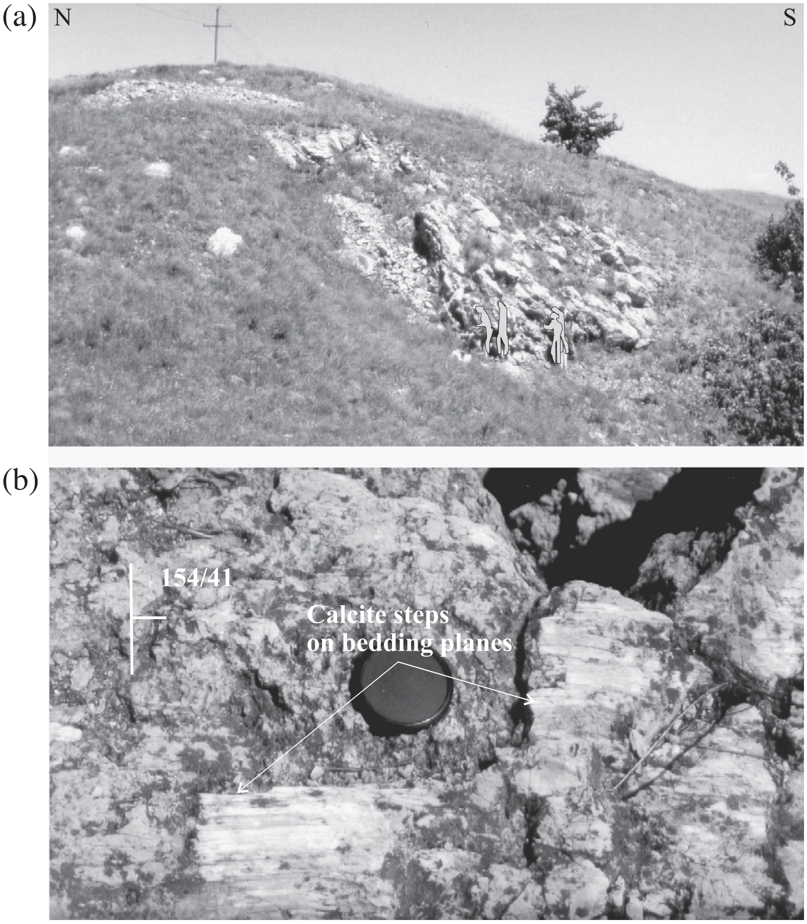

Fig. 12. (a) Anticline with N060 axis (top) with (b) reverse slips (directed N150–N170) on bedding planes (S_0 154/41), near Lutugino (located in Fig. 9).

pattern south of it, Fig. 7). At Bulavinskoe (located in Fig. 6a), we have observed a typical Z-shaped fold with nearly vertical axes (Fig. 6b), which could have developed during dextral movement along the hinge of the MA. Dextral movement was also accompanied by reverse movement along the hinge of the MA. Fig. 8 shows examples of shortening in the hinge of the MA that developed fold and thrust structures. The late structural development along the MA reveals a transpressive right lateral regime with a regional NW–SE- to N–S-trending σ_1 paleostress axis.

3.2. Northern zone: from the Main Anticline to the northern marginal fault zone

Regional (crustal scale) and shallow refraction seismic data indicate that the normal faults of northern rift margin have been inverted (Belokon, 1975; Ryabokon, 1975; Mikhalev and Borodulin, 1976). The present-day structures of the northern margin of the DF form major north-vergent thrusts (Figs. 7 and 9). The offsets on thrusts can be substantial (1000–2000 m), and as great as 4000 m (Popov, 1963). To the northwest, towards the uninverted part of the Donets segment of the DDB, offsets decrease and fade out. According to Popov (1963) and Zhykalyak et al. (2000), thrusting was episodic, with movements occurring during major tectonic phases at the end of Palaeozoic, in the Mesozoic, and the Cainozoic. Going from the margin to the MA, we observed numerous mesoscale folds and thrust faults. We have reconstructed the paleostress field leading to the inversion of the northern boundary faults and to the formation of mesoscale folds and thrusts in the sedimentary cover (Figs. 7 and 9). Generally, deformation appears to have occurred in a compressive regime except at some sites where a strike-slip stress field is recorded. Fig. 10 shows examples of reverse microfaults that allowed the determination of the attitude of the stress axes in a transpressive paleostress field. According to the orientations of the maximum principal stress axis (Fig. 9), we can assume that, in addition to reverse displacements, some dextral component of movement occurred along the major thrust zones. The curved and even lenticular traces of the thrust planes as a whole (well observed on the map of Fig. 9) could have resulted from such an applied transpressive stress field.

South of the north-vergent Almazny thrust (located in Figs. 7 and 9), secondary mesoscale structures developed as a north-vergent thrust at Repniensky (Fig. 11) or as an anticline with slip parallel to bedding planes at Lutugino (Fig. 12). Both structures possess kinematic indicators indicating a NNW–SSE trend of

Fig. 13. Thrust plane in Bashkirian Moscovian sandstones (at Guardinsky, located in Fig. 9) developed in a nearly N–S compression (measurements on the plane: N120 20S 010; N100 28S 178; N100 32S 160). Keys for fault measurements in caption of Fig. 10.

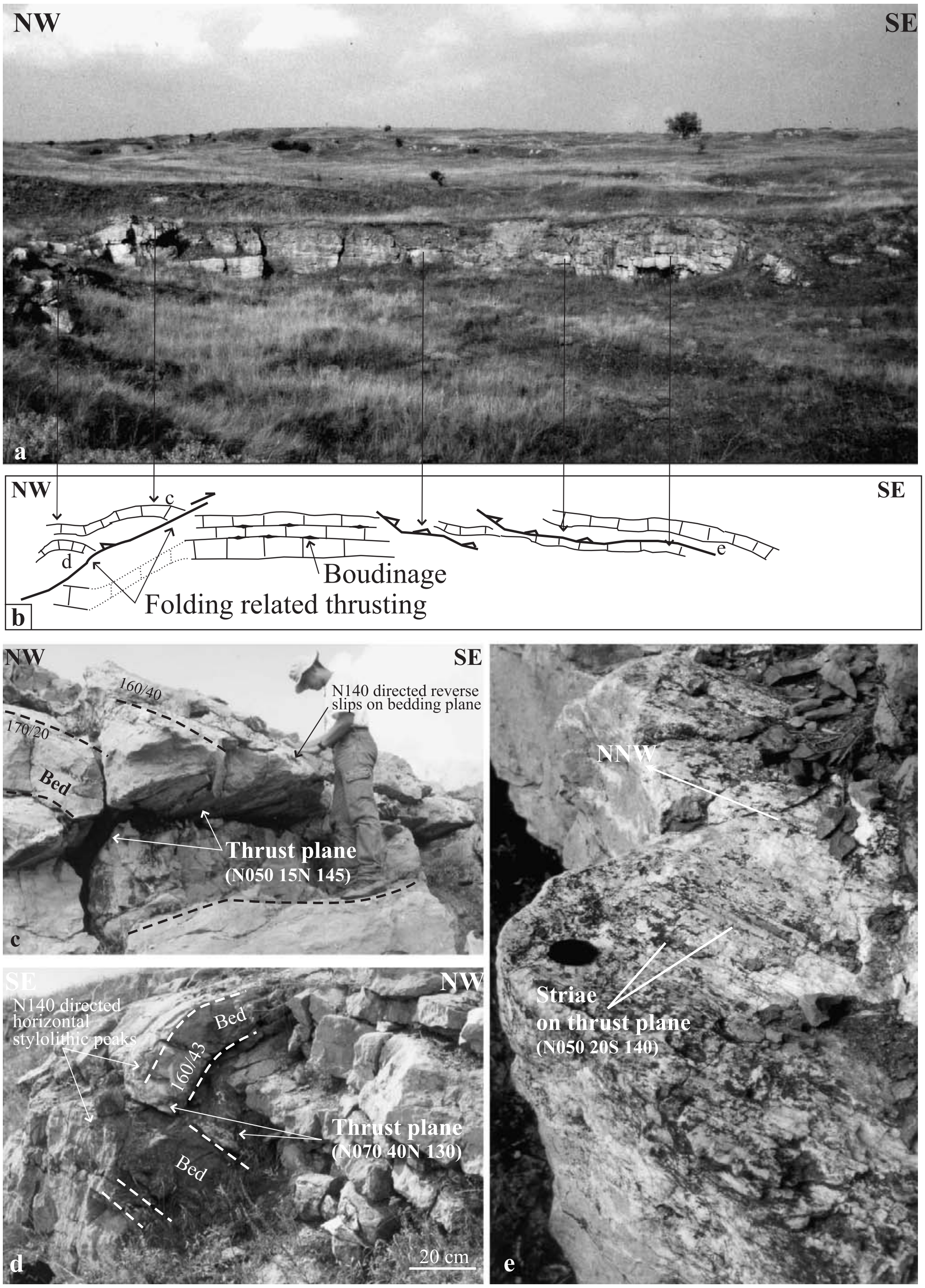

Fig. 14. (a) General view of a conjugate system of thrusts developed in Moscovian Limestones (at Malo Ivanovka, located in Fig. 9), with reverse slips (commonly striae on calcite steps) directed NW–SE. (b) General scheme with location of (c), (d) and (e). (c and d) Detailed view of the southeast-vergent thrust plane and associated fold. (e) Striae on the northwest-vergent thrust plane. Dip directions and dips of beds are indicated and keys for fault measurements as in caption of Fig. 10.

contraction. The same contraction is recorded by the development of a north-vergent thrust plane at Guardinsky (Fig. 13), south of the major Marievsky thrust (located in Fig. 9), and at Malo Ivanovka (located in Fig. 9) with the formation of a NE–SW anticline flanked by two conjugate thrust planes (Fig. 14).

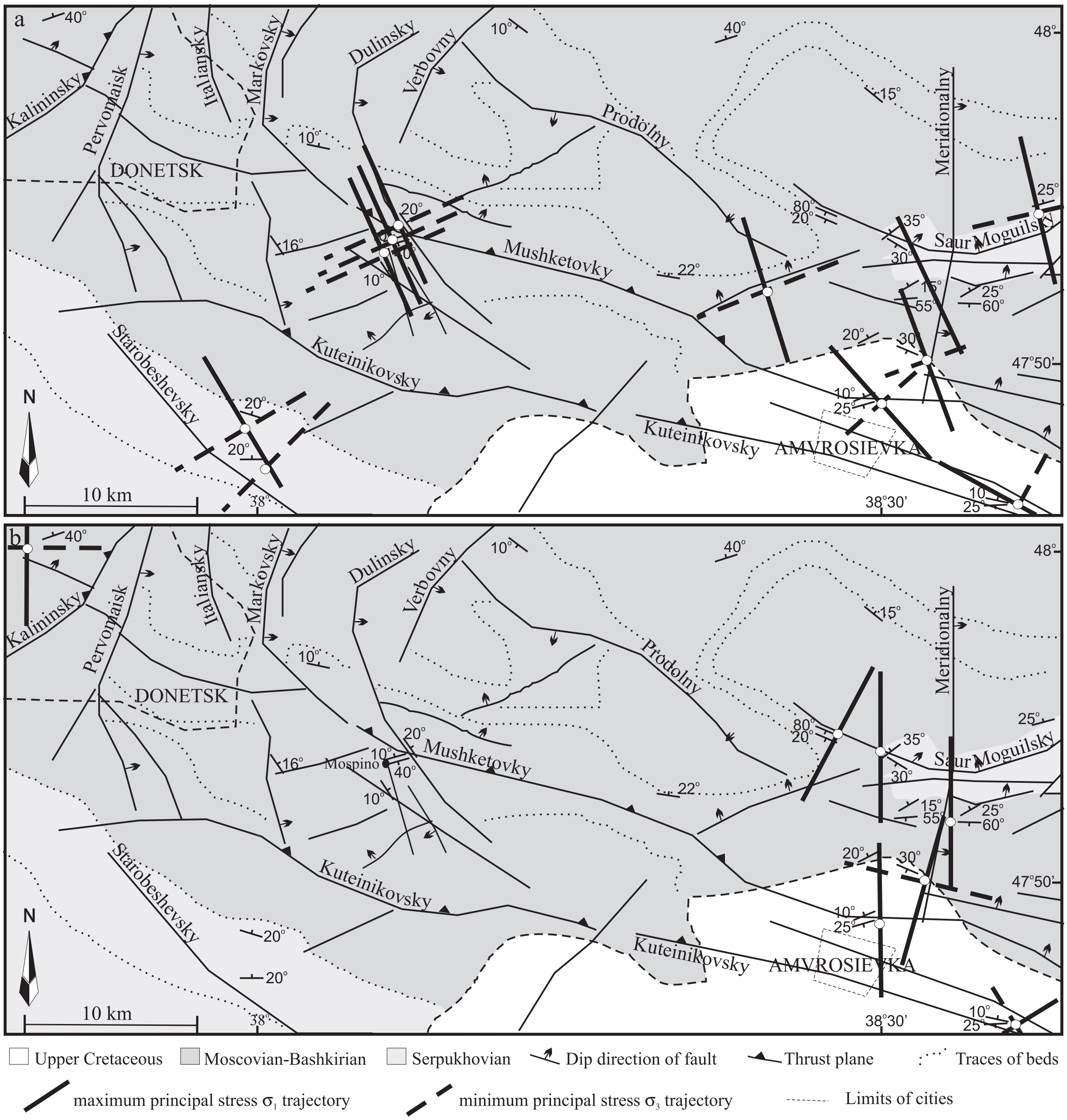

Fig. 15. Compressive paleostress states in the southern zone of the Donbas Foldbelt recorded in Carboniferous and Upper Cretaceous series (after Saintot et al., in press). (a) NW–SE trend of compression and (b) N–S trend of compression. As background: extract of the Geological and Structural Map of the Donbas 1/500,000 (1985).

These compressive structures are flat thrust planes (dipping 40°), mostly north in vergence and having associated folds.

3.3. Southern zone: from the Main Anticline to the southern margin

Most of southern zone of the DF is unconformably overlain by Upper Cretaceous sediments, which are not preserved in the axial part of the DF (cf. Fig. 1b). The map in Fig. 15 shows structural peculiarities encountered in the southern zone of the DF. Near the city of Donetsk is a zone of transverse faults (Kalininsky, Pervomaisk, Markovsky faults; cf. Fig. 15 from Donetsk to the southeast). Gentle WNW–ESE folds are overprinted by a widely developed system of NE–SW to E–W folds. At Mospino (located in Fig. 15), we have studied a flat thrust plane upon which folded structure developed (Fig. 16). Kinematic indicators reveal a NNW–SSE direction of contraction. In this area, the NNW–SSE direction of contraction is well recorded in Carboniferous and Upper Cretaceous strata by development of reverse and strike-slip microfaults (Fig. 15a, Saintot et al., 1999, in press). The reconstructed paleostress field presented in Fig. 15 indicates a transpressive stress regime. We can assume that some of the transverse major structures as the Kalininsky fault zone (in Fig. 15) were oblique thrusts under this paleostress field.

A second N–S to NNE–SSW trend of compression is recorded in the same area (Fig. 15b) as well as along the southern zone of the Russian DF (Fig. 7). Figs. 17 and 18 are examples of brittle structures that developed under the related transpressive paleostress field. At Chakhty Quarry (located in Fig. 7), the strike-slip regime is recorded by synchronous N–S-directed tension gashes and N–S-directed stylolitic

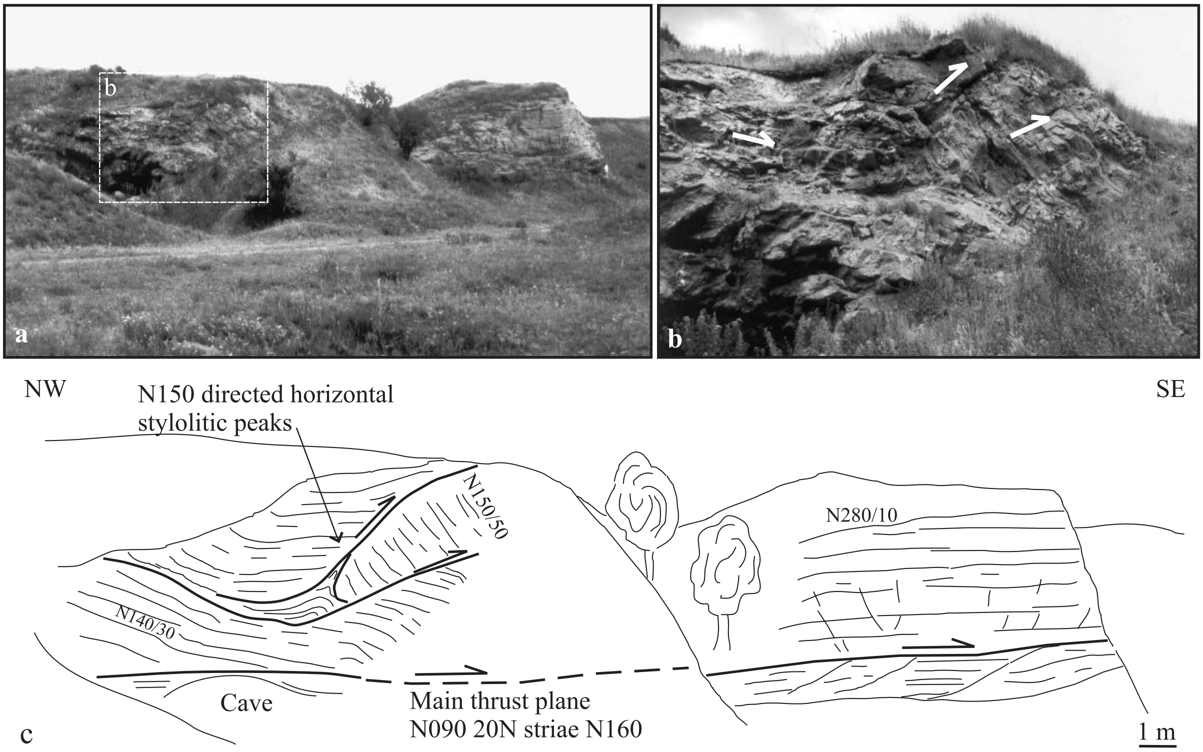

Fig. 16. Structures developed under a NNW–SSE-directed compression and observed in Bashkirian sandstones (at Mospino, located in Fig. 15). (a and b) Pictures of the outcrop and (c) interpretative scheme. Dip directions and dips of beds are indicated.

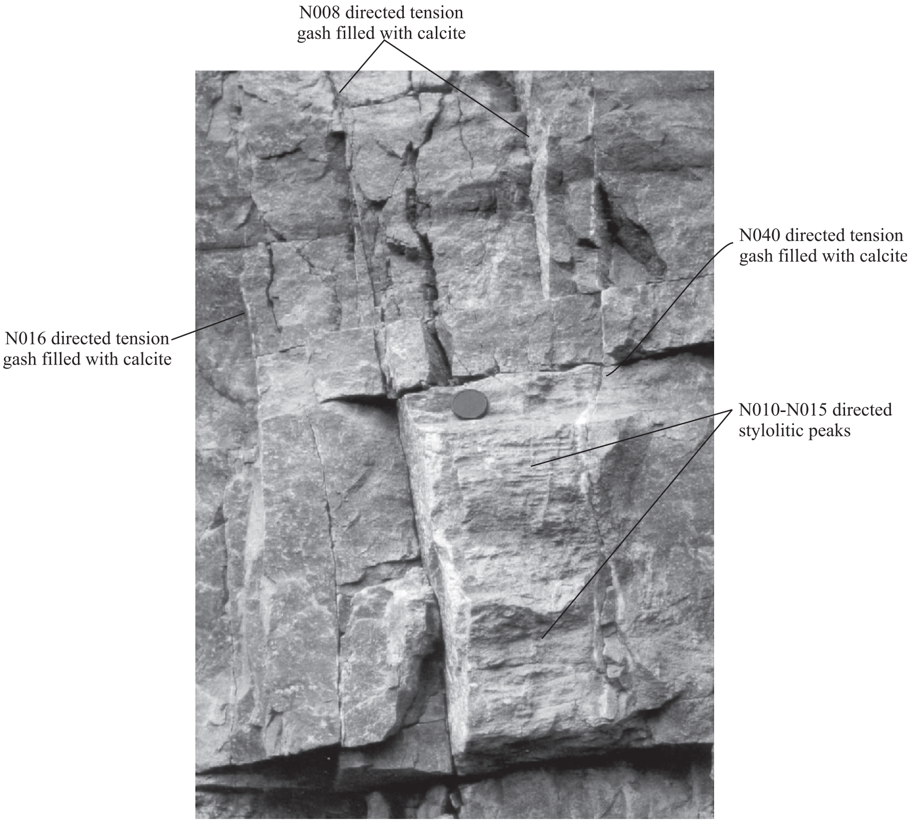

Fig. 17. Stylolitic peaks and tension gashes synchronously developed in Bashkirian limestones (Chakhty quarry, located in Fig. 7) under a strike-slip stress regime with an E–W tension axis (σ_3) and a N–S pressure axis (σ_1).

peaks (Fig. 17). Fig. 18 illustrates right lateral strike-slip faults in Upper Cretaceous chalks consistent with a NNE–SSW direction of contraction. Under the N–S to NNE–SSW trend of compression, the WNW–ESE-trending fault zones were therefore activated as south-vergent thrusts (Mushketovsky Fault, Kuteinikovsky Fault in Fig. 15, the Persianovsky Fault in Fig. 7). If we take into account the attitude of bedding planes close to the Saur Moguilsky fault zone (cf. Fig. 15), we observe that the dip directions of steeper beds (55–80°) are parallel to the direction of contraction. The tilting of beds, i.e., the renewed folding, could have occurred with reverse displacement along the Saur Moguilsky fault plane.

At the mesoscale, the occurrence of such flat thrusts associated with E–W to NE–SW folds is common in Carboniferous and Cretaceous rocks of the southern part of the DF and interferes with the previously developed WNW–ESE structural grain. Fig. 19 shows a close south-vergent anticline in Upper Cretaceous chalks. We may interpret it as an anticline developed upon a south-vergent thrust plane, under a NNE–SSW shortening. Such an anticline is also mapped in Carboniferous rocks (in Fig. 7 at Lissogorka). At this site, the direction of compression, i.e., the σ_1 stress axis, was reconstructed using reverse and strike-slip microfaults (as illustrated in Fig. 19 on the right) and is roughly perpendicular to the anticline axis.

At the regional scale, compared to the northern zone of the DF where thrusts are mostly north-vergent, the southern zone is characterised by south-vergent thrusts. The inversion of the DF has produced a fan-shaped development of thrusts.

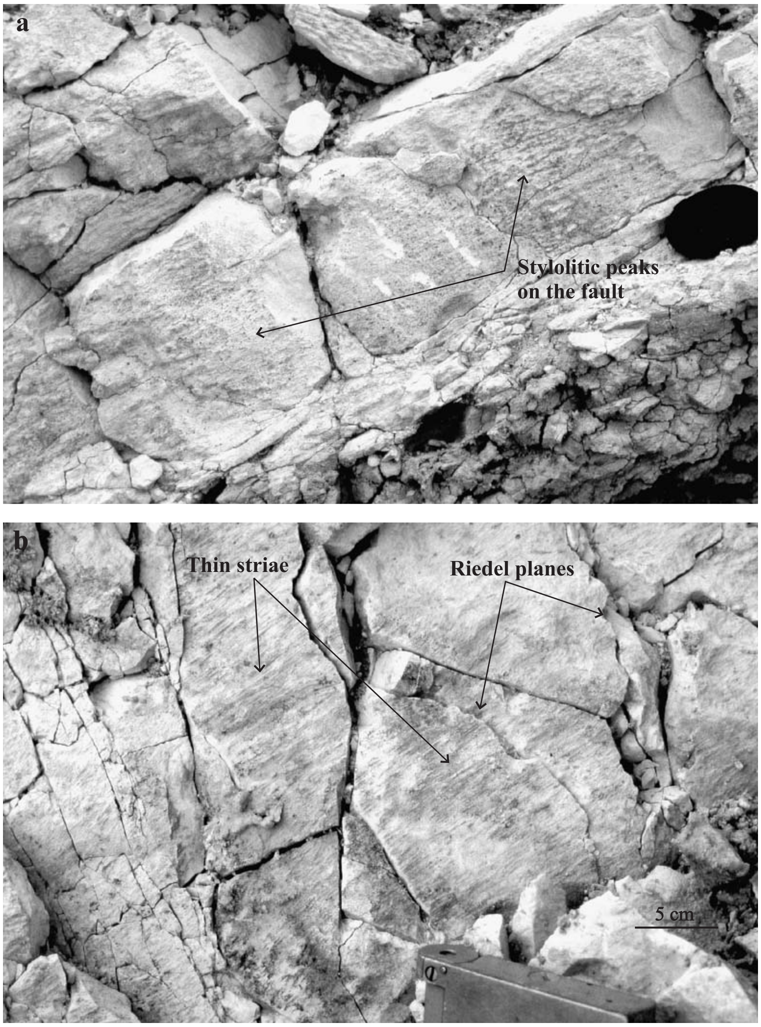

Fig. 18. (a) Right lateral strike-slip fault with stylolitic peaks and striae (measurement: N160 70E pitch and pitch direction of striae: 34S). (b) Right lateral strike-slip fault with thin striae and Riedel planes. These faults are both developed in Upper Cretaceous chalks (at Darievsky quarry, located in Fig. 7), under NNE–SSW compression and prior to tilting of beds. Note that the tilting of beds (due to folding) is also consistent with the axis of compression (NNE–SSW dip direction of beds).

The southernmost marginal zone of the DF is characterised by faults and block structures that occur mainly in a narrow strip zone along the boundary between the DF and Pri-Azov Massif (Fig. 1). These structures are well studied only in the westernmost part, where Devonian and Lower Carboniferous sediments and volcanic rocks crop out (Fig. 20). These strata display well preserved extensional structures and this particular zone was our natural laboratory for studying the Devonian and Visean phases of rifting. This zone is located between the WNW–ESE Vassilievka and Yujni Fault zones, which were normal faults and boundaries of half grabens at the time of rifting (McCann et al., 2003). But compressive structures related to the tectonic inversion of the DF are also present and particularly well developed in competent upper Famennian–Tournaisian–lower Visean thick platform carbonates. In this area, two

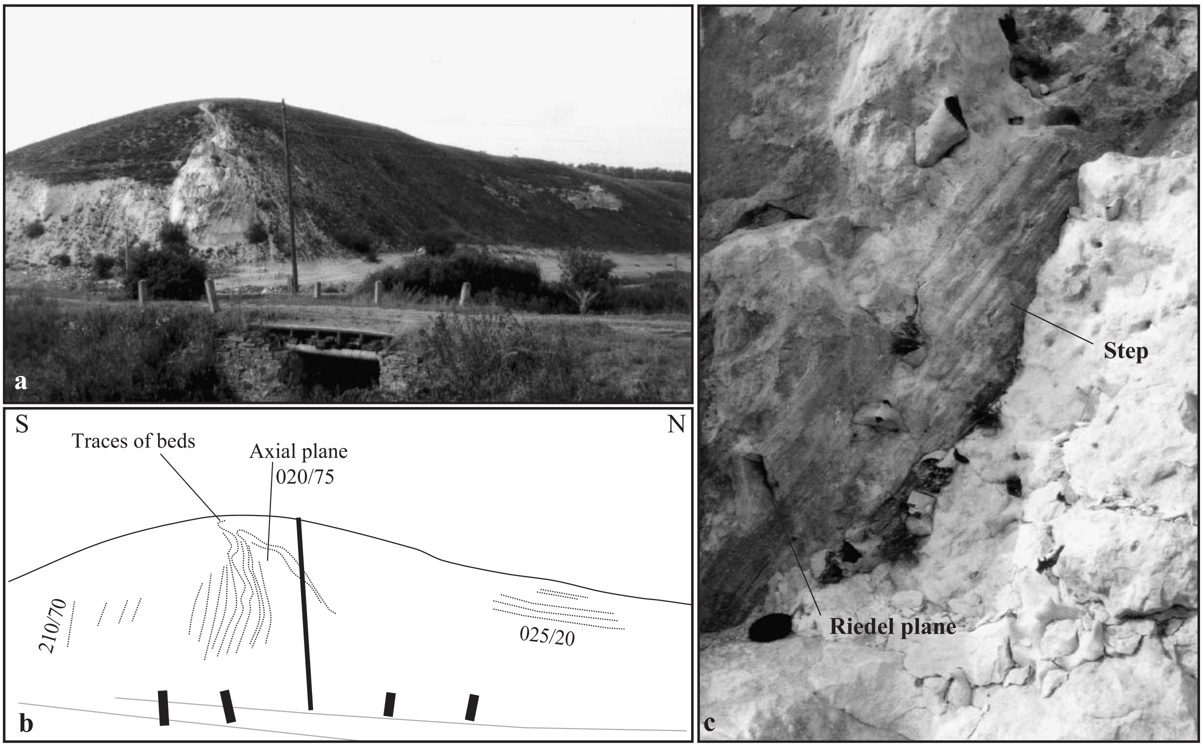

Fig. 19. Records of a NNE–SSW-directed compression in Upper Cretaceous chalks (Lissogorka, located in Fig. 7). (a) Localised south-vergent anticline (N110-directed axis). (b) Scheme of the anticline with dip directions and dips of beds. (c) Left lateral strike–slip fault consistent with a N–S pressure axis.

main trends of compression are recorded (Fig. 20, Saintot et al., in press) and are identical to those determined further to the East (cf. Fig. 15). Compressive structures developed initially under a NW–SE and, later, under a N–S compression. In Frasnian basalts, close to the Vassilievka fault zone (located in Fig. 20), the more recent N–S compression (Fig. 20b) led to the development of numerous reverse microfaults with striated calcite steps (Fig. 21). An exceptional E–W trend of contraction is recorded (Fig. 20a on the left corner) and associated flat N–S thrust planes are widely present in the carbonates (examples in Fig. 22). Similar to the paleostress fields reconstructed in Amvrosievka region (Fig. 15) and in the southern Russian DF (Fig. 7), the inferred paleostress regime here was transpressive and led also to the development of conjugate systems of strike-slip faults (with examples in Fig. 23).

At most sites, all three trends of contraction are recorded, such as at Zhogolevsky Quarry (located in Fig. 20), where N–S east-vergent thrust planes (illustrated in Fig. 24 to the left) as well as E–W thrust planes with dip-slip striae (illustrated in Fig. 24 to the right) occur. At sites such as this where polyphase deformation occurred, chronological criteria indicate that the NW–SE and E–W transpressions occurred prior to the N–S one. However, no chronology was determined between the E–W and NW–SE compressive stress trends. We argue that deviation of the compressive stress trajectory occurred and that the NW–SE and the E–W trends belong to the same stress event. Numerical techniques were used to model the paleostress trend deviation along major fault zones that was observed through stress tensor determination (Brem, 2000). The result is that synchronous dextral movement along both the Yujni and Vassilievka faults could have produced such a strong deviation of the compressive stress trajectory (Fig. 25). In support of this hypothesis, dextral shearing along the WNW–ESE contact (steep, 70° south) between Pri–Azov

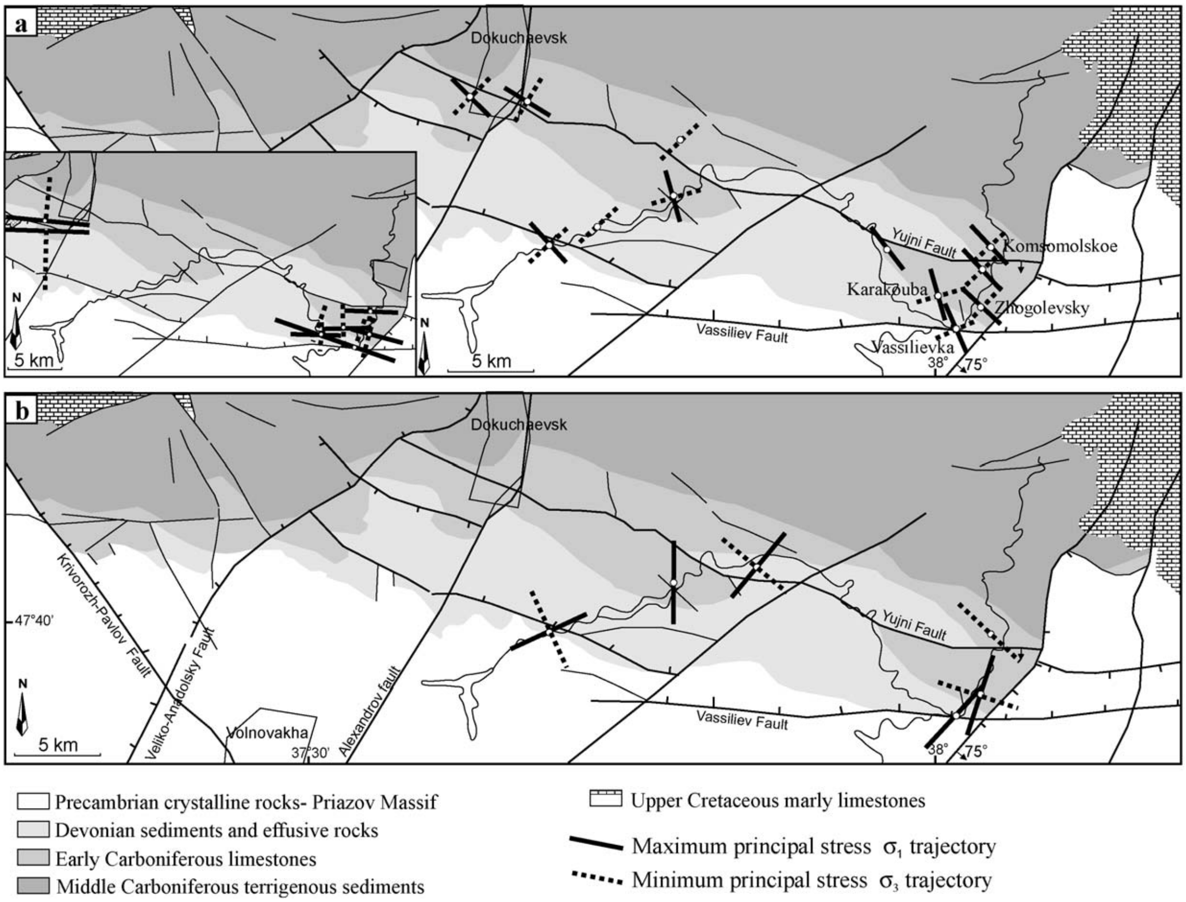

Fig. 20. Paleostress field succession in the southern margin of the Donbas Foldbelt recorded in Proterozoic cristalline rocks, Devonian and Lower Carboniferous volcanic and sedimentary succession (after Saintot et al., in press). (a) A strike-slip and compressive regime with NW–SE trending σ_1 and E–W σ_1 stress axis deviation. (b) Compressional and strike-slip regime with NE–SW and N–S trending σ_1. As background: extract of the Geological Map of the Ukrainian Donbas Foldbelt (1995).

granite and Devonian basalt has been observed (Fig. 26); this contact is defined as the prolongation at the surface of the Vassilievka fault zone (Fig. 20).

4. Discussion

4.1. The Main Anticline and WNW–ESE-related gentle fold development

First, it is well established that the MA developed prior to the generally NE–SW- to E–W-trending compressive structures (thrusts-and-folds), which are clearly linked to the tectonic inversion of the basin. These latest structures have overprinted the WNW–ESE structural grain. Well-known data related to organic maturation levels confirm that the MA developed before the most recent folding event (cf. Sachsenhofer et al., 2002). In brief, when isolines of vitrinite reflectance are restored to their initial horizontal disposition (assuming that maturation is mainly a function of burial depth), the stratigraphic layers retain the shape of the MA. Some folding, therefore, took place prior to maximum burial.

Second, the development of the MA alone cannot be well understood at the scale of the DF in the classical scheme of basin inversion. It is difficult to

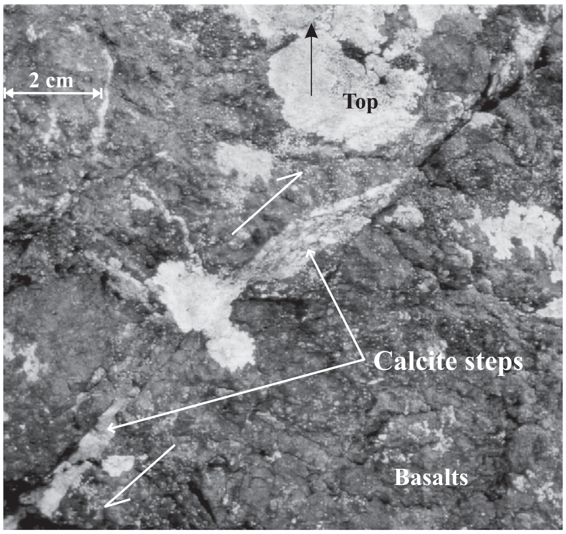

Fig. 21. E–W-directed reverse fault developed under a N–S compression in Devonian basalts at Vassilievka (located in Fig. 20).

postulate that contraction at the scale of the whole basin can be responsible for the development of such a single, close to tight linear fold. In any case, no trend of regional contraction/shortening consistent with the growth of the MA has been found anywhere in the DF through inversion of microbrittle structures or strikes of fold axes (cf. maps where the direction of the pressure axes are shown; (Figs. 6, 7, 9, 15 and 20); Saintot et al., 2000, in press).

The timing of MA development is well constrained by the angular unconformity of the overlying units: it is a Permian structure (the model of DF development related to the Varisan/Uralian orogeny was based on this single unconformity). As already mentioned, however, recent seismic-based studies have revealed that in Permian times, the DF area was extensionally reactivated (Stovba and Stephenson, 1999). We can note that the Permian extension of the lithosphere is well known in Western and Central Europe with the development of widespread rift systems (cf. Ziegler, 1990). It was in this extensional context that the uplift (but not shortening) of the DF, and particularly its southern margin, occurred, contributing to the angular unconformity of overlying stratigraphic units. A Permian "mantle diapir" was proposed (Gavrish, 1985; Chekunov, 1994) to explain such a doming of the region; though not explicitly mentioned by the authors, this also fits with the occurrence of an extensional stress regime. Some magmatic activity (trachyliparites) of this age is reported (Chekunov and Naumenko, 1982). New analyses of these rocks revealed that they are extrusive (Chalot-Prat, personal communication) and not intrusive as described in the literature (Chekunov and Naumenko, 1982). However, no geochemical analyses are available to constrain the magma source and to determine the occurrence of a mantle diapir. Another mechanism to explain the growth of the MA during the Permian extensional regime is salt diapirism. Several arguments are in favour of the presence of salt at depth below the MA along the rift axis. First, no major structural differences are noted in the Palaeozoic evolution of the

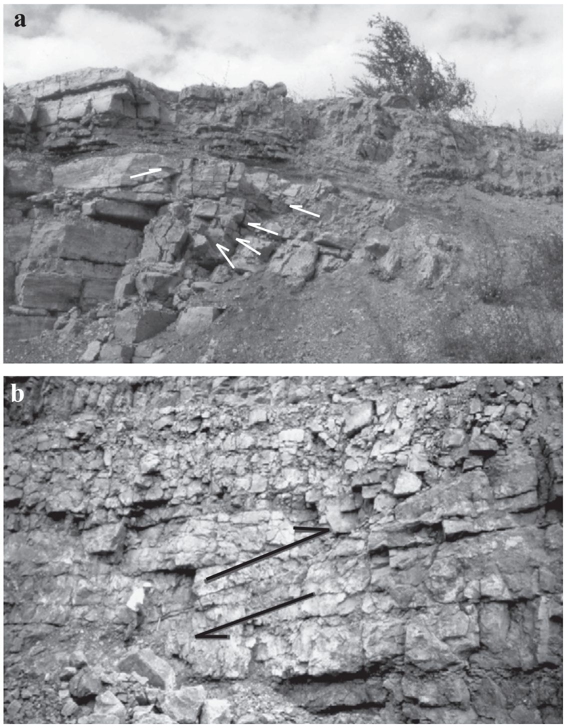

Fig. 22. Records of a nearly E–W-directed compression in Tournaisian–lower Visean limestones. (a) Thrust plane with N70- to N110-directed striae on calcite steps (Karakouba quarry, located in Fig. 20). (b) Thrust plane with N090- to N110-directed striae (Komsomolskoe quarry, located in Fig. 20).

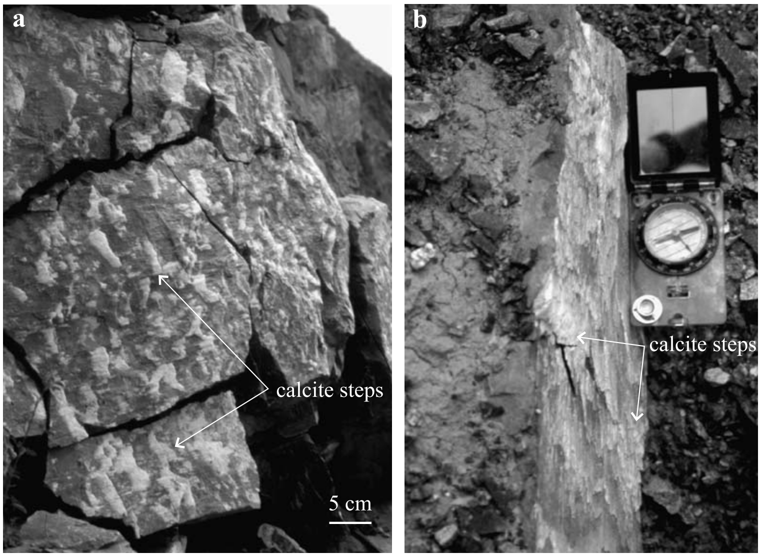

Fig. 23. Conjugate system of strike-slip faults with calcite steps, in Tournaisian–lower Visean limestones (Komsomolskoe quarry, located in Fig. 20), developed under a strike-slip regime with NNW–SSE σ_1 axis. (a) N176 vertical left lateral strike-slip fault and (b) N116 vertical right lateral strike-slip fault.

different parts of the wide DDB-DF rift system: the rift formation was Devonian and reactivated in Visean and Permian times. The major difference in the DF area is the thicker Carboniferous postrift succession compared to the other parts of the rift. The respective Devonian histories are comparable and Devonian salt is widely present in the DDB (Chekunov et al., 1992, 1993; Stovba et al., 1996, 2003; Stovba and Stephenson, 1999, 2002). The removal of Devonian salt layers have produced spectacular diapirs in the DDB (Stovba et al., 1996, 2003; Stovba and Stephenson, 2002). In addition, the P- and S-wave velocity characteristics of the sedimentary succession just below the MA as well as indications from the coincident DOBRE reflection deep seismic line (perpendicular to the rift axis) suggest the possibility of a salt-rich body in this area (DOBREflection-2000 and DOBREfraction'99 Working Groups, 2002). Finally, a very similar picture, i.e., a single linear, close anticline, developed in the Nordkapp basin of the Western Barents shelf. This structure was due to salt diapirism following the axis of the prior rift and these salt movements occurred during an extensional stress regime (Gabrielsen et al., 1990).

Thus, the Permian was an epoch of relief inversion of the DF, with development of the singular, positive Main Anticline structure. It was not a time of tectonic inversion of the basin, in terms of fold-and-thrust belt development.

4.2. Cimmerian and K/T tectonic inversion of the Donbas Foldbelt

The majority of structures described in this paper are related to the compressive events that formed the present-day Donbas fold-and-thrust belt. In the field, the mesoscale structures related to the inversion of the basin are shallow and flat thrust planes commonly associated with anticlines on fault planes. Whereas the thrust planes are north-vergent in the northern zone, they are south-vergent in the southern zone of the DF. These opposite vergences, observable at the scale of the outcrops, are also in agreement with the expected vergences along the inverted rift boundary fault zones dipping north along the southern margin and dipping south along the northern one. The vergences of thrusts have produced a classical fan shape of deformation.

At the scale of the basin, the regional NW–SE to N–S trend of contraction produced a wide transpressive dextral shear zone (because of orientation of preexisting structures—WNW–ESE boundary rift fault and MA zones—related to stress trends). Right lateral displacements are recognised along the southern major fault zones and along the MA faulted hinge. Since the transverse (nearly N–S-trending) fault zones passing through Donetsk city and going to the MA (Pantelei monovsky and Frantsusky faults in Fig. 6) show reverse displacements, they could be linked to the dextral displacement of the southern zone of the DF accompanying right lateral movement along the faulted hinge of the MA.

Within the basin, we have determined fluctuations of compressive stress trends and related structural trends controlled in part by preexisting structures. For example, along the southernmost margin of the DF, the trajectory of the pressure axis changed from NW–SE to E–W because of right lateral movements along preexisting Yujni and Vassilievka fault zones (Fig. 20a). In the Russian part of the DF (Fig. 7), the trend of contraction appears to have been more stable: N–S from the southern margin to the northern one. In the northern Ukrainian part, the trend of contraction is also single: NW–SE; N–S trend is not recorded. The various trends of contraction are only found in the southern Ukrainian part of the basin (Figs. 15, 20). These zones are characterised by the elevated position of the basement (compared to the other parts of the basin) probably because of the residual effects of the Permian uplift. We can assume that this particularity (the shallow presence of crystalline basement) led to a strong perturbation of the compressive structural trends that can be observed in the relatively thin sedimentary cover (in other words, the effect of the rheological contrast between cover and basement rocks is strong in this area of thinner sedimentary cover). Two main phases of tectonic inversion occurred in the DF: a Cimmerian one and an Alpine one at the K/T boundary. The Cimmerian inversion of the northern marginal fault zones is well documented by analyses of seismic lines but because of the lack of outcropping lower Mesozoic rocks, it is not well constrained by field analyses. It is difficult to assign an absolute age to the compressive structures that developed in Carboniferous strata. They could correspond to the Cimmerian phase as well as to the Alpine one (at the K/T boundary). At the outcrop scale, the compressive structures found

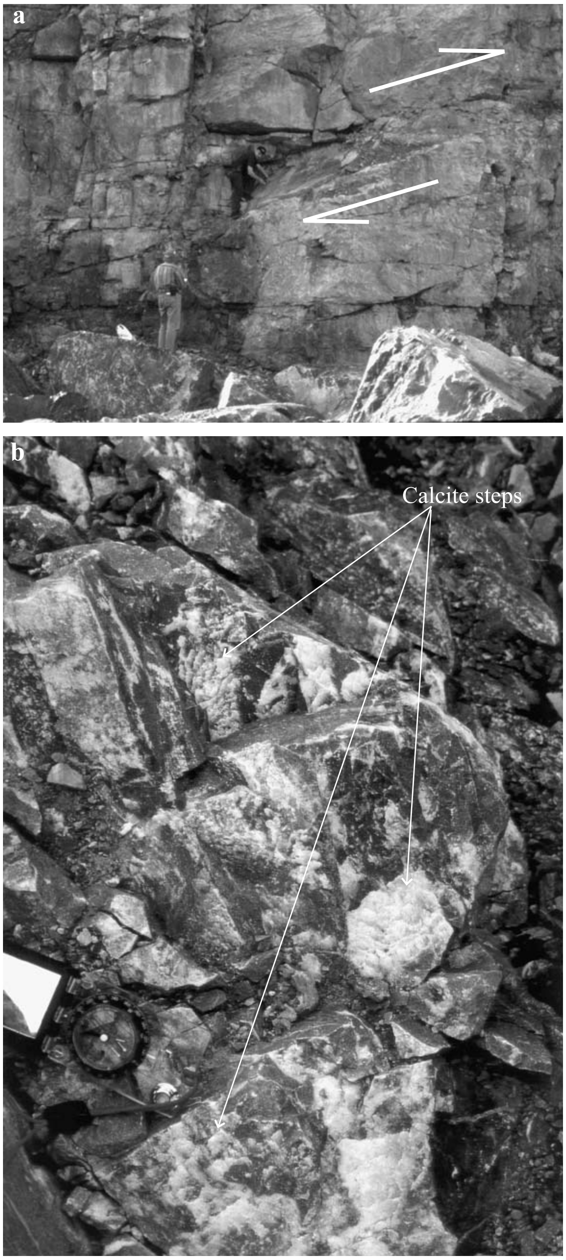

Fig. 24. Records of the N–S compression and of the E–W compression in Tournaisian–Visean limestones (Zhogolevsky Quarry, located in Fig. 20). (a) N–S-directed thrust plane along which the western block moved dip-slip upon the eastern block and (b) N100 26N reverse fault plane with dip-slip striae on calcite steps.

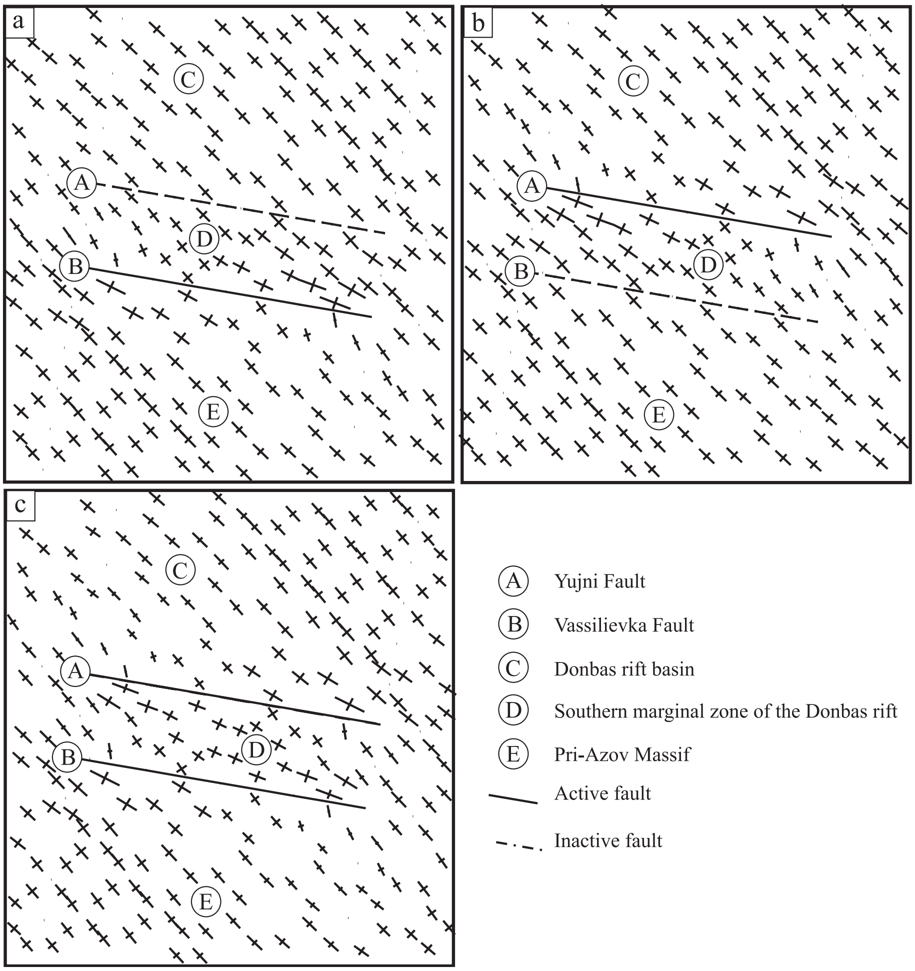

Fig. 25. Three numerical models showing the deviation of stress axis trends when the Yujni and the Vassilievka faults moved or not. The regional maximum stress axis is orientated NW–SE. Material properties of blocks: Young's modulus $E = 50$ GPa, Poisson's ratio $v = 0.25$, density = 2700 kg/m^3. Material properties of discontinuities, if active: cohesion and friction = 0, and if inactive: cohesion = 1000 GPa and friction = 100; magnitude of stresses used: $\sigma_1 = 15$ MPa and $\sigma_3 = 5$ MPa. (a) Vassilievka fault active and Yujni fault inactive. (b) Vassilievka fault inactive and Yujni fault active. (c) Both faults active.

in Upper Cretaceous rocks (and therefore associated with the Alpine inversion) are very similar in style to those observed in Carboniferous rocks (flat and shallow thrust planes and localised folds). If structures observed in Carboniferous strata are related to Cimmerian and to Alpine phases, it appears that they cannot be distinguished from one another. It probably means that the direction of contraction was similar and that the inversion was episodic with a Cimmerian phase followed by an Alpine phase having the same structural trend.

The K/T tectonic inversions affected numerous intraplate basins in Europe (cf. Ziegler, 1990), such as the Danish Trough (Hansen et al., 2000; Thybo, 2001) and the Polish Trough (Kutek and Glazek, 1972; Dadlez et al., 1995; Swidrowska and Hakenberg, 2000; Stephenson et al., 2003) forming the Holy Cross mountains (Lamarche et al., 1999), on the Norwegian shelf (Vågnes et al., 1998), and in south England (Hibsch et al., 1995). The exact mechanism by which plate boundary stresses are transmitted into plate interiors to produce intraplate inversion struc-

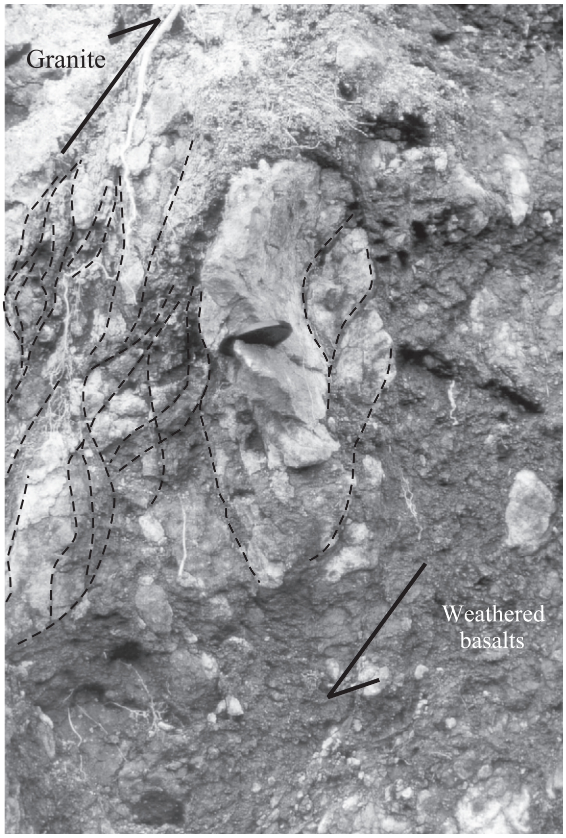

Fig. 26. View from above of lenticular shapes indicating a dextral shear along N100–N110 Vassilievka Fault zone (Vassilievka located in Fig. 20).

tures remains unclear (e.g., Ziegler et al., 1998) but, in any case, it seems highly likely that a common, plate-scale process is responsible.

5. Conclusion

The predominant structural grain of the Donbas Foldbelt (DF) trends WNW–ESE. This corresponds to the major, normal, rift boundary faults and is parallel to the main fold structure of the DF, the spectacular, close to tight so-called Main Anticline (MA), which developed upon and along the previous rift axis. There are no other such structures in the DF with similar trend or structural style as the MA and it is concluded that its formation was at least initiated during a (trans)tensional phase of rift reactivation in Permian times. As such, the MA would have developed synchronously with an intense regional uplift that affected, in particular, the southern part and margin of the DF and resulted in relief inversion of the basin and consequent erosion of several kilometres of pre-Permian rocks. The MA was classically thought to have been formed during tectonic shortening of the basin as part of a Variscan/Uralian orogenic belt that fringed the East European Craton. However, the structural field analyses reported here show that there is an absence of compressive structures elsewhere in the DF that can be associated to the growth of the MA. Our analyses, in contrast, are in favour of a mechanism such as salt diapirism to explain the development of the MA during a phase of regionally displayed (trans) tensional tectonics. Such a mechanism forming structures similar to the MA during Early Permian times are clearly in evidence in uninverted parts of the adjacent Dniepr–Donets Basin.

Subsequently, two main phases of tectonic inversion formed the Donbas fold-and-thrust belt proper, having generating oblique reverse displacements along preexisting normal (rift-related) faults. A Cimmerian (Late Triassic–Jurassic) phase of tectonic inversion is well documented along the northern margins of the DF and the southeasterly adjacent Karpinsky Swell. An Alpine (Late Cretaceous–Tertiary) phase of basin inversion is the youngest significant tectonic phase responsible for the present-day observed structures of the DF. Upper Cretaceous strata unconformably overlying Carboniferous rocks in the southern zone of the DF have widely recorded Alpine compressional effects. Cimmerian and Alpine folds and thrusts in the DF have various trends from NE–SW to E–W and clearly overprint the structural trend of the MA and earlier WNW–ESE rift-related trends.

The field analysis has allowed good constraints to be placed on the types of compressional structures related to each of the two phases of tectonic inversion of the DF. These comprise generally shallow and flat thrust planes, commonly associated with folds, northwest- to north-vergent north of the MA, and south to southeast-vergent south of the MA. The fan shape of deformation is also observed at the scale of the whole basin in recently acquired deep seismic profiling (Maystrenko et al., 2003). The trends of contraction are oblique relative to the (initial, rift-related) WNW–ESE structural grain of the basin and the tectonic inversion of the

DF occurred in a transpressive regime with right lateral and reverse displacements along the WNW–ESE marginal fault zones and along the faulted hinge of the MA.

Along the southwestern margin of the DF, anomalous N–S-trending thrusts and folds are recognised. These deviations in the strikes of compressive structures are thought to be the effects of inherited structures (evidently as major WNW–ESE faults and basement blocks at shallow depths along the southern margin) reactivated under NW–SE to N–S regional trends of compression.

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