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Crustal-scale pop-up structure in cratonic lithosphere: DOBRE deep seismic reflection study of the Donbas fold belt, Ukraine

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ABSTRACT

The DOBRE project investigated the interplay of geologic and geodynamic processes that controlled the evolution of the Donbas fold belt, Ukraine, as an example of an inverted intracratonic rift basin. A deep seismic reflection profile provides an excellent image of the structure of the Donbas fold belt, which is the uplifted and compressionally deformed part of the late Paleozoic Pripyat-Dniepr-Donets basin. Both the effects of rifting and those of later structural inversion are recognized in the seismic and geologic data. The interpretation of the reflection data shows that the inversion of the Donbas fold belt occurred at the crustal scale as a "mega–pop-up," which involved a major detachment fault through the entire crust and an associated back-thrust. The DOBREflection image provides a simple concept of intracratonic basin inversion, with the crustal pop-up being uplifted and internally deformed. The association of such a structure with inverted intracratonic basins such as the Donbas fold belt implies brittle deformation of relatively cold crust.

Keywords: intracratonic rift; inversion; deep seismic reflection profile; Donbas fold belt, Ukraine.

INTRODUCTION

The Donbas fold belt is the uplifted and compressionally deformed southeastern segment of the Pripyat-Dniepr-Donets basin, which is located in the southwestern East European platform (Fig. 1). The structure and sedimentary fill of the Pripyat-Dniepr-Donets basin has been studied via hundreds of wells and seismic lines in the context of oil and gas exploration (Chirvinskaya and Sollogub, 1980; Gavrish, 1989; Stovba et al., 1996). In contrast, knowledge about the Donbas fold belt relies mostly on near-surface data gathered during extensive coal mining activities together with studies of complementary, shallow, wells. Deep seismic sounding (DSS) studies were carried out in the 1960s and early 1970s in an attempt to reveal the deep structure of the Donbas fold belt (Belokon', 1975; Sollogub et al., 1977). However, the resolution of these data is not detailed, and the tectonic evolution and deeper structure of the Donbas fold belt are still disputed (Sobornov and Khatzkel', 1991; Yudin and Artemenko, 1996). The experiment complements the EUROPROBE "Georift" research performed over an decade and adds interesting aspects to the inversion of intracontinental basin.

In 2000 the Ukrainian exploration company Ukrgeofizika and an international scientific consortium (Germany, Netherlands, and Denmark) acquired ~140 km of explosive and Vibroseis reflection seismic data across the Donbas fold belt (Fig. 1). This seismic profile was named "DOBRE," an acronym for Donbas Basin Reflection and Refraction that also means "good" in Ukrainian (cf. DOBREflection-2000 and DOBREfraction'99 Working Groups, 2003).

REGIONAL GEOLOGY AND EVOLUTION OF THE PRIPYAT-DNIEPR-DONETS BASIN

The Pripyat-Dniepr-Donets basin formed as a result of intracratonic rifting in the Late Devonian with extensional reactivations during the Carboniferous followed by passive postrift subsidence (Stephenson et al., 2001). The basin has a generally northwest strike and subdivides the Sarmatian segment of the East European craton (Shchipansky and

Bogdanova, 1996) into two parts, the Ukrainian Shield and the Voronezh massif (Fig. 1). The Pripyat-Dniepr-Donets basin can be subdivided into a number of segments, including the relatively shallow Pripyat Trough, the deeper Dniepr-Donets basin, and the uplifted and inverted Donbas fold belt. The southeastern continuation of the Pripyat-Dniepr-Donets basin is represented by the compressionally strongly deformed Karpinsky swell.

Synrift sediments, including a significant amount of salt, accumulated during the Late Devonian in diverse depositional environments. Synrift magmatism included volcanic rocks (tuffs, mafic and silicic lavas) as well as intrusive bodies (Aizenverg et al., 1975; Lyashkevich, 1987). The Upper Devonian sequence is overlain by thick postrift sedimentary rocks of Carboniferous and younger age (Chirvinskaya and Sollogub, 1980; Gavrish, 1989; Chekunov et al., 1992; Stovba et al., 1996). For the most part, the preserved sedimentary succession of the present-day Donbas fold belt (excluding Paleogene and younger rocks) comprises only Devonian and Carboniferous strata, as a result of uplift and erosion (Popov, 1965a, 1965b; Pogrebnov et al., 1985). Devonian salt deposits were mobilized, leading to the formation of widespread salt pillows and diapirs in the Dniepr-Donets basin (Stovba and Stephenson, 2003). Significant uplift of the southeastern part of the Dniepr-Donets basin occurred during Early Permian time, contemporaneously with salt movements within a transtensional tectonic setting. However, the main phases of shortening in the Donbas fold belt occurred during Late Triassic time and latest Cretaceous–early Tertiary time (Stovba and Stephenson, 1999; Saintot et al., 2003).

The Donbas fold belt is >650 km long and up to 150 km wide and is characterized by open folds along strike. The original basin center is characterized by a single dominant fold, called the Main anticline, which is almost symmetric with steeply dipping limbs (up to 60°–80°). The Main and Southern synclines are adjacent to the Main anticline (Popov, 1963; Saintot et al., 2003). A thrust fault zone that dips (approximately) southward is developed near the northwestern margin of the Donbas fold belt. Minor faults and rotated fault blocks are common along the structurally complex transition zone from the Preazovian massif to the Donbas fold belt (Bogdanov et al., 1947; Ustinovskiy, 1955). Many Devonian dikes cut the Preazovian massif, south of the Donbas fold belt, indicating that this crystalline massif was also affected by Late Devonian rifting (Muratov, 1972; Shatalov, 1986). However, most pre-, syn-, and postrift sedimentary units were eroded during the later uplift and inversion processes that affected the Donbas fold belt (Levenshtein, 1963; Stovba and Stephenson, 1999).

DATA ACQUISITION AND PROCESSING

The migrated DOBREflection-2000 Vibroseis and explosive-source profiles are displayed in Figure 2. Good to excellent resolution of the basin fill and the crystalline crust is evident. The data were acquired by Ukrgeofizika with an “IO-2000” recording system using 681 channels and a geophone group spacing of 35 m. A symmetric 24 km split-spread (12–12 km) was used in the southern part of the line, and an asymmetric 20 km spread (8–12 km) was used on the northern part of the line (DOBREflection-2000 and DOBREfraction’99 Working Groups, 2002). Acquisition parameters are given in Figure 2. Data acquisition was hampered locally by mining activities, indicated by gaps along the line. Attempts were made to “undershoot” the critical area between 90 and 100 km although it is evident that deep structures are not resolved as clearly as elsewhere on the Vibroseis profile. Deep reflectors are seen more clearly in this area on the explosive-source profile (Fig. 2B). Processing of the DOBREflection data (by the Ukrgeofizika Technological

Centre, Kyiv) followed a standard industrial processing sequence that included prestack procedures (statics correction, gain and mute analysis, predictive deconvolution, velocity analysis, residual static corrections, frequency analysis). Deconvolution, band-pass, and coherency filtering were then applied to the stacked data, followed by Kirchhoff time migration and a 45-degree time finite-difference migration. Additionally, the new common reflection surface (CRS) stack technique (Jaeger et al., 2001; Menyoli et al., 2002) and prestack depth migration were applied to the Vibroseis data at the University of Hamburg to elucidate several key structural features of the reflection profile (Figs. 3E).

In 2001, Ukrgeofizika extended the DOBRE Vibroseis line an additional 110–120 km to the north (using an 18 km symmetric spread and, otherwise, similar acquisition parameters). These data were not recorded as part of the DOBREflection consortium project and cannot be reproduced here in whole. Nevertheless, Ukrgeofizika has permitted replication of a fragment of these data, which crosses the thrust zone on the northern margin of the Donbas fold belt, a key area for interpreting the adjacent DOBREflection-2000 data.

INTERPRETATION

The interpreted DOBREflection-2000 seismic section reveals folding and faulting patterns in the sedimentary basin and allows tracing faults to greater depth. It is in very good agreement with the shallow geologic section (Fig. 3A). The basement surface is imaged by a band of strong reflections, indicative of Devonian prerift sedimentary rocks ($D_{2–3}$) unconformably overlying the Precambrian. The geologic identification of this reflective packet is well established elsewhere in the Dniepr-Donets basin (cf. Stovba et al., 1996). The basement reaches the surface at km 37 in accordance with the exposed geology.

Within the basin, patterns of folding adjacent to the Main anticline and the almost flat prerift sedimentary strata ($D_{2–3}$) beneath folded Carboniferous strata demonstrate the presence of an intervening ductile layer that may indicate the presence of a salt-rich layer as may be inferred from the Dniepr-Donets basin (Stovba and Stephenson, 2003).

A series of small half grabens developed during Late Devonian rifting is well displayed between km 35 and 70 (Fig. 3D). Similar structures are also identified south of the Donbas fold belt in the Preazovian massif (Figs. 3B and 3C). These grabens, as well as the southward thinning of Carboniferous strata, indicate that the original sediment fill likely continued considerably farther to the south. The prerift sedimentary sequence may terminate around km 68–75, probably related to major northward-dipping faults at km 70 and 90. These faults clearly played an important role during rifting, with significant synrift normal offset, but also display a moderate postrift reverse displacement related to basin inversion. At km 55–60, depth 2–4 s, and at km 115–120, depth 7–9 s, two other major reverse faults are interpreted, significantly displacing pre-, syn-, and postrift sedimentary strata (Figs. 3B and 3C). The former affects the whole of the sedimentary succession as well as basement, has a reverse detachment of 2.8 km (Figs. 3D and 3E), and can be traced to the surface where it coincides with a mapped fault system (Fig. 3A). It is recognized by the presence of high-amplitude reflections related to Mississippian (Lower Carboniferous - Tournasian) limestones (i.e., C_1t). The second fault is inferred from a vertical duplication of the reflective packet associated with the prerift sedimentary strata (i.e., $D_{2–3}$; Fig. 3F). The duplication is indicated by lateral correlation to both sides. The terminations of the prerift sediment layer at the inferred fault indicate a horizontal shortening of ~7 km. The surface trace of this reverse fault lies north of the northern limit of the DOBREflection-2000 profile, at a location covered by the profile acquired in 2001. A fragment of the new data with a preliminary interpretation provided by Ukrgeofizika (Figs. 3B and 3C) clearly indicates that the fault extrapolates into an imbricate thrust zone near the surface (Fig. 3G) involving Carboniferous to Cretaceous sedimentary rocks. This zone displays considerable complexity and, even with surface geologic constraints and penetration of one borehole (to depth 3800 m), the seismic data cannot completely resolve its detailed geometry.

In general, the entire crystalline crust is reflective, in particular in the southern half of the line. Close to km 10, near-surface reflectors are likely related to lithological changes within the Ukrainian Shield. Otherwise, the nature of the basement reflectivity remains a matter of speculation. The reflectivity fabric dips almost parallel to the basement surface in the uppermost crust and southwestward in the lower crust. The Moho is imaged by a 1–2-s-wide zone of strong reflectivity (shaded areas in Figs. 3B and 3C). The base of this zone corresponds to the M discontinuity determined from coincident wide-angle and refraction seismic (DOBREfraction Working Group, 2003). North of km 105, the lower crust and the Moho are characterized by exceptionally strong reflectivity. The zone of strong reflectivity corresponds to a lower-crustal high-velocity layer identified by the refraction data (DOBREfraction Working Group, 2003). The high reflectivity in normal incidence (Fig. 3) and wide angle makes it likely that the zone originates from a magmatic underplate, as identified in modern rift zones (e.g., Thybo et al., 2000). Between km 30 and 40, the reflective Moho zone appears doubled, separated by a nonreflective layer (Fig. 3H). The vertical offset is ~2 s TWT. This is interpreted as the termination of a crustal thrust zone, with ~10–15 km horizontal displacement, affecting the Moho.

STYLE OF COMPRESSIONAL INVERSION OF THE DONBAS FOLD BELT

The imbricate thrust fault zone on the northern flank of the Donbas fold belt connects with the thrust fault interpreted from the DOBREflection data cutting through the basement surface at km 110–120. In turn, this fault zone, if extrapolated to the southwest, links directly with the thrust fault interpreted to displace the Moho at km 30–40. On the basis of only geologic data from Donbas fold belt, Yudin and Artemenko (1996) suggested a similar structure. Extrapolation of the complementary northeast-dipping reverse fault imaged on the southern flank of the Donbas fold belt (surface trace at km 55) leads to the intersection of both fault zones in the crystalline crust beneath the Donbas fold belt at a depth of 25–30 km at km 95. Together, these faults form a crustal-scale pop-up structure; the main detachment surface, dipping to the southwest and offsetting the Moho, controlled deformation during compressional inversion of the Donbas fold belt. The trace of the main detachment zone in the crystalline crust, between the base of the sedimentary basin and the Moho, is mainly inferential although there is some suggestion of a change in seismic fabric (Fig. 3). The offset of this fault is greater at the Moho level than where it cuts the basement surface because of the shortening accommodated by the primary back-thrust and related reverse faults. A preshortening palinspastic reconstruction of the seismic profiles (DOBREflection-2000 and southernmost part of profile extension of 2001) has been made from the depth converted section (Fig. 4A), supplemented by the geological cross-section shown in Fig. 3A, using the commercial software package “2D Move”. Shortening is ~9% and the restoration balances well; a crustal-scale pop-up structure provides a good interpretation of the geometries seen in the seismic section.

The interpretation of the Donbas fold belt as a crustal-scale “mega–pop-up” implies a brittle rather than ductile bulk rheology for the whole Sarmatian cratonic crust at the time of inversion. Brittle deformation is favored by low temperatures and a high strain rate (e.g., Ranalli, 1995). The strain rate in the case of the Donbas fold belt is unlikely to be much greater than 10^{-15} s^{-1}, even assuming that all of the 9% shortening occurred in not more than 1 m.y. It follows that the lithosphere was not very hot at the time of inversion, a reasonable situation given that inversion took place at the end of the Cretaceous, whereas the last high-temperature, extensional event was at the end of the Carboniferous to the Early Permian (Stovba and Stephenson, 1999), >200 m.y. earlier. However, bulk rheological models of the lithosphere generally predict thermal weakening as a precondition of “whole lithospheric failure,” given conventionally adopted rheological parameters and intraplate forces (e.g. Kusznir and Park, 1985). The association of a “mega–pop-up” structure with this inverted intracratonic basin, however, implies brittle deformation of relatively cold crust. Similar results involving elastic buckling have been reported by Marotta et al (2000) from the North German basin.

SUMMARY AND CONCLUSIONS

The DOBREflection-2000 seismic reflection profile provides an excellent image of the structure of the Donbas fold belt, part of the Dniepr-Donets basin, which has had a long tectonic history from Late Devonian rifting to inversion in Cretaceous–Tertiary time. Both the effects of Late Devonian rifting and later inversion are widely recognized by seismic and geologic data in the Dniepr-Donets basin. The results show that the inversion of the Dniepr-Donets basin occurred at a crustal scale as a “mega–pop-up,” which involved a major detachment fault through the entire crust and an associated back-thrust. The DOBREflection image provides an especially simple concept of intracratonic basin inversion, with a large pop-up structure being uplifted and internally deformed.

ACKNOWLEDGMENTS

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FIGURES

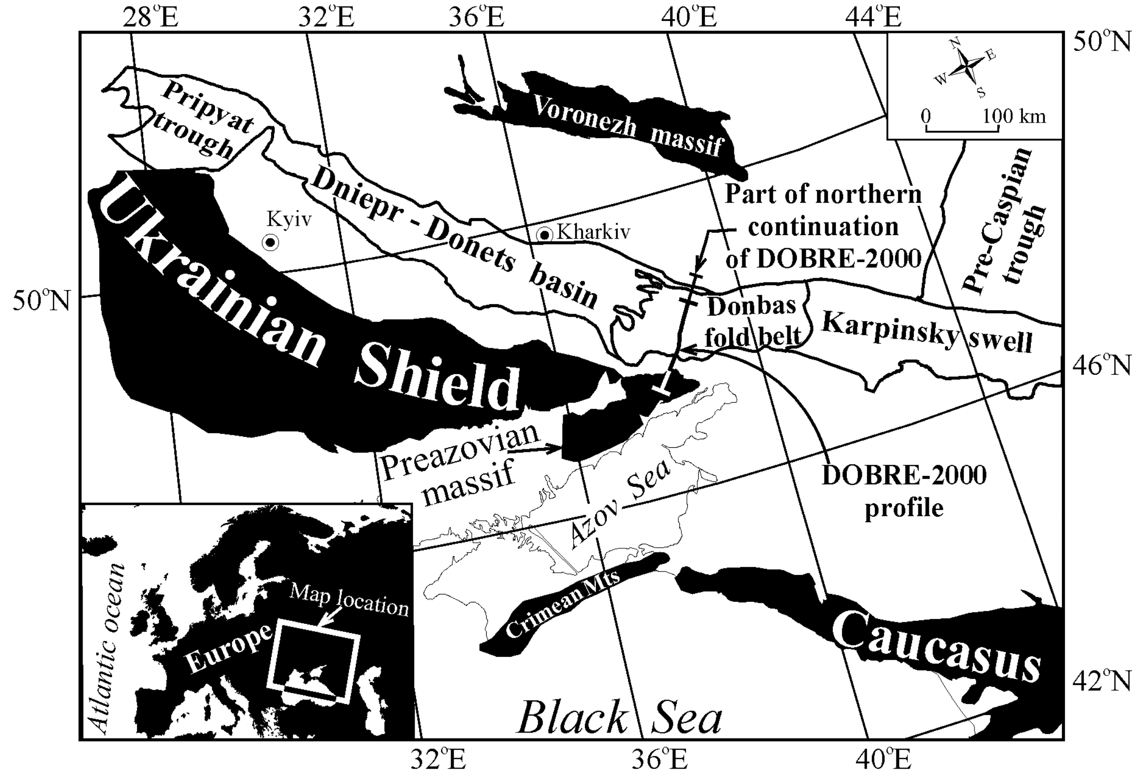
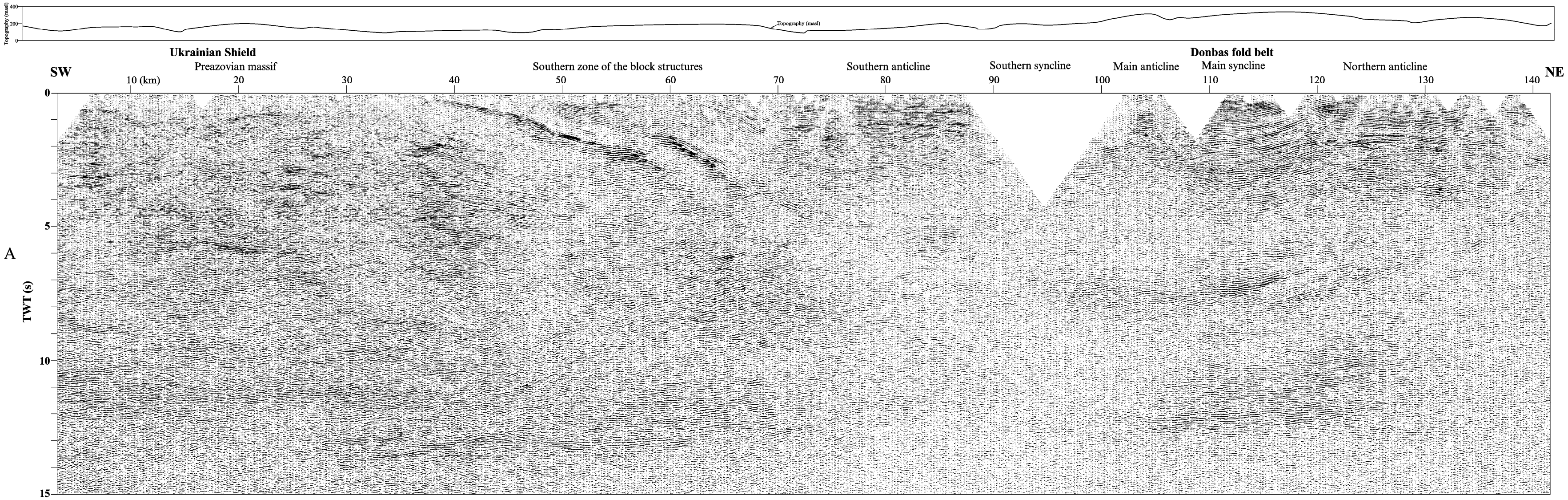
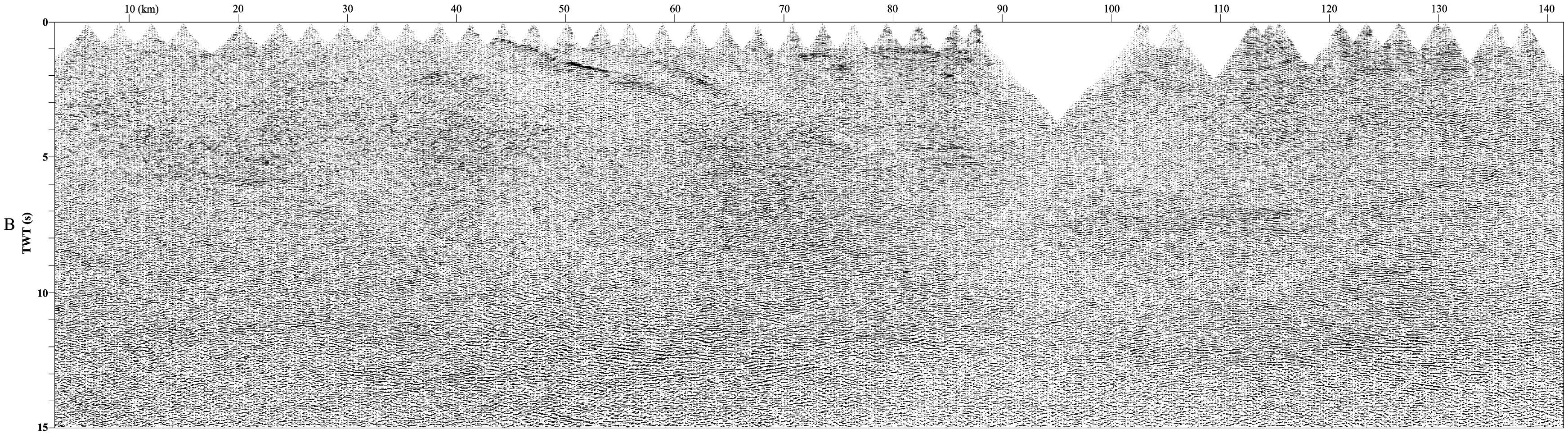


Figure 1. Main tectonic provinces in the vicinity of Pripyat-Dniepr-Donets basin and Donbas fold belt with location of DOBREflection-2000 profile and part of the northern continuation of this line.



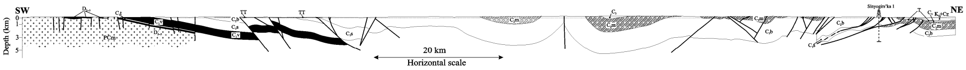
Vibroseis data, time-migrated: source spacing 140 m; energy 4 x 27 ton vibrators; 16 s up-sweep; signal 8-64/80 Hz; 16x vertical stack/vibration point; nominal fold 60-85; record length 30 s; 2 ms sampling rate.



Explosive data, time-migrated: source spacing 2940 m; 80 kg TNT in 10-30 m shot holes; nominal fold 4; record length 64 s; 4 ms sampling rate.

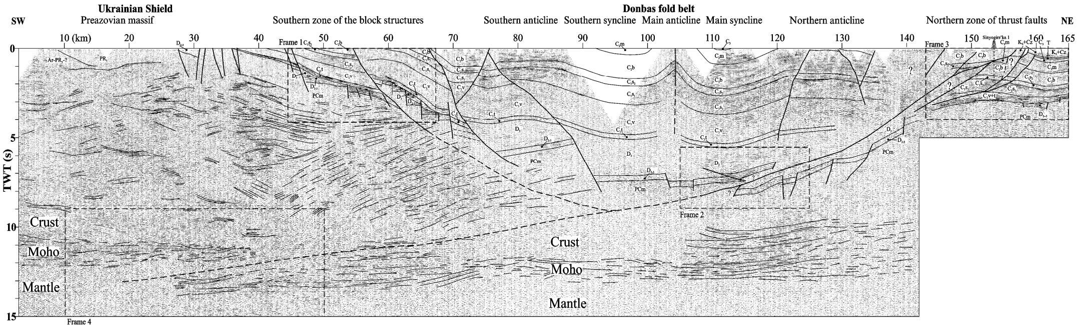
Figure 2. DOBREflection-2000 comprised 133 km of deep seismic reflection data obtained with Vibroseis and explosive sources from Preazovian massif across axial part of Donbas fold belt. A: Time-migrated Vibroseis data; source spacing, 140 m; energy, four 27 ton vibrators; 16 s up sweep; signal, 8–64/80 Hz; 16× vertical stack/vibration point; nominal fold, 85; record length, 30 s; sampling frequency, 2 ms. B: Time-migrated explosive data. Source spacing, 2940 m; 80 kg TNT in ten 30 m shot holes; nominal fold, four; record length, 64 s; sampling frequency, 4 ms. TWT—two-way traveltime; masl—m above sea level.

A



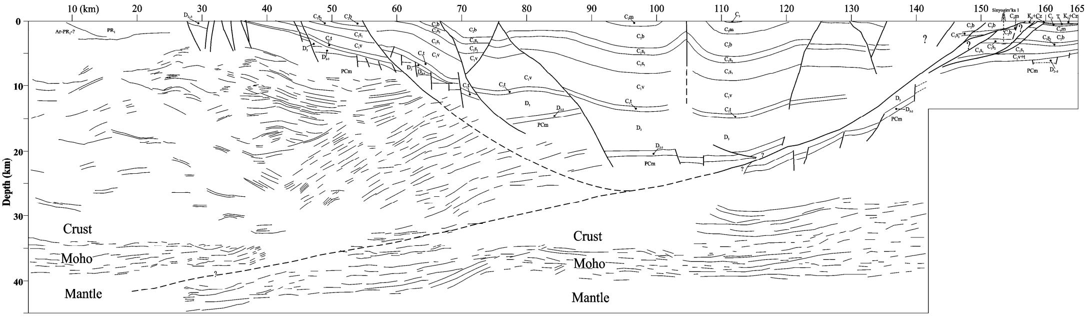
Geological cross section along the DOBREflection-2000 profile and southernmost part of the profile extension of 2001.

B



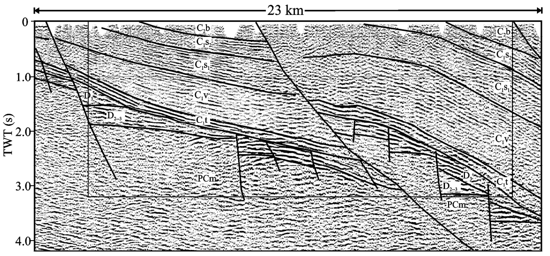
DOBREflection-2000 and southernmost part of the profile extension of 2001, Vibroseis, time-migrated, with interpretation.

C



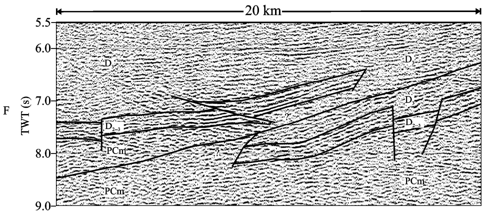
Depth-converted DOBREflection-2000 profile and southernmost part of the profile extension of 2001.

D



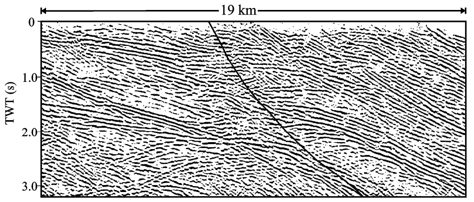
Fragment of DOBREflection-2000 (frame 1 on C) showing in detail a basement involving thrust on the southern flank of the Donbas fold belt.

F



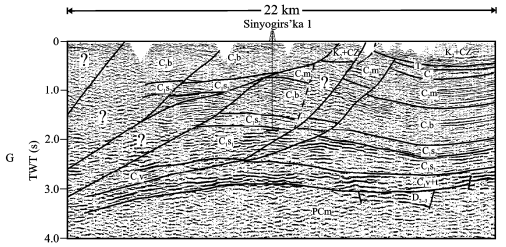
Fragment of DOBREflection-2000 (frame 2 on B) showing in detail the duplicated pre-rift sedimentary layer in the central part of the basin.

E



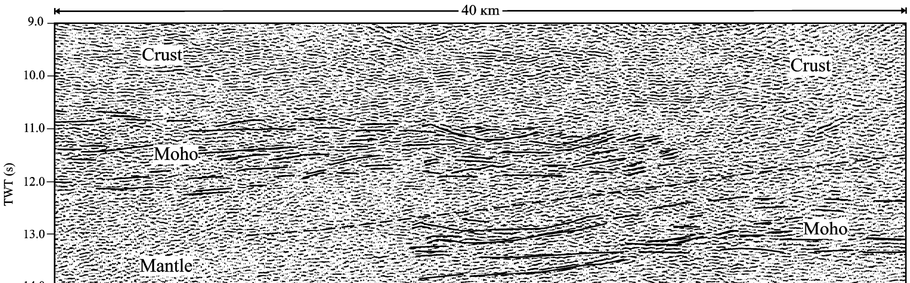
Common reflection surface (CRS) post-stack time migrated image of the thrust zone on the southern flank of the DF (frame on D). The change in reflector orientation clearly shows the trace of the thrust fault.

G



Fragment of the southernmost part of the profile extension of 2001 (frame 3 on B) showing in detail an imbricate thrust zone near the surface.

H



Fragment of DOBREflection-2000 (frame 4 on B) showing in detail inferred doubling of the Moho transition zone.

Figure 3. A: Geologic cross section along DOBREflection-2000 profile and southernmost part of profile extension of 2001. B: DOBREflection-2000 and southernmost part of profile extension of 2001, time-migrated Vibroseis, with interpretation. C: Depth-converted DOBREflection-2000 profile and southernmost part of profile extension of 2001. D: Fragment of DOBREflection-2000 (frame 1 on B) showing in detail a basement-involving thrust on southern flank of Donbas fold belt. E: Common reflection surface (CRS) poststack time-migrated image of thrust zone on southern flank of Donbas fold belt (frame on D). Change in reflector orientation clearly shows trace of thrust fault. F: Fragment of DOBREflection-2000 (frame 2 in B), showing in detail duplicated prerift sedimentary layer in the central part of basin. G: Fragment of the southernmost part of the profile extension of 2001 (frame 3 on B) showing in detail an imbricate thrust zone near the surface. H: Fragment of DOBREflection-2000 (frame 4 in B), showing in detail inferred doubling of Moho transition zone. TWT—two-way traveltime.

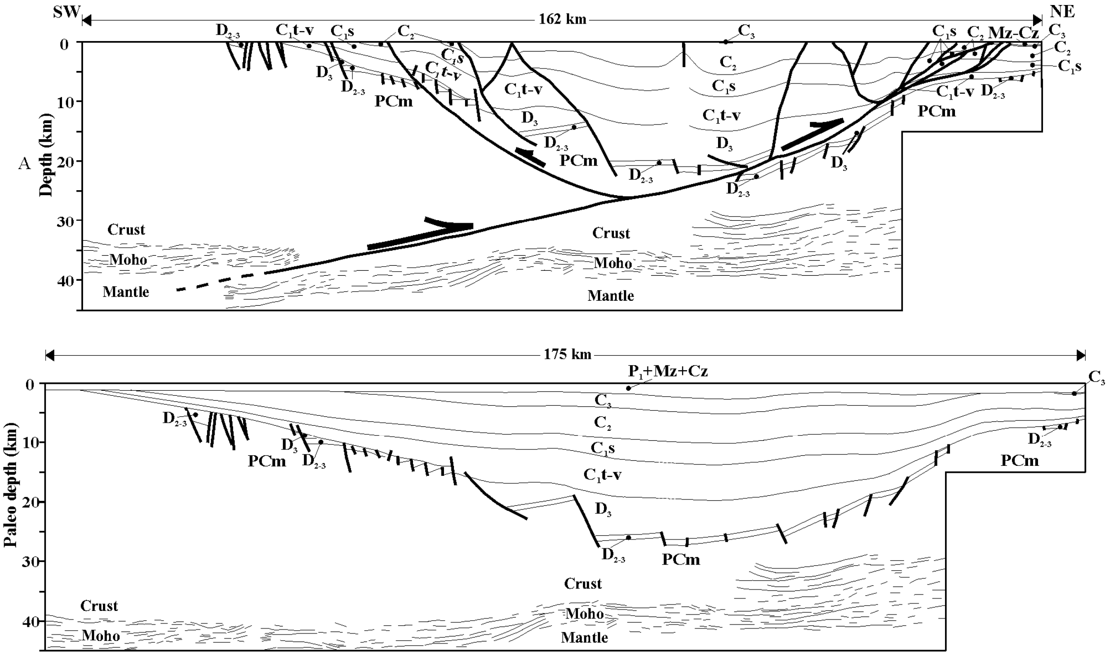


Figure 4. A: Supplemented depth section along DOBREflection-2000 and southernmost part of profile extension of 2001. B: Palinspastic reconstruction along depth section prior to shortening.