GEOLOGICAL STRUCTURE OF THE NORTHERN EASTERN BLACK SEA FROM REGIONAL SEISMIC REFLECTION DATA, INCLUDING THE DOBRE-2 CDP PROFILE

by

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Abstract

The margin of the northeastern Black Sea is formed by the Crimea and Kerch peninsulas separating it from the Azov Sea to the north. The age and architecture of the sedimentary successions in this area are described from exploration reflection seismic profiling acquired in the area as well as the "one-off" regional DOBRE-2 CDP profile acquired in 2007. The sediments range in age from Mesozoic to Quaternary and can be divided into five "seismo-stratigraphic" complexes linked to the tectono-sedimentological evolution of the area. The present regional basin architecture consists of a series of basement structural highs separating a series of sedimentary depocentres and is mainly a consequence of the compressional tectonic regime affecting the area since the Eocene and which has focused shortening deformation and uplift along the axis of the Crimea-Caucasus inversion zone on the Kerch Peninsula and Kerch Shelf of the Black Sea. Two major sedimentary basins that mainly formed during this time – the Sorokin Trough in the Black Sea and the Indolo-Kuban Trough to the north of the Kerch Peninsula in the Azov Sea – formed as marginal troughs to the main inversion zone.

Keywords: Crimean Mountains, Greater Caucasus Mountains, East Black Sea Basin, Azov Sea, seismic reflection profiles, inversion tectonics, sedimentary basin formation

This paper focuses on the subsurface geology of the northeastern part of the Black Sea (Fig. 1), in particular its regional architecture of basin depocentres and basement ridges. The margin of the northeastern Black Sea is formed by the Crimea and Kerch peninsulas separating it from the Azov Sea to the north.

The Black Sea as a whole consists of a roughly east-west orientated depression, mainly formed in the Cretaceous in the hinterland of the Pontide magmatic arc due to subduction of Neotethyan lithosphere below the southern Eurasian continental margin (Dercourt *et al.* 1993; Okay *et al.* 1994; Robinson & Kerusov 1997; Nikishin *et al.* 2003; Stephenson & Schellart 2010). At present the Black Sea is underlain by a flat, approximately 2 km deep, abyssal plain that obscures two separate large depressions called the West and East Black Sea (WBS and EBS) basins. These overlie crustal basement of uncertain composition and tectonic age and structure and are filled with up to 14 km of Mesozoic and Cenozoic sediments (Graham *et al.* 2013; Nikishin *et al.* 2015a,b). The WBS and EBS basins are separated by a Mid-Black Sea

Ridge (MBSR), the northernmost component of which is the Andrusov Ridge, as seen in Figure 1.

The Crimean Mountains, on the southern margin of the Crimea Peninsula, is the main onshore expression of the Crimea-Greater Caucasus orogenic belt in the northeastern Black Sea study area, running eastwards into southern Russia and Georgia. The contiguous offshore part of the orogen in the present study area is referred to here as the Crimea-Caucasus inversion zone (Fig. 1). It retains the memory of Mesozoic-Early Palaeogene extension as well as Eocene to Miocene contraction of the lithosphere, effected mainly by thrusting. The greater regional tectonic setting of the study area is described in accompanying papers in this volume (e.g. Gobarenko *et al*. this volume; Starostenko *et al*. this volume).

The regional geological structure of the Black Sea has been under investigation since the 1980s when regional seismic lines for the entire area were published (Tugolesov *et al.* 1985; Finetti *et al*. 1988; Belousov & Volvovsky 1989). More recent seismic data acquired in the EBS and adjacent areas have been published by Robinson *et al.* (1996), Afanasenkov *et al.* (2007), Shillington *et al.* (2008), Rangin *et al.* (2002), Khriachtchevskaia *et al.* (2010), Stovba *et al.* (2009), Nikishin *et al.* (2010), Mityukov *et al*. (2012), Almendinger *et al*. (2011), TPAO/BP Eastern Black Sea Project Study Group (1997), Gozhyk *et al.* (2010) and Graham *et al*. (2013). A set of long regional deep seismic lines acquired in 2011 in the framework of the international project "Geology Without Limits" allowed a new map of acoustic basement for the whole Black Sea to be proposed (e.g. Nikishin *et al*. 2015a,b).

Marine seismic reflection surveys within the present study area were first done before the end of the last century. Among the first regional 2D seismic surveys in the area were the Western Geophysical (1994) and Polar Trade Research Associates (2005) surveys (Fig. 1; right-hand panel). A successful exploratory well was drilled on the Subbotina anticline structure, followed up by additional wells (Fig. 1; right-hand panel) and the more detailed 3D CDP Titul survey undertaken by Ukrgeofizika in 2008 (Fig. 1; right-hand panel). The focus of the present study is on the area lying to the south of Kerch Peninsula within the Kerch Shelf, Sorokin Trough, North Black Sea High, Shatsky Ridge and East Black Sea Basin (Fig. 1).

The wide-angle refraction and reflection (WARR) profile DOBRE-2 (Starostenko *et al.* this volume), utilizing on- and offshore recordings and energy sources, was acquired in 2007 by

Ukrainian organizations and international partners across the Azov Sea, eastern Kerch Peninsula and the eastern Black Sea. The coincident DOBRE-2 regional CDP line, crossing the Azov Sea, Kerch Peninsula, and the north-eastern part of the Black Sea (Fig. 1), was acquired by Ukrgeofizika (the Ukrainian national geophysical company) also in 2007. The geological interpretation of the DOBRE-2 CDP data are presented here, carried out in the context of other seismic reflection profiling in the area and its ties to wells. The results illuminate the structural relationships and ages of extensional and subsequent basin inversion tectonic events as well as the 2D geometry of basement displacement associated with post-Eocene inversion in this key segment of the Crimea-Caucasus deformation belt. Further, the complete DOBRE-2 CDP profile (including its Kerch Peninsula and Azov Ridge segments) is briefly examined in view of the presented results to examine the structural style of the Crimean-Caucasus inversion zone as a whole and its associated sedimentary basins.

Geological setting

Rifting is the major (first-order) geodynamic process responsible for the tectonic evolution of the Black Sea basins, related to closure of the Tethys and Neotethys oceans (Zonenshain & Le Pichon 1986; Letouzey *et al.* 1977; Görür 1988; Okay *et al.* 1994; Robinson *et al.* 1996; Nikishin *et al.* 2003; Stephenson & Schellart 2010). However, the timing of opening of the Black Sea basins (i.e., the age of the oldest sediments) remains controversial. A Cretaceous age was inferred from onshore geological observations by Adamia *et al.* (1974), Letouzey *et al.* (1977), Görür (1988) and Nikishin *et al*. (2003). An Early Cretaceous to Palaeocene opening was deduced by Finetti *et al.* (1988) from extensive seismic reflection data, corresponding with the concepts of Zonenshain & Le Pichon (1986) and Robinson *et al.* (1996). Stephenson & Schellart (2010) suggested that there was a single stage opening of Black Sea as a back-arc basin resulting from asymmetric slab roll-back. Nikishin *et al.* (2015b) concluded that continental rifting manifested itself from the Late Barremian to the Albian, while the age of opening of the deepest basins with (sub-) oceanic crust was from Cenomanian until mid-Santonian.

At present the Black Sea is undergoing compressional deformation that has been active since the Eocene (Saintot *et al.* 2006b; Khriachtchevskaia *et al.* 2010; Stovba & Khriachtchevskaia 2011), or possibly Palaeocene (Sheremet *et al.* this volume), related to convergence of the Eurasian and Afro-Arabian plates, seen, for example, as underthrusting of the Black Sea crust

147 below the crust of the Scythian platform of the Crimean and Kerch-Taman peninsulas
148 (Gobarenko *et al*. this volume).
149
150 The Crimean Mountains can be considered as the western prolongation of the Greater
151 Caucasus orogen. It is widely associated with strongly deformed Upper Jurassic-Lower
152 Cretaceous sedimentary strata, which are overlain by thin Cenozoic sediments (Kruglov &
153 Tsypko 1988). Popadyuk (2013) reported an Albian age for these strata (which they assigned
154 to the Tauric Group), which compares with recent nannofossil dating of them in the eastern
155 Crimean Mountains reported by Sheremet *et al*. (this volume). These flysch series are
156 characterized by detrital deposits, turbidites and large olistostromes containing blocks of
157 different sizes and ages. The presence of substantial volcanic ash reported by Sheremet *et al.*
158 (this volume) suggests their deposition at the same time as Early Cretaceous volcanic activity
159 in the area, which is supported the radiometric dating of Meijers *et al.* (2010) in eastern
160 Crimea and Nikishin *et al*. (2013) in western Crimea.
161
162 The DOBRE-2 CDP profile is located in the transition from the subdued offshore part of
163 Crimean orogenic belt south of the eastern Crimea Peninsula to the EBS Basin, crossing
164 numerous thrust and thrust-related folds and syn-compressional sedimentary depocentres.
165 These include the Sorokin Trough and associated positive structures, such as the Tetyaev
166 Uplift, the North Black Sea High and the Shatsky and Andrusov ridges (Fig. 1). The last two
167 form the northeastern and southwestern margins respectively of the parallel EBS Basin, which
168 is filled with Cretaceous and younger sediments as thick as 14 km that overlie a high-velocity
169 crystalline crustal layer with Moho lying at a depth of 20-24 km (Starostenko *et al.* 2004; Scott
170 *et al*. 2009; Shillington *et al*. 2009; Yegorova et al. 2010, 2013). The Andrusov Ridge is part
171 of the Mid-Black Sea Ridge, which is underlain by continental crust as thick as 28-29 km (e.g.
172 Shillington *et al*. 2009; Yegorova *et al.* 2010).
173
174 The study area is known to host significant oil and gas potential (e.g. Pobedash 2006; Stovba
175 *et al.* 2009). The most important discoveries in this regard are related to compressional
176 structures in an area referred to as the Kerch-Taman Trough immediately south of the Kerch
177 Strait (cf. Nikishin *et al.* this volume), the inlet to the Azov Sea from the Black Sea between
178 the Kerch and Taman peninsulas.
179

Regional basin architecture in the northern eastern Black Sea from seismic reflection profiling

CDP seismic dataset: acquisition and processing

Regional investigations of the Ukrainian sector of the northeastern Black Sea have been carried out using a vast set of regional seismic reflection profiles (~10000 km), including those acquired by Western Geophysical in 1994 and by Polar Trade Research Associates in 2005. These data, augmented by Ukrgeofizika data acquired in 2007 (DOBRE-2) and 2008 (Titul), form the basis of the present paper. The location and distribution of these datasets are shown in Fig. 1 (right-hand panel) with the specific profiles reproduced in this paper highlighted accordingly. The main acquisition and processing parameters for the utilized seismic surveys are listed in Table 1.

Stratigraphic correlation

Onshore seismic reflection surveys for hydrocarbon exploration were carried out on the Kerch Peninsula since the middle of the 20th century and led to the discovery of a number of oil, gas and gas condensate deposits in sedimentary strata of mainly Cenozoic age (cf. Fig. 1). The seismic stratigraphy established onshore by Ukrgeofizika (and other Ukrainian organisations such as Odesmorgeologia) was extrapolated and further developed in the offshore region beginning with the 1994 Western Geophysical survey. Figure 2 shows the main seismic horizons, some of which correspond to local and regional unconformities, that are readily identified according to a lengthy and vast experience of seismic interpretation in the study area.

Well-ties with seismic offshore are scarce in the study area except around the Subbotina discovery mentioned above. Figure 3 exemplifies the geological interpreted seismic stratigraphy of the area for one profile calibrated by the wells drilled on the Subbotina structure. For the present study specifically, which includes the unique DOBRE-2 regional CDP profile, correlation of regional reflections with stratigraphic horizons was reassessed in two stages. The first of these was based on calibration with the Subbotina wells as seen in Figure 3, with Subbotina-403, the discovery well and also the deepest, terminating in the Lower Eocene succession. (More details of these wells and the seismic in the immediate area

of the Subbotina field can be found in Stovba *et al.* [2009], Gozhyk *et al.* [2010] and Starostenko *et al*. [2011]). The second stage involved extrapolating the DOBRE-2 profile from the (onshore) Kerch Peninsula, where the subsurface seismic stratigraphy has been well-established, to the deeper part of the EBS Basin. What follows in this section is, first, a general description of the established seismic stratigraphy of the study area with examples from the utilized exploration datasets (Figs. 3-5; profiles located in Fig. 1) and then the Black Sea segment of the DOBRE-2 regional CDP profile with a geological interpretation in this context (Fig. 6).

Regional seismo-stratigraphic complexes

The seismic stratigraphy of the northern EBS area has conventionally been subdivided into seven main "seismo-stratigraphic complexes" (e.g. Gozhyk at al. (2011). In the present paper, a more robust subdivision of only five such complexes is considered: a Mesozoic complex, a Palaeocene-Eocene complex; the Maykopian succession of Oligocene and Early Miocene age; a Middle and Upper Miocene complex and a Pliocene-Quaternary succession. These are based primarly on the work of Pobedash (2008), which utilised the stratigraphy results of the Subbonina-403 well (cf. Fig. 1), as well as those of Popadyuk (2009).

The Mesozoic seismo-stratigraphic complex is characterized by low-grade (weak) reflections on the seismic sections in this area. The top of this complex is horizon IIIm (Fig. 2), which is expressed clearly on the Andrusov and Shatsky ridges and in the intervening EBS Basin (e.g. Fig. 6). It is generally an erosional surface on the top of Mesozoic strata. It is difficult to identify within the Sorokin Trough (e.g. Fig. 4) probably because of its high dip angle conformable with overlying Cenozoic sediments. The relatively chaotic nature of reflectivity within the the Mesozoic strata underlying IIIm (e.g. Figs. 4, 5) is likely related to faulting of probable Cretaceous age associated, for example, with Black Sea rifting. The age of underlying Mesozoic strata, below horizon IIIm, varies from place to place, which complicates the seismic stratification and the erosional gap may be considerable.

The Palaeocene-Eocene seismo-stratigraphic complex lies between horizons IIIm and IIa. The Subbotina-403 well penetrated the Eocene succession, which consist mainly of marl with interlayers of clay. This complex displays good dynamic reflections in the time sections. In general, the sediments of this complex occur in troughs and depressions of the northern EBS

248 area (e.g. Figs. 5, 6) and it may be partly (e.g. Fig. 3) or wholly missing in places such as
249 across the North Black Sea High (Fig. 4). The complex may be present within the Sorokin
250 Trough but the overlying horizon IIa is not clearly identifiable, for example, on seismic line
251 161-94 (Fig. 4).
252
253 The Maykopian seismo-stratigraphic complex (Oligocene-Lower Miocene), lying between
254 seismic horizons Ia and IIa, is characterized by reflections of variable amplitude. According to
255 the Subbotina-403 well lithostratigraphy, the Lower Miocene succession is represented by clay
256 with siltstone interlayers, with some sandtone layers near its base, and the Oligocene
257 succession is represented mainly by clay and, towards its base, by clay with interlayered
258 siltstones and sandstones. Hydrocarbons are found in some of sand units. In the Sorokin
259 Trough the Maykopian complex is tectonically folded (e.g. Figs. 4, 6). Within the EBS Basin
260 it conformably repeats the structural forms of the Mesozoic complex with gradual flattening
261 (Figs. 4, 5) and covers the positive structures within the basin (e.g. North Black Sea High,
262 Shatsky and Andrusov ridges; Figs. 4-6) as well as the troughs as the basin subsides as a
263 whole. It is noted that the thickness of the Maykopian complex in the present interpretation
264 (e.g. Fig. 6) is much thicker over the EBS Basin and Andrusov Ridge than is other recent
265 interpretations (e.g. Stovba *et al.* 2013; Nikishin *et al.* 2015a,b; Nikishin *et al.*, this volume).
266 This is because the present interpretation was made prior to release of information from the
267 Sinop-1 well drilled on the Andrusov Ridge in Turkish territory (located in Fig. 1) and,
268 accordingly, was based on extrapolation from the Subbotina wells and other correlation points
269 on and near the Ukrainian Black Sea margin.
270
271 The Middle-Upper Miocene seismo-stratigraphic complex lies between seismic horizons Ip
272 and Ia. The latter, basal, horizon has no obvious signs of unconformity but can be associated
273 with a change in how the amplitude dynamics of the seismic wave field is expressed. Within
274 the Subbotina field the Upper Miocene is represended by clay and the the Middle Miocene by
275 clay with marl interbeds of the Tortonian age. Horizon Ip, marking the top of this complex and
276 the end of the Miocene, is an erosional surface (e.g. Figs. 3, 4).
277
278 The Pliocene-Quaternary seismo-stratigraphic complex is composed mainly of terrigenous
279 sediments. It is supposed that the component clastic materials were transported into the basin
280 by the predecessors of the modern Don, Kuban and other rivers.
281

Geological interpretation of the DOBRE-2 CDP profile in the northern eastern Black Sea (Figure 6)

The Black Sea segment of the DOBRE-2 CDP profile shown in Figure 6 provides a regional scale image of the geological structure of the main study area. A brief description follows, highlighting the main diagnostic features of the geological structures – depocentres and structural highs – traversed along it. Much of the detailed structural complexity associated with the Cenozoic compressional tectonic stage, including mud diapirism, is obscured at the scale of interpretation and, in turn, much of the Mesozoic extensional tectonic structures are obscured by the later shortening processes. It is beyond the scope of the current paper to go into details that may be relevant to specific hydrocarbon exploration targets, including lithologies that could represent source rocks, traps or reservoirs and associated structures. The main focus is on the regional-scale relationships between structural highs and depocentres and the relative ages of each.

The northernmost part of the DOBRE-2 CDP profile (Fig. 6) images the submerged (below sea level) southernmost part of the Crimean-Caucasus foldbelt, which is complicated by fault tectonics and volcanic activity (e.g. Meijers *et al.* 2010). Jurassic- Lower Cretaceous complexes can be identified in the seismic section, partly on the basis of correlation with subsurface data from the southernmost part of Kerch Peninsula and partly on gravity coring in the Black Sea (e.g. Tsiokha *et al.* 2008). Immediately south of the inversion zone, the profile crosses what is referred to as the Kerch Shelf, which, being composed of strongly block-faulted Jurassic and Cretaceous sedimentary strata, is geologically very similar to the inversion zone itself. The Jurassic and Cretaceous successions are as thick as at least 2500 m and more than 700 m, respectively, and show the presence of an anticlinal structure that has been eroded. The southern flank of the anticline is separated from its axis by a reverse fault. The Upper Jurassic sediments here are deformed by a series of low-amplitude faults in small folds. Cretaceous, Palaeocene-Eocene and Maykopian strata are missing because of erosion. Erosional surfaces are indeed typically found within the Oligocene-Miocene succession of the Kerch Shelf. The strata on the shelf, along a system of faults affecting basement and the Mesozoic succession, are dipping southwards towards the Sorokin Trough. The transition from the shelf to the Sorokin Trough occurs along a fault with some 2500 m displacement. The interpretation shown indicates that there is normal displacement on this fault (e.g. offset of what is interpreted as horizon IIIm), in which case it was formed initially during Black Sea

316 rifting and has been inverted during the later Cenozoic compressional phase of tectonics
317 although this cannot be documented at the scale of the image.
318
319 The Sorokin Trough is filled mainly with Maykopian sediments (Oligocene-Lower Miocene)
320 and, in this respect, differs significantly in structure and seismic appearance to the Kerch Shelf
321 to the north and and the North Black Sea High to the south. The Sorokin Trough formed at the
322 beginning of the Oligocene and is filled with up to 5250 m of clay-rich Maykopian sediments,
323 overlain by Middle Miocene and younger strata, these being dominated by alluvial fan
324 deposits. Seismic horizon IIa, which marks the base of the Maykopian complex, is observed as
325 deep as 6.5 s (~8300 m depth) at the deepest point of the Sorokin Trough but cannot be
326 identified with confidence on the northen flank of the trough, which is structurally very
327 complex and is also affected locally by mud diapirism. Maykopian strata in the north-western
328 part of the trough form rather high-amplitude thrust-related folds that display a clear southern
329 vergence on the southern margin of the Trough along the DOBRE-2 profile.
330
331 On its southwestern margin the Sorokin Trough adjoins the North Black Sea High (and
332 contiguous Shatsky Ridge). The southern flank of the North Black Sea High, in turn, adjoins
333 the EBS Basin through a zone in which the Cretaceous and older strata are highly faulted. A
334 notable feature of the North Black Sea High (also seen well in Fig. 4) is the antiformal
335 structure composed of Mesozoic rocks as thick as 1500 m in its core. Numerous normal and
336 reverse faults affect the Mesozoic strata on the southern flank of the North Black Sea High-
337 Shatsky Ridge positive structure but faulting does not define the Palaeocene-Eocene (and, in
338 part, the Oligocene) depocentre of the adjacent EBS Basin. Stratal horizons of the EBS Basin
339 onlap the interpreted IIIm horizon (top Mesozoic) on both its flanks, less steeply on the
340 northern margin with the Shatsky Ridge-North Black Sea High than the southern margin with
341 the Andrusov Ridge. According to the interpretation seen in Figure 6, the maximum depth to
342 the base Cretaceous (horizon IV) in the EBS Basin is located at a depth of ~11650 m.
343
344 The DOBRE-2 CDP profile terminates on the Andrusov Ridge, which is part of the Mid-Black
345 Sea Ridge that separates the WBS and EBS basins. The positive structure of Andrusov Ridge
346 is distinguished on the basis of seismic reflection horizon IIIm, which defines a wide arch.
347 Cretaceous as well as Upper and Middle Jurassic units have been inferred in the Mesozoic
348 strata on Andrusov Ridge according to patterns seen in the reflection section (e.g. stratal
349 terminations, erosional truncations and other features; Tsiokha *et al.* 2008).

The DOBRE-2 CDP profile as a whole

The main focus of this paper is the regional basin architecture of the northeastern EBS, coincident with the southern margin of the Crimea-Caucasus inversion zone and south of it, where it has been imaged by the Black Sea segment of the DOBRE-2 regional CDP profile. It is nevertheless instructive to consider this in the context of the basin architecture imaged by the rest of the DOBRE-2 CDP profile and the coincident DOBRE-2 WARR profile.

Figure 7 shows in its upper panel a compressed version of the DOBRE-2 CDP profile (the segment displayed in Figure 6 as well as segments acquired onshore the Kerch Peninsula and offshore in the Azov Sea). The main features to be seen in the basin architecture below the Kerch Peninsula and Azov Sea segments include a marked asymmetry of the Crimea-Caucasus inversion zone, with a much thicker Maykopian complex on the northern margin of the inversion zone than on the south. This in turn overlies a succession interpreted to be Cretaceous that is much thicker than on the southern margin of the inversion zone. This major sedimentary depocentre is called the Indolo-Kuban Trough and lies essentially conformably on Jurassic basement that shallows rapidly to the north. Further north is a series of partially inverted half grabens containing Mesozoic and Palaeogene strata called the North Azov Trough. The zone of shallower basement between the Indolo-Kuban Trough is the Middle Azov Uplift, where basement is shallowing, and the Azov Ridge, where the basement surface is more or less flat.

The lower panel of Figure 7 displays the WARR velocity model of Starostenko *et al.* (this volume) converted to two-way travel-time and displayed at the same scale as the CDP profile above it. In general in the WARR model velocities in the range 1.8-4.5 km/s can be considered to represent relatively undisturbed sedimentary rocks while velocities above this but less than ~5.8 km/s may also represent sedimentary strata though deeply buried and highly indurated, including carbonates such as those representing the Upper Jurassic succession in study area (e.g. Nikishin *et al.* 2015a). Higher velocities almost certainly represent crystalline basement (cf. Starostenko *et al.* this volume). No exact correspondence of velocity-seismic boundaries is expected, of course, since the CDP method delineates clearly horizontal or gently inclined reflectors while the WARR method can recognize near vertical discontinuities due to the refraction of a wavefront.

Key seismic horizons taken from the DOBRE-2 CDP profile (upper panel; Fig. 7) are superimposed on the time-converted WARR velocity model (lower panel; Fig. 7). The yellow line corresponds to seismic horizon Ia (top Maykopian), the pinkish line to IIIm (top Mesozoic). The dotted white line represents the base of anything in the seismic image that looks "sedimentary". It corresponds roughly with the bottom of the coloured in parts of the CDP image. According to the WARR velocity model anything that is below the top of the pink layer (i.e., velocity > ~5.8 km/s) likely corresponds to crystalline basement rocks whereas the overlying orange layer (velocity ~5.4-5.7 km/s and lying largely below the dotted white line marking the base of sedimentary strata from the CDP image) could be interpreted as representing highly indurated (meta-)sedimentary rocks.

Figure 7 (lower panel) indicates that the structural high below the main Crimea-Caucasus inversion on the southern Kerch Peninsula and Kerch Shelf, where older sedimentary strata, including Mesozoic strata occur at or near the surface, is supported by a deeper crystalline basement high. The same is true of the North Black Sea High-Shatsky Ridge positive structure. On the northern flank of the inversion zone, where the Maykopian succession is thicker than on the southern flank and overlies a Cretaceous succession thicker than elsewhere on the entire profile, the WARR velocities suggest the existence of a substantial pre-Cretaceous sedimentary succession, the base of which lies at a depth greater than 20 km (Starostenko *et al.* this volume).

Discussion

In the northeastern Black Sea the Crimea-Caucasus Inversion Zone is bordered on its southern flank by a basin – the Sorokin Trough, which is in turn bordered by a basement high – the North Black Sea High-Shatsky Ridge, then another depocentre – the EBS, and the another basement high – the Andrusov Ridge. The Sorokin Trough is mainly filled with Maykopian sediments but is structurally complicated by reverse faulting, some faults displaying geometries suggesting that they are inverted extensional structures. To the north of the Crimea-Caucasus Inversion Zone, as seen in the whole DOBRE-2 CDP image, the Indolo-Kuban Trough is also primarily filled with Maykopian strata, although the Indolo-Kuban Trough is much less structurally complex that the somewhat symmetric Sorokin Trough on the southern side of the inversion zone. The younger (post-Mesozoic) sedimentary complexes are

mostly absent in the inversion zone itself where Mesozoic strata are near the surface, structurally equivalent to the Cretaceous-Jurassic strata that is uplifted and exposed in the Crimea Mountains to the west.

The WARR velocity model shows that the southern flank of the main inversion zone is underlain by a basement uplift below the Mesozoic complex, indicating a thick-skinned, basement-involved, mode of shortening. Seismic horizon IIIm (top Mesozoic; pinkish line in the lower panel of Figure 7) and the sub-parallel dotted white line at the base of clear sedimentary layering can be taken as representations of vertical displacement of basement during Cenozoic inversion. These show, despite some degree of asymmetry, that the Indolo-Kuban and Sorokin troughs can be considered as marginal troughs formed synchronously and adjacent to a developing central inversion zone as predicted theoretically by Hansen & Nielsen (2003), who built a numerical model of the compressional shortening of a pre-existing rift basin at the crustal scale. In the Hansen & Nielsen (2003) model the "marginal troughs" of basin inversion axes (such as clearly expressed, for example, along the inverted Polish Basin; e.g. Dadlez *et al.* 1995) form as a flexural isostatic response to crustal scale thickening and concomitant density changes caused by the compressional shortening. This is not crustal folding or buckling, which is an anelastic response to loading, nor is it flexural foreland basin subsidence, which is caused by the regional isostatic response to surface loading of thrust sheets. Nevertheless, the formation of these marginal trough basins is intrinsically linked to the tectonic shortening and mountain-building processes that are occurring, as was recognised for the Crimean Mountains and Sorokin Trough by Yudin (2011) and Yudin & Gerasimov (1992).

In a more regional context, the Indolo-Kuban Trough continues to the east of the present study area (e.g. Fig. 1) to lie north of the Greater Caucasus Orogen in Russia (cf. Figure 1 in Nikishin et al. [this volume], where it is labelled the West Kuban Basin). In the context of the symmetry and co-genetic implications for the Indolo-Kuban Trough and Sorokin Trough inferred in the present study, the Tuapse Trough, south of the Russian margin of the EBS, can be considered to be the analogous marginal trough counterpart basin on southern flank of the Greater Caucasus Orogen. Thus, on a regional scale, the Sorokin and Tuapse troughs form one single tectonic entity to the south of the Crimea-Caucasus Inversion Zone and related to its formation.

The asymmetry of the marginal Sorokin and Indolo-Kuban troughs displayed in the present study area, centred on the southern Kerch Peninsula-Kerch Shelf, is likely related to an initially asymmetric basement structure. There is an older deeper basin inferred by the WARR velocity model to the north of the inversion directly underlying the thick Mesozoic sucession of the southern Indod-Kuban Trough imaged by the CDP profile. This might well represent the deeper expression of the Jurassic Greater Caucasus Basin, which is the primary entity being inverted to form the Greater Cauacasus orogen (e.g. Nikishin *et al.* 2010). Sheremet *et al.* (this volume) and Saintot *et al.* (2006b) both mention geological evidence from Crimea for active extensional tectonics and rapid basement subsidence in the Jurassic contemporaneous with the main rifting phase of the Greater Caucasus Basin in the area of the present Greater Caucasus orogeny (Saintot *et al.* 2006a). Accordingly, it is plausible that the Greater Caucasus Basin rift basin lies buried between the Crimea Mountains and the Greater Caucasus itself where it is seen in the exposed geology. In this case, then the seismic image suggests that the main structure controlling inversion in the Kerch Peninsula-Kerch Shelf area could be the bounding faults of the southern margin of the Greater Caucasus rift zone.

The Palaeocene-Eocene strata of the EBS Basin are not fault-bounded (e.g. Fig. 6) but rather onlap the North Black Sea High-Shatsky Ridge on its north flank. The interpretation shown here accordingly implies an absence of extensional/rift tectonics for this basin in the Palaeogene, which had been previously argued (e.g. Finetti *et al.* 1988; Robinson *et al.* 1996). The current interpretation, with its thin, albeit poorly constrained Cretaceous layer underlying the Palaeogene depocentre is a conservative interpretation, made as such given the poor imaging below what is confidently identified as seismic horizon IIIm (top Mesozoic). It is noted that Niksihin *et al.* (this volume) suggest from other, close-by, regional seismic profiles that a substantial, fault-bounded, syn-rift (Black Sea phase of rifting) Cretaceous succession underlies the IV (?) horizon as shown in Figure 6. This is a plausible interpretation that presupposes but does not diagnostically document that the EBS Basin was formed by active rifting in the Cretaceous, more or less contemporaneously with the WBS (e.g. Stephenson & Schellart 2010). In either case, the Palaeogene succession as seen in Figure 6 may have formed at least in part as a result of post-rift subsidence over a central EBS rift zone (i.e., as inferred by Nikishin *et al.* this volume) but the lack of the more regional expression more typical of a broader, overlapping thermal sag over a syn-rift axial depocentre suggests that its formation has also been in part controlled by the compressional tectonics that started in the Eocene (or possibly Palaeocene; Sheremet *et al.* this volume). As such, the North Black Sea High-Shatsky

Ridge would have formed primarily as a compressional structure during this time, not as a flexural bulge (cf. Nikishin *et al.* this volume) and probably involving inversion of older structures, contemporaneous with that in the main inversion zone to its north and the subsidence of its marginal Sorokin Trough (cf. Stovba *et al.* 2013). In this regard it is noted that the northward-dipping zone of seismicity recognized by Gobarenko et al. (this volume) projects to beneath the North Black Sea High-Shatsky Ridge strengthening an interpretation in which this positive structure is actively involved in current compressional tectonic processes in the northern eastern Black Sea.

It is noted that the contrast in interpretations regarding the thickness of the Maykopian succession overlying this area (e.g. the present interpretation [e.g. Fig. 6] and those of Stovba et al. [2013] and Nikishin et al. [this volume]) has significance for inferring the timing of a key compressional deformation event in the Cenozoic. The latter interpretations permits this to be later than the former: more or less synchronous with (Oligocene-Early Miocene) Maykopian deposition rather than terminated prior to the end of the Oligocene.

Summary and conclusions

The age and architecture of the sedimentary successions of the northeastern EBS basin have been documented from reflection seismic profiling acquired in the area and investigated by Ukrgeofizika and other Ukrainian organisations. These include the one-off regional DOBRE-2 CDP profile acquired by Ukrgeofizika in 2007. These studies have allowed the sedimentary successions of the area – from the Kerch Peninsula and Kerch Shelf south to the central Black Sea – to be subdivided into a number of tectono-sedimentary complexes and have revealed a series of basement structural highs separating a series of sedimentary depocentres. This regional architecture of the northeastern EBS was then compared to that imaged to the north of the Kerch Peninsula in the Azov Sea from the regional DOBRE-2 CDP as a whole.

The dominant driver of the present-day architecture of the study area, as indicated by structural and stratigraphic relationships including erosional gaps and hiatuses, folding and reverse faulting, has been the compressional tectonic regime affecting the area during the Cenozoic. Some but not all reverse faults can be seen to be inverted normal faults developed during earlier extensional regimes when the Jurassic Greater Caucasus and Cretaceous Black Sea back-arc basins were formed.

Compressional deformation and shortening is most severe in the Kerch Peninsula-Kerch Shelf area, which can be characterised as the central inversion zone within the study area. It is part of the contiguous Crimea-Caucasus orogenic belt that is more developed in the Crimean Mountains to the west and most developed in the Greater Caucasus Orogeny to the east.

Some specific conclusions are as follows:

(1) Cenozoic sediments are as thick as 5 km in the area of the Subbotina hydrocarbon discovery (part of what is called the Kerch-Taman Trough). The discovery is within an anticlinal structure complicated by thrust faults unconformably overlain by Quaternary-Pliocene deltaic deposits.

(2) The Sorokin Trough is some 40-50 km wide, covering the major part of Black Sea continental margin, locates ~50 km south of the Crimean Peninsula coast and running for ~150 km along the coastline. It is filled with Maikopian sediments, predominantly) clays of greater than 5 km thickness overlain with the Middle Miocene-Quaternary sandy-clay deposits as thick as 3.5-4 km.

(3) The Sorokin Trough is a marginal trough to the main Crimea-Caucasus Inversion Zone with the Indolo-Kuban Trough beneath the Azov Sea its northern margin counterpart in the present study area.

(4) The Shatsky Ridge and the EBS Basin (Palaeocene) are at least in part syn-compressional structures.

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775 Table 1. **Acquisition parameters and basic processing sequence for CDP data within the Black**
776 **Sea (Ukrainian sector) used in the present study.**
777

ACQUISITION PARAMETERS			
Seismic survey	DOBRE-2 (2007) & Titul-407 (2008)	Polar Trade Research Associates (2005)	Western Geophysical (1994)
Ship`s name	Iskatel	Professor Polshkov	Western Challenger
Recording system	MSX I/O	MSTS Syntrak 480-16	TITAN 1000
Recording format	SEG-D	SEG-D	SEG-D
Record length (s)	15	15	9
Sampling rate (ms)	2	2	2
Streamer type	INPUT/OUTPUT	Syntrak 480 Digital Model LDA	Streamer
Recorded seismic channels	240	480	324
Length of streamer (m)	3000	6000	4050
Group interval (m)	12.5	12.5	12.5
Minimal offset (m)	165	120	137
Cable depth (m)	9	8	9
Seismic source	Sleeve airgun array	Airgun array system	Sleeve airgun array
Total volume (cubic inches)	1520	3800	4500
Shot interval (m)	50	50	25
Source depth (m)	6	6	6
DATA PROCESSING FLOW			
Reading of the field seismic data in SEG-D format and reformat to ProMAX system			
Geometry definition and create database profile			
Interactive editing bad shots and receivers			
CDP velocity analysis			
Getting stack brute			
Amplitude recovery			
Bandpass filtering			
The weakening of linear wave noise (FK filtering)			
Predictive minimum-phase deconvolution			
Velocity analysis (step each 100 CDP)			
Suppression of multiples (Radon filtering)			
Velocity analysis (each 50 CDP step).			
Additional bottom and top muting			
DMO			
Velocity Analysis after DMO			
Final stacking			
Minimum-phase deconvolution			
FX deconvolution			
Kirchhoff post-stack migration			
Variable in time bandpass filtering			

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Figure captions

Figure 1. The study area in the northeastern Black Sea-Crimea (Kerch Peninsula)-Azov Sea: tectonic and structural background (left panel) and locations of seismic lines (55-407, 161-94, 54-94 and DOBRE-2; both panels) and wells (Sinop-1, Subbotina 1, 2, 3 and 403; right panel) mentioned in the text. Blue contour lines (50, 100, 200, 500, 1000, 1500 and 2000 m) represent bathymetry (water depths are less than 50 m everywhere in the Azov Sea) and black contour lines represent the structural disposition of horizon IIIm (see text), the top of the Mesozoic succession (contour interval generally 200-300 m, depending on detail). The seismic grids seen in the right-hand panel are those the interpretation of which has contributed to the present study (Western Geophysical 1994 – black lines; Polar Trade Research Associates 2005 survey – torquoise lines; Ukrgeofizika Titul-407 2008 – green lines). The highlighted profiles are reproduced with geological interpretations in this paper.

Figure 2. Ukrgeofizika regional stratigraphic column for the study area identifying seismic horizons interpreted on seismic profiles seen in Figures 3-7. Not all labelled horizons or uncomformities are discussed in the present text.

Figure 3. Seismic profile 55-407 (located on Figure 1) across the Subbotina oil field, within the Kerch Trough dominated by thrust tectonics and showing wells 1-3 and 403 (Fig. 1). Solid black lines indicate seismo-stratigraphic horizons with labels related to the stratigraphic column in Figure 2. Red lines indicate inferred thrusts.

Figure 4. Seismic profile 161-94 (located on Figure 1) across the Sorokin Trough and North Black Sea High. Solid black lines indicate seismo-stratigraphic horizons with labels related to the stratigraphic column in Figure 2. Red lines indicate inferred thrusts.

Figure 5. Seismic profile 54-94 (located on Figure 1) across the northern termination of the EBS Basin. Solid black lines indicate seismo-stratigraphic horizons with labels related to the stratigraphic column in Figure 2. Red lines indicate inferred thrusts.

Figure 6. Seismic profile DOBRE-2 (northern eastern Black Sea segment) from the Kerch Shelf south to the Andrusov Ridge on the southern flank of the EBS Basin axis.
Solid black lines indicate seismo-stratigraphic horizons with labels related to the stratigraphic column in Figure 2. Red lines indicate inferred faults.

Figure 7. Upper panel: the whole of the DOBRE-2 regional CDP profile, horizontally compressed, showing the seismo-stratigraphic complexes of the Kerch Peninsula and Azov Sea correlatable with those of the northern eastern Black Sea. Solid black lines indicate seismo-stratigraphic horizons with labels related to the stratigraphic column in Figure 2. Red lines indicate inferred faults. Lower panel: DOBRE-2 WARR velocity model over the extent of the DOBRE-2 CDP profile shown in the upper panel with the vertical axis converted to two-way travel-time, with key horizons from the DOBRE-2 CDP profile superimposed (as explained in the text).

Table 1. **Acquisition parameters and basic processing sequence for CDP data within the Black Sea (Ukrainian sector) used in the present study.**

ACQUISITION PARAMETERS			
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Sampling rate (ms)	2	2	2
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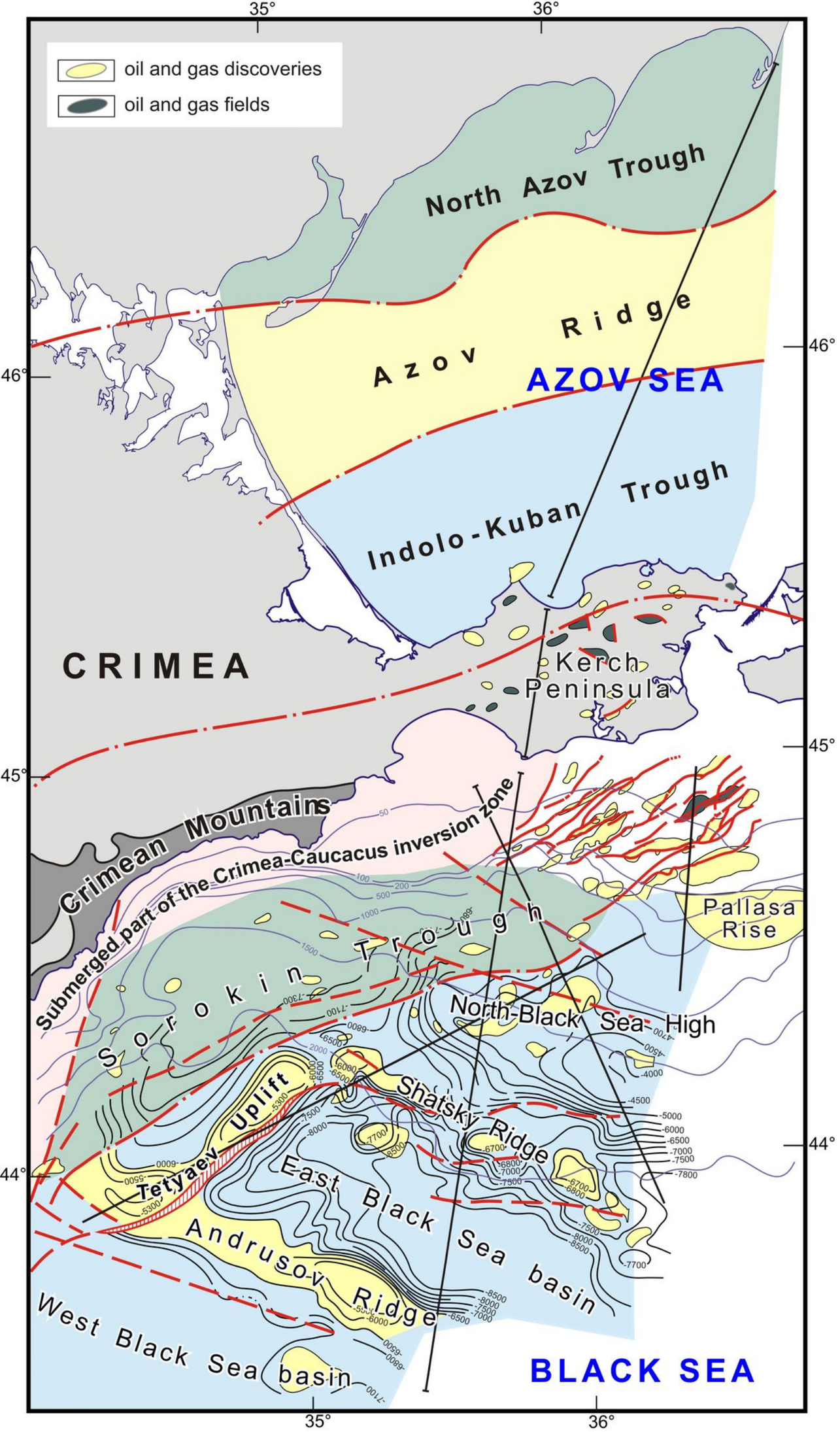
Recorded seismic channels	240	480	324
Length of streamer (m)	3000	6000	4050
Group interval (m)	12.5	12.5	12.5
Minimal offset (m)	165	120	137
Cable depth (m)	9	8	9
Seismic source	Sleeve airgun array	Airgun array system	Sleeve airgun array
Total volume (cubic inches)	1520	3800	4500
Shot interval (m)	50	50	25
Source depth (m)	6	6	6
DATA PROCESSING FLOW			
Reading of the field seismic data in SEG-D format and reformat to ProMAX system			
Geometry definition and create database profile			
Interactive editing bad shots and receivers			
CDP velocity analysis			
Getting stack brute			
Amplitude recovery			
Bandpass filtering			
The weakening of linear wave noise (FK filtering)			
Predictive minimum-phase deconvolution			
Velocity analysis (step each 100 CDP)			
Suppression of multiples (Radon filtering)			
Velocity analysis (each 50 CDP step).			
Additional bottom and top muting			
DMO			
Velocity Analysis after DMO			
Final stacking			
Minimum-phase deconvolution			
FX deconvolution			
Kirchhoff post-stack migration			
Variable in time bandpass filtering			


oil and gas discoveries
oil and gas fields
North Azov Trough
Azov Ridge
AZOV SEA
Indolo-Kuban Trough
CRIMEA
Kerch Peninsula
Crimean Mountains
Submerged part of the Crimea-Caucacus inversion zone
Pallasa Rise
Sorokin Trough
North-Black Sea High
Shatsky Ridge
Tetyaev Uplift
East Black Sea basin
Andrusov Ridge
West Black Sea basin
BLACK SEA
35°
36°
46°
45°
44°

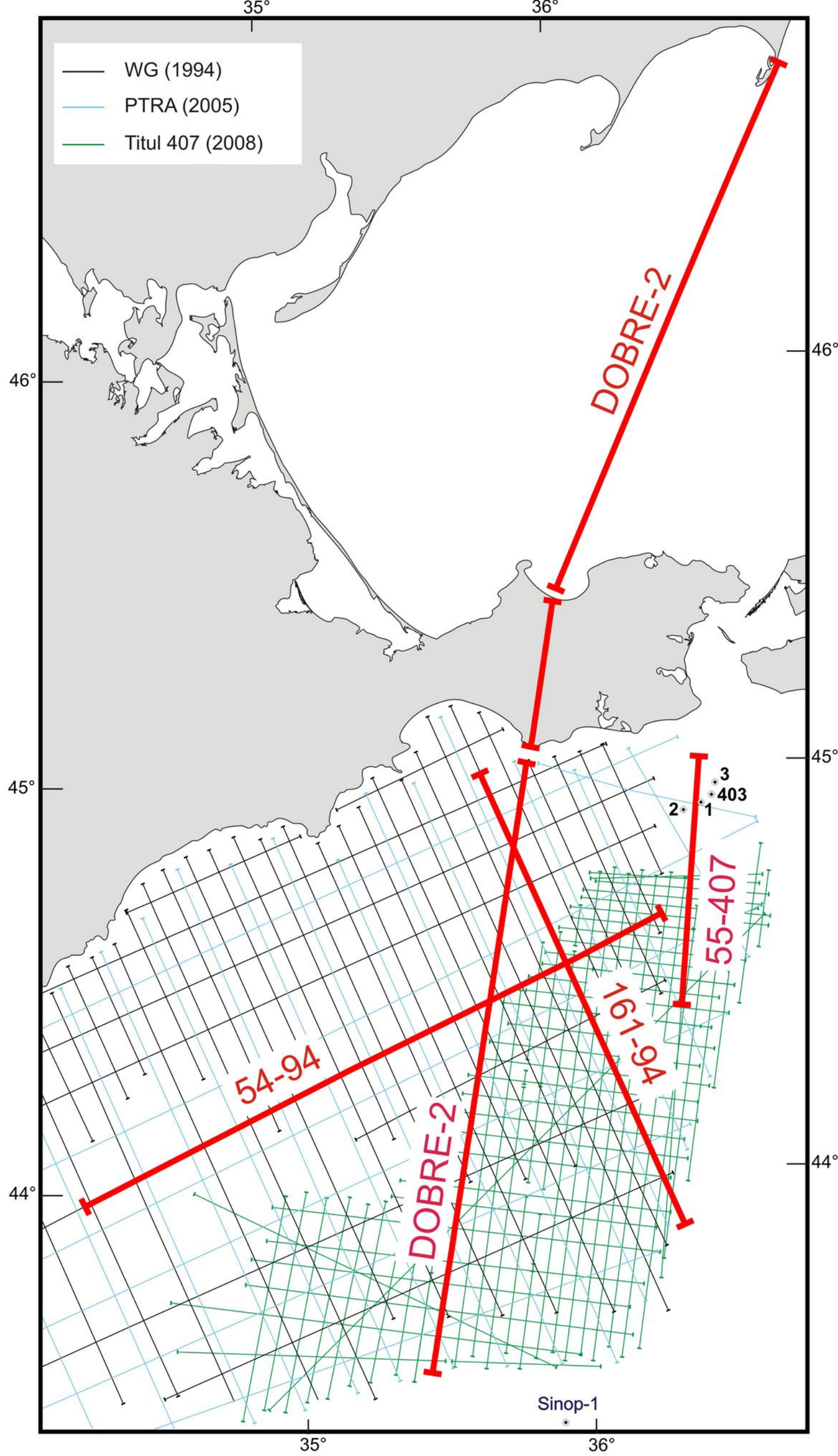
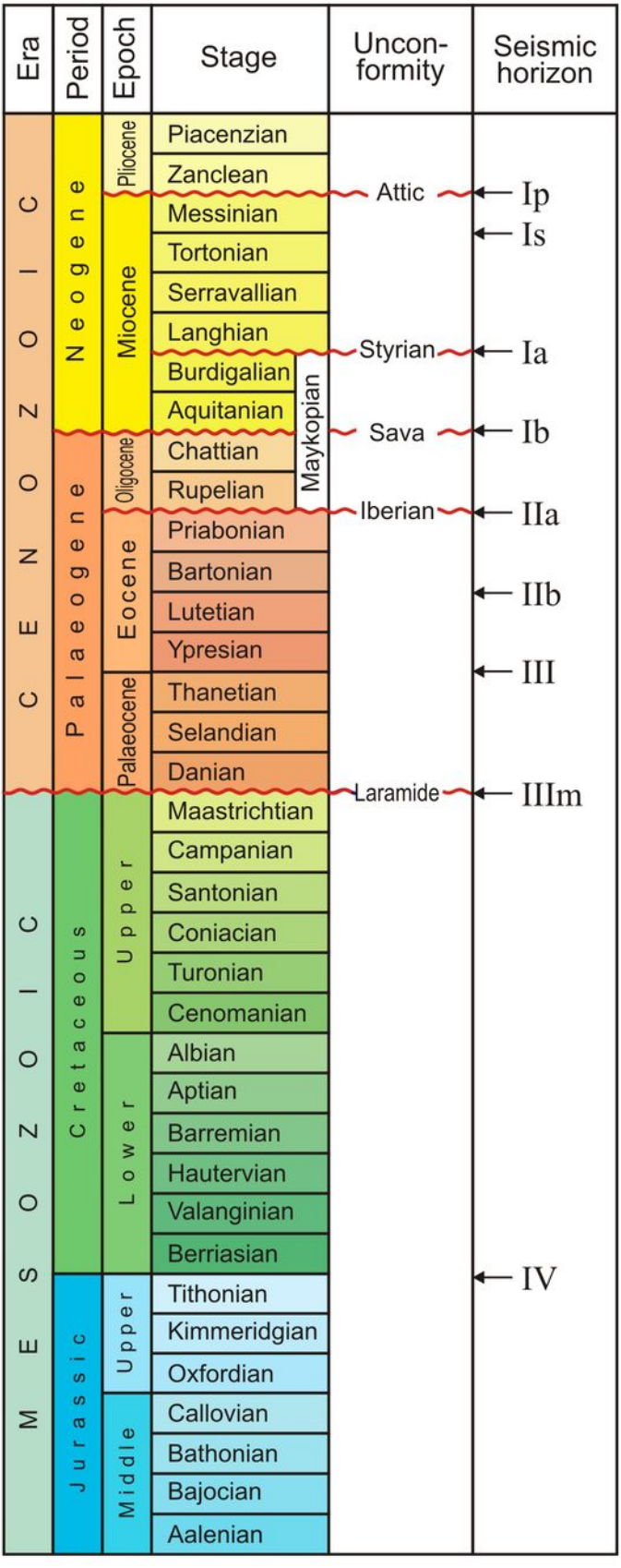

WG (1994)
PTRA (2005)
Titul 407 (2008)
DOBRE-2
3
403
2
1
55-407
161-94
54-94
DOBRE-2
Sinop-1
35°
36°
46°
45°
44°

Fig. 1


Era
Period
Epoch
Stage
Uncon-formity
Seismic horizon
CENOZOIC
MESOZOIC
Neogene
Palaeogene
Cretaceous
Jurassic
Pliocene
Miocene
Oligocene
Eocene
Palaeocene
Upper
Lower
Upper
Middle
Maykopian
Piacenzian
Zanclean
Messinian
Tortonian
Serravallian
Langhian
Burdigalian
Aquitanian
Chattian
Rupelian
Priabonian
Bartonian
Lutetian
Ypresian
Thanetian
Selandian
Danian
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
Aptian
Barremian
Hautervian
Valanginian
Berriasian
Tithonian
Kimmeridgian
Oxfordian
Callovian
Bathonian
Bajocian
Aalenian
Attic
Styrian
Sava
Iberian
Laramide
Ip
Is
Ia
Ib
IIa
IIb
III
IIIm
IV

SEISMIC LINE 55-407

WITH GEOLOGICAL INTERPRETATION

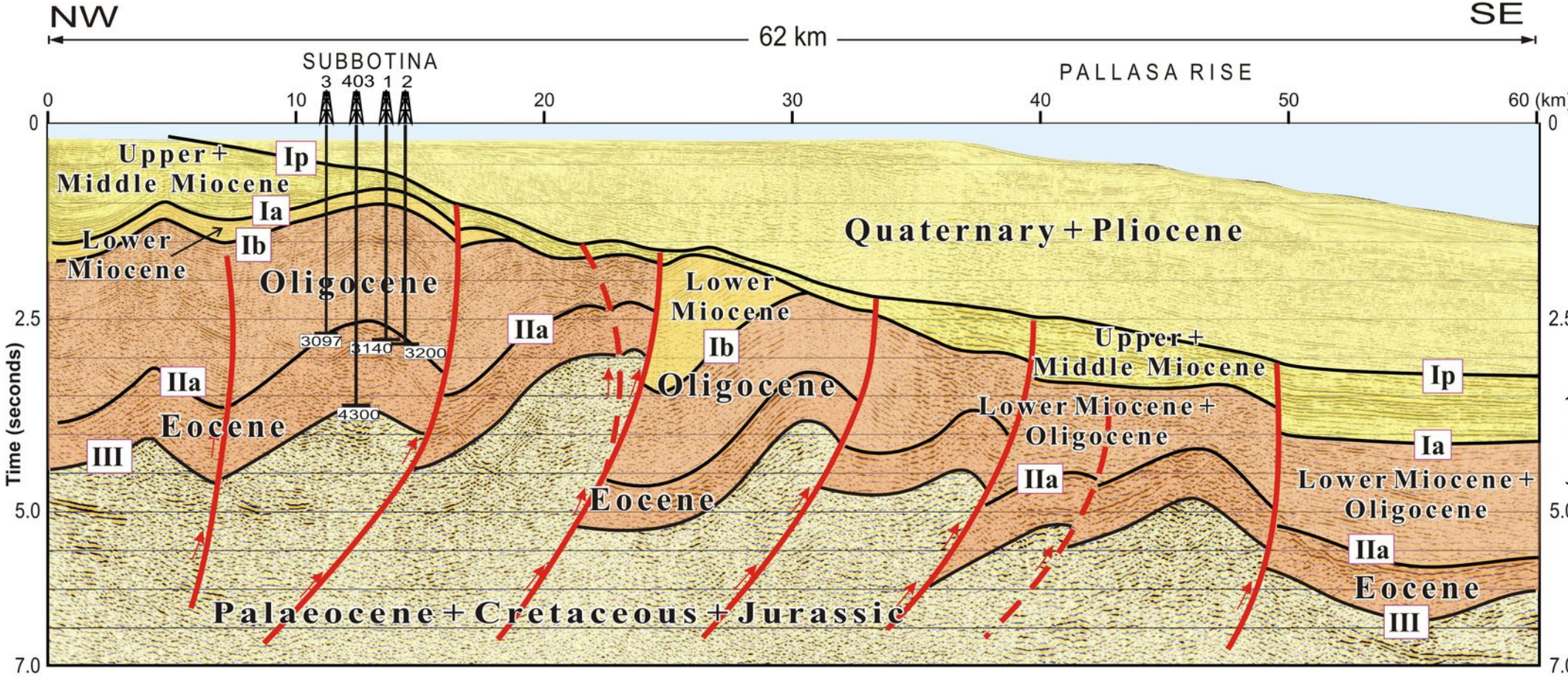


Fig. 3

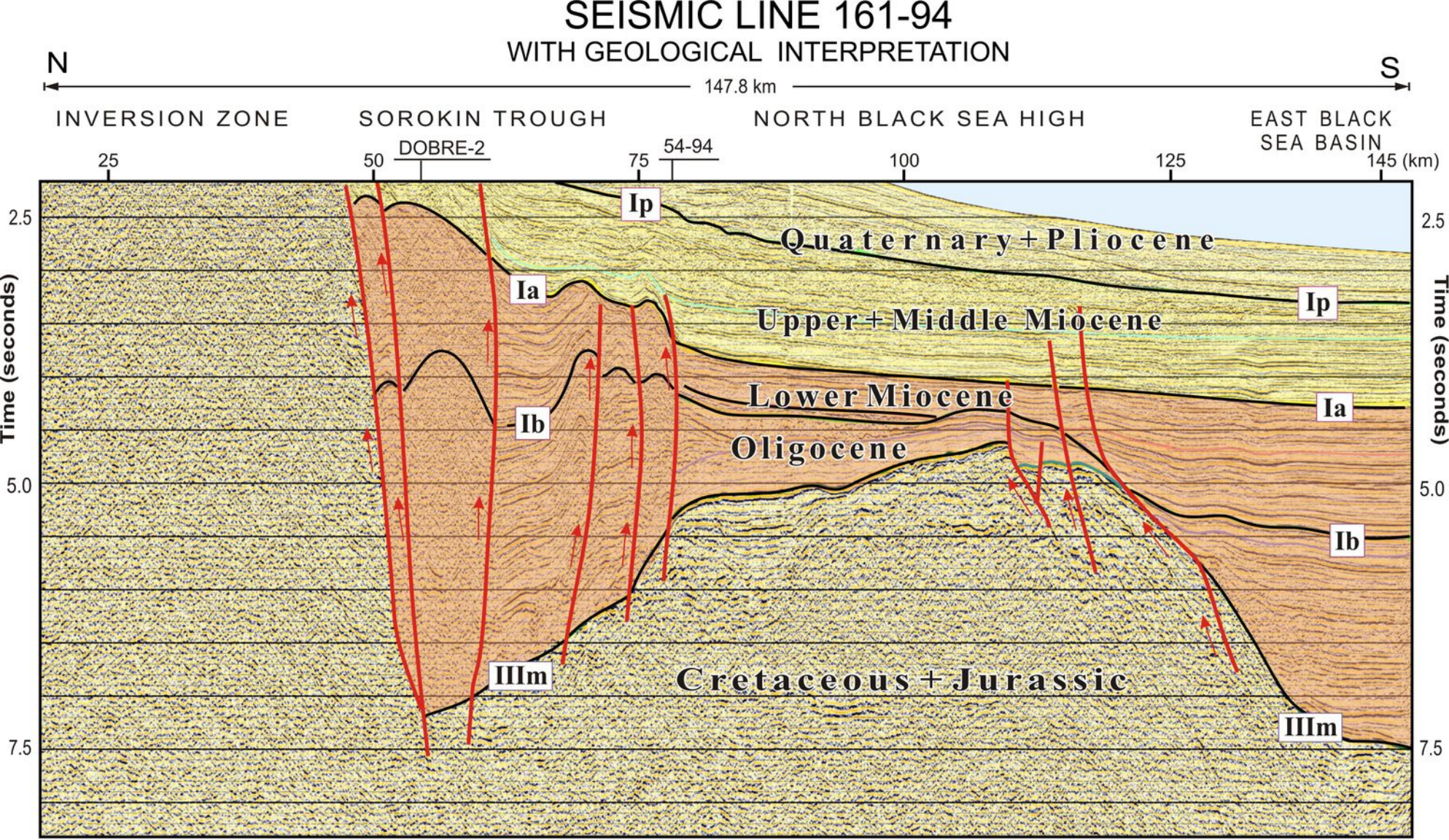

SEISMIC LINE 161-94
WITH GEOLOGICAL INTERPRETATION
N
S
147.8 km
INVERSION ZONE
SOROKIN TROUGH
NORTH BLACK SEA HIGH
EAST BLACK SEA BASIN
DOBRE-2
54-94
25
50
75
100
125
145 (km)
Time (seconds)
2.5
5.0
7.5
Ip
Ia
Ib
IIIm
Quaternary+Pliocene
Upper+Middle Miocene
Lower Miocene
Oligocene
Cretaceous+Jurassic

Fig. 4

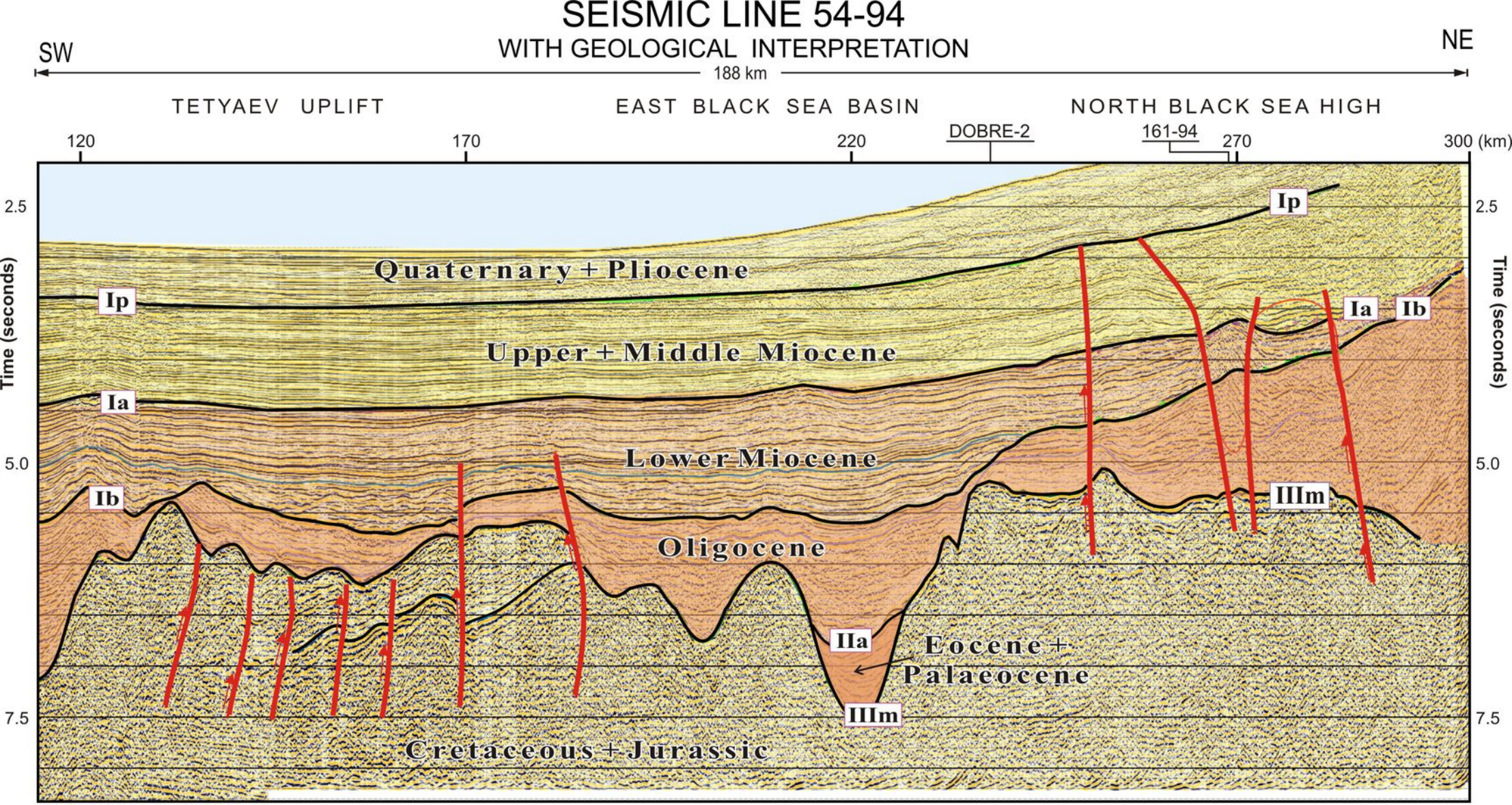

SEISMIC LINE 54-94
WITH GEOLOGICAL INTERPRETATION
SW
NE
188 km
TETYAEV UPLIFT
EAST BLACK SEA BASIN
NORTH BLACK SEA HIGH
DOBRE-2
161-94
120
170
220
270
300 (km)
Time (seconds)
2.5
5.0
7.5
Ip
Ia
Ib
IIa
IIIm
Quaternary + Pliocene
Upper + Middle Miocene
Lower Miocene
Oligocene
Eocene + Palaeocene
Cretaceous + Jurassic

Fig. 5

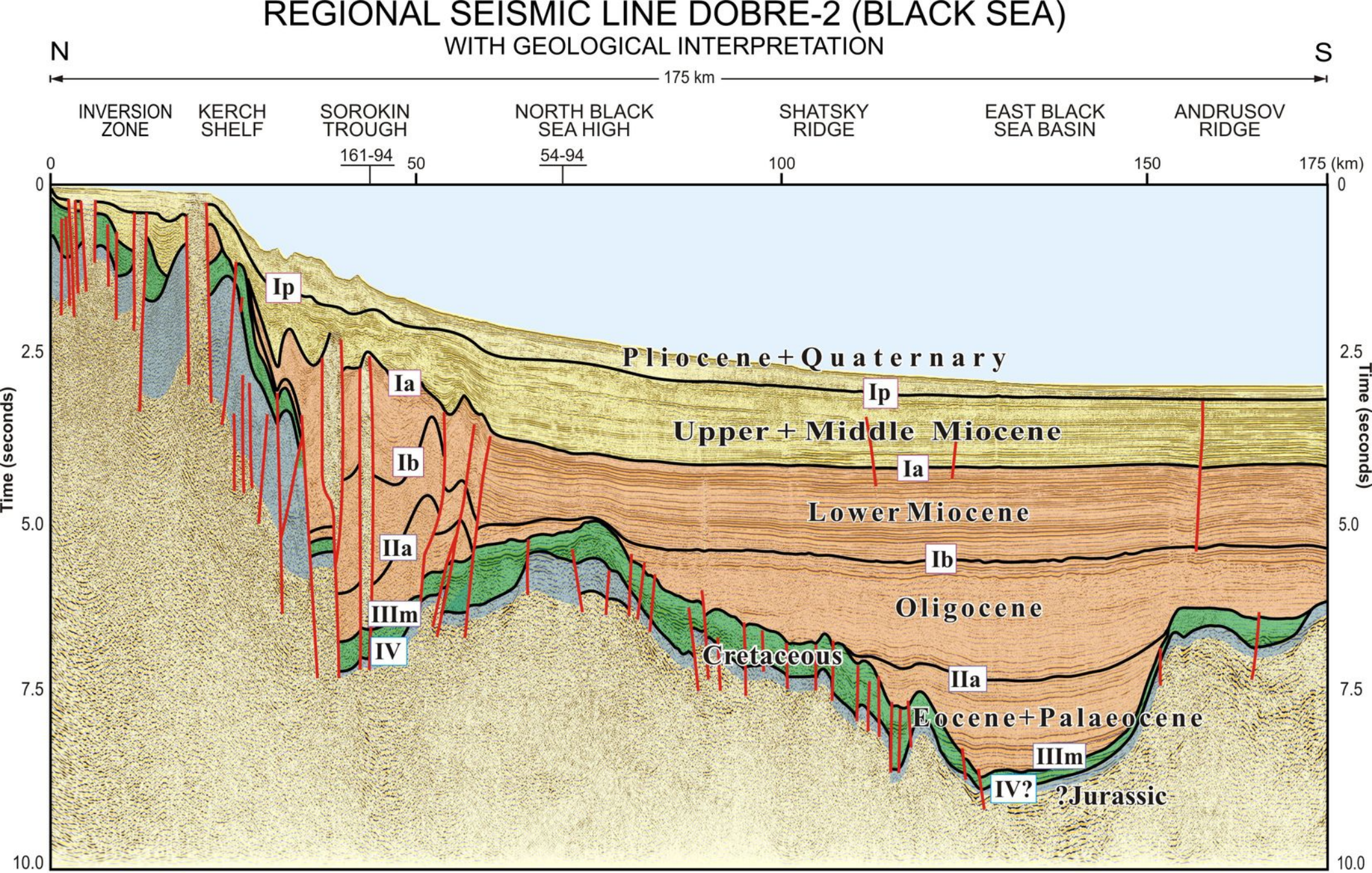
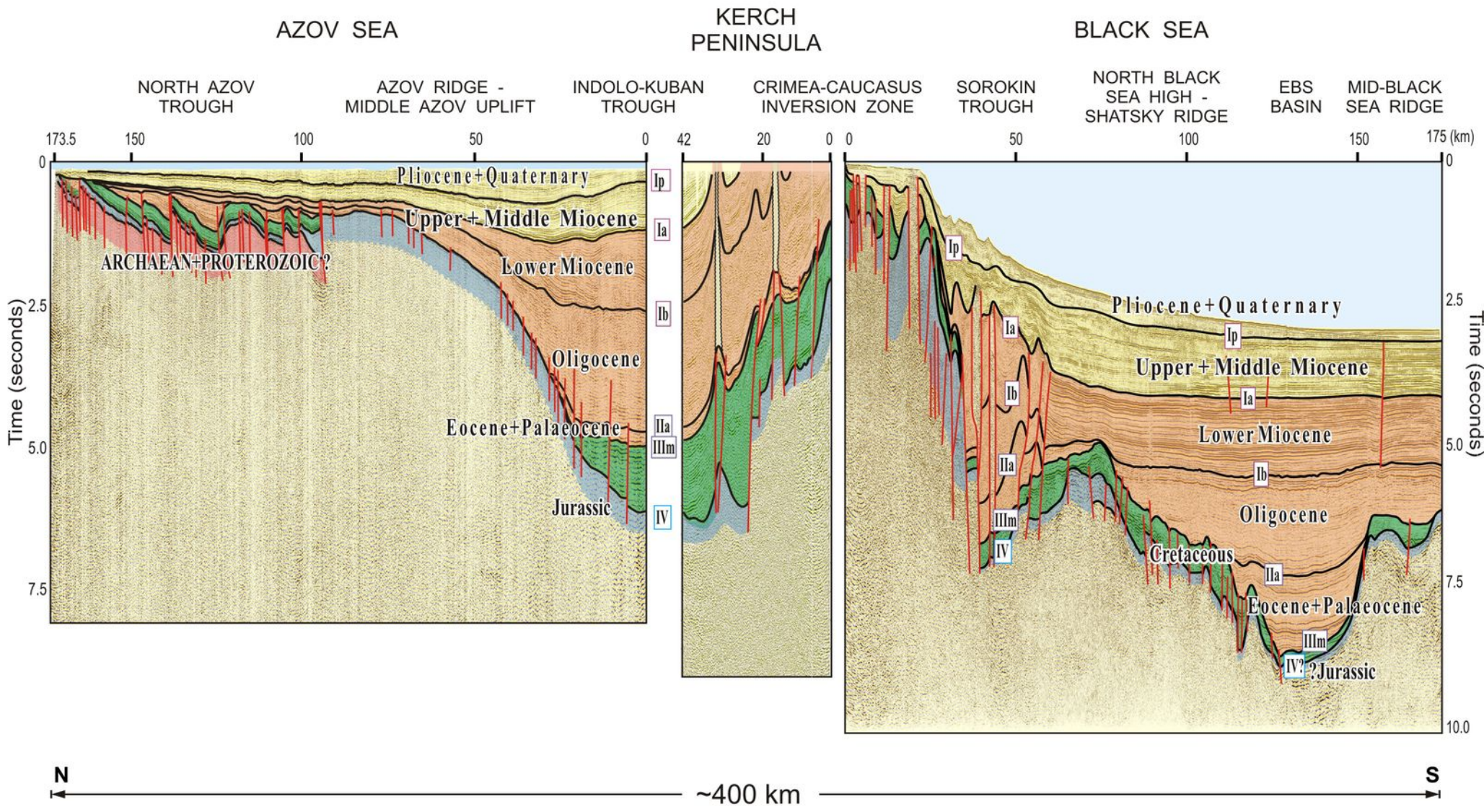

REGIONAL SEISMIC LINE DOBRE-2 (BLACK SEA)
WITH GEOLOGICAL INTERPRETATION
N
S
175 km
INVERSION ZONE
KERCH SHELF
SOROKIN TROUGH
NORTH BLACK SEA HIGH
SHATSKY RIDGE
EAST BLACK SEA BASIN
ANDRUSOV RIDGE
161-94
54-94
0
50
100
150
175 (km)
Time (seconds)
0
2.5
5.0
7.5
10.0
Ip
Ia
Ib
IIa
IIIm
IV
Pliocene+Quaternary
Upper + Middle Miocene
Lower Miocene
Oligocene
Cretaceous
Eocene+Palaeocene
IV?
?Jurassic

Fig. 6

REGIONAL SEISMIC LINE DOBRE-2
WITH GEOLOGICAL INTERPRETATION



REGIONAL SEISMIC LINE DOBRE-2
WITH WARR VELOCITY MODEL SUPERIMPOSED

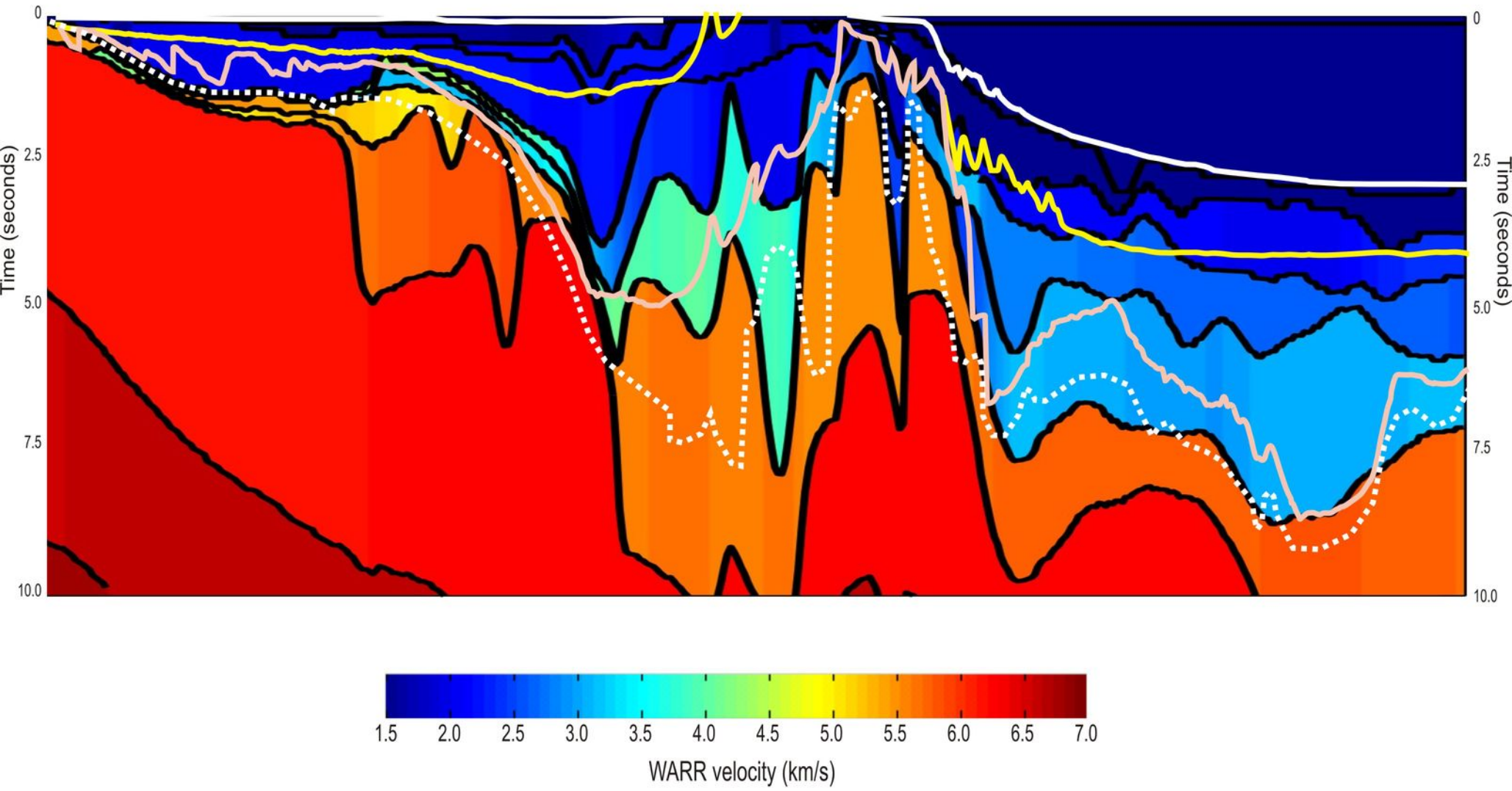


Fig. 7